Experimental results on the use of flux concentrators in an IPT system

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***Abstract*— The paper presents a critical evaluation of different approaches for designing the magnetic system of an inductive WPT (IPT). The common question that need to be addressed, early on, from the designer is will there be any benefits when the magnetic system includes a flux concentrator. This paper considers a FEA of a magnetic design with or without flux concentrators. The self-inductance is kept the same, so it can be applied to the designed power converter for the experimental results. Simulational data for the magnetic coupling, mutual inductance and the resulting magnetic field are given. Experimental verification of the results is also given, along with some additional comments on the influence the magnetic design has on electrical operation of the power converter.**

***Keywords*— inductive power transmission, wireless power transfer, magnetic flux concentrators, power electronics, electromagnetic modeling**

I. Introduction

The widespread academic and industrial interest in WPT (and more specifically IPT) leads to an increasing number of competing methods for the design of WPT system, with different power levels, gap sizes and efficiency [1]. The magnetic part of the system is a key ingredient of any such system, and usually the one that is the most expensive to model and design reliably. This is the reason why every designer requires in addition to analysis, some degree of simulational and experimental data to properly design the system. There are four main questions that must be answered in order to design the magnetic subsystem: What should be the shape of the transmitter and receiver winding? How many of them to include? (Classical case with one RX and TX coils, use of repeaters or multicoil configuration for magnetic resonant coupling), What power converter to use?, and finally, whether and how to include magnetic flux concentrators? The answers depend heavily on the application, which requires different power levels, overall efficiency and volume. This papers tries to answer the last of these questions.

A very detailed research based on the design of magnetic field concentrators is given in [2]. This paper is based on a similar approach for a designed power converter operating at 100kHz. This converter, based on a half bridge resonant inverter is specifically designed to experimentally verify the results obtained from the FEA analysis of the coils. It should be noted that there are some other available alternatives either base on direct ac-ac converter [3], or a modified resonant converter [4], but their efficiency comparison will be discussed in a future paper.

First, for the same desired inductance of the transmitter and receiver two cases with and without magnetic concentrators are simulated, using a FEA analysis software from ANSYS Maxwell. The results for the obtained field, magnetic coupling, number of turns and mutual inductance are given. Then, the two cases of transmitters and receivers are added to the power converter for verification of the obtained simulation results. Finally, the influence of the magnetic system, in both cases, on the electrical operation of the converter is studied.

The paper is structured as follows: In section II the two cases of the modeled magnetic system are presented, along with key design information. Than in section III the main results of the comparison for the case with and without concentrators is given – independently with the simulation software and the experimental verification. Finally, section IV summaries the obtained data and the advantages and disadvantages of both cases considered.

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II. MAGNETIC PART OF IPT SYSTEM

The investigated transmitter and receiver design for the two cases with and without ferrite magnetic concentrations are given in Figure 1. The number of turns on the bare coils is greater than the number of turns on the ferrite coils to maintain equal self-inductance on both coil sets. The obtained data for the self-inductance (L_{SELF}), and the coupling coefficient are given in Table 1 for the coil set without ferrite concentrators and in Table 2, for the coil set with ferrite concentrators.

The chosen ferrite core PS35 with N22 material has an optimum maximum frequency of 200kHz, so the losses in the material can be ignored. The physical dimensions are given in figure 2.

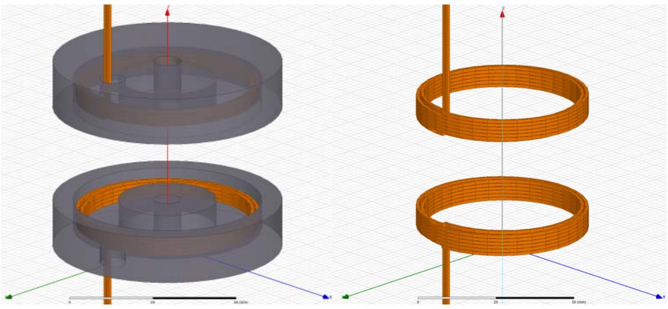

Figure 1. The transmitter and receiver design - with and without magnetic flux concentrations.

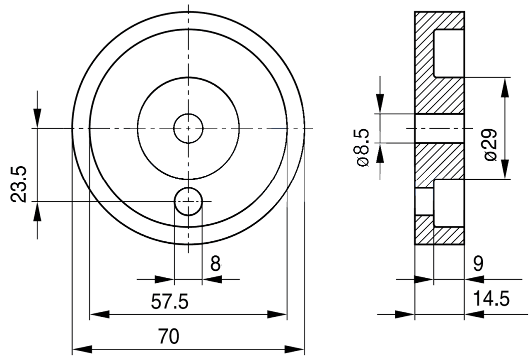

Figure 2. The ferrite flux concentrators dimensions.

The physical realization of the two coil sets have the same geometry as the simulated coil sets. The configurations are shown on figures 3 and 4. The gap between the transmission and receiving coil is measured from face to face. The number of turns for the one without flux concentrators is 12, while the one with concentrators is 8. Both of them have an external diameter of 57mm.

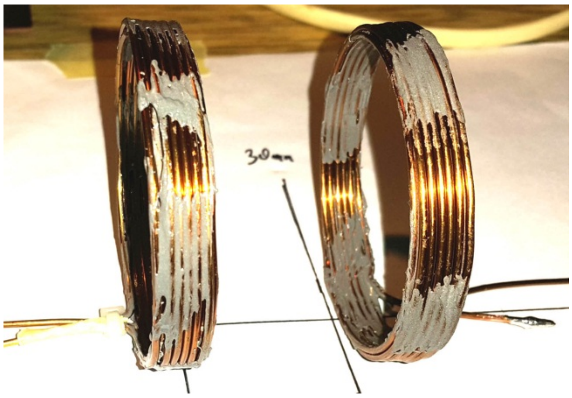

Figure 3. Coil set without magnetic concentrators.

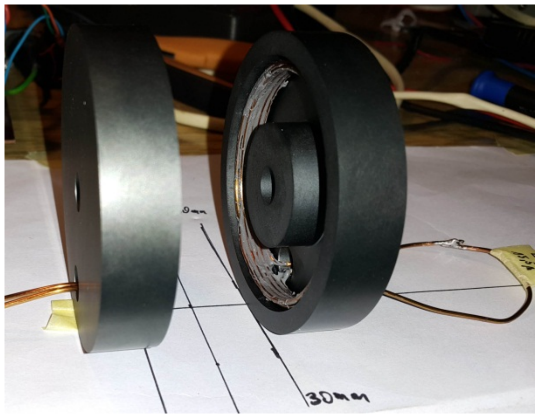

Figure 4. Coil set with ferrite magnetic concentrators.

The self-inductances are measured using a series RLC resonant method. The full testing setup schematic diagram is given in figure 5.

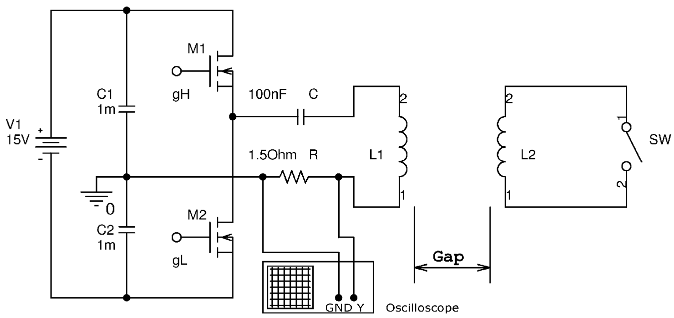

Figure 5. Testing setup schematic diagram.

The coupling coefficient is measured by the same resonant method - figure 6, in two steps: Firstly, the self-inductance is measured with the switch (sw) opened. Secondly, the self-inductance is measured again, but with closed switch. The self-inductance decreases in the second step. Hence, the result coupling coefficient is calculated using equation (1) [5]. The results are shown in table 3, table 4 and figure 6.

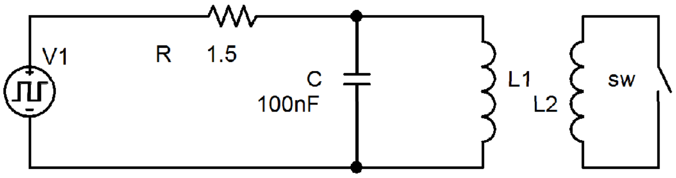

Figure 6. Coupling coefficient measurement schematic diagram

$$k = \sqrt{\left(1 - \frac{L_s}{L_1}\right)} \quad (1)$$

III. RESULTS

The Simulational data for the two coils with and without flux concentrators obtained from FEA Maxwell are shown in Table 1 and Table 2. In Table 3 and Table 4 are shown the ones obtained from the experimental setup.

Table 1 – Simulation data of the coil set without ferrite concentrators

Gap [mm]	Number of turns	L_{self}, μH	k
5	12	12.51	0.336
15	12	12.49	0.179
30	12	12.48	0.081

Table 2 – Simulation data of the coil set with ferrite concentrators

Gap [mm]	Number of turns	L_{self}, μH	k
5	8	20.13	0.534
15	8	15.25	0.229
30	8	14.56	0.081

Table 3 – Measured data of the coil set without ferrite concentrators

Gap [mm]	L_1, μH	L_S, μH	k
5	14.17	12.85	0.31
15	14.17	13.57	0.21
30	14.17	14.17	0.00

Table 4 – Measured data of the coil set with ferrite concentrators

Gap [mm]	L_1, μH	L_S, μH	k
5	19	14.16	0.50
15	15.5	14.63	0.24
30	14.75	14.75	0.00

The graphical comparison for the obtained coupling coefficient are shown in Figure 7 (Simulational from Maxwell) and Figure 8 (Experimental)

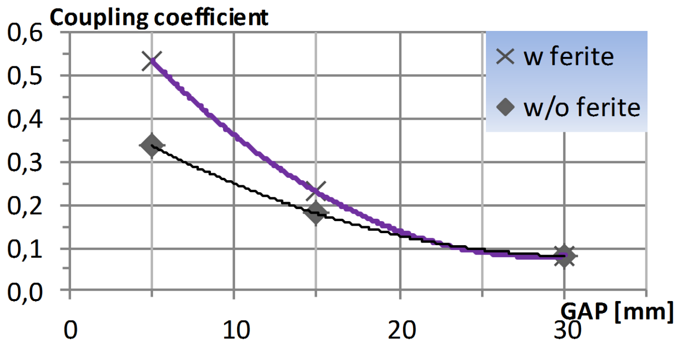

Figure 7. Simulated coupling coefficient with (w) and without (w/o) ferrite concentrators

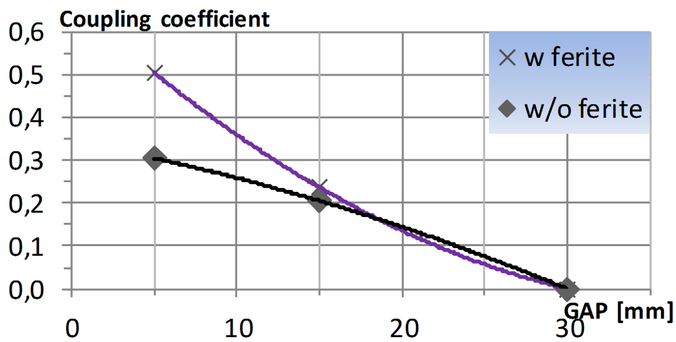

Figure 8. Measured coupling coefficient with (w) and without (w/o) ferrite concentrators

The obtained magnetic field distribution is presented in Figure 9 – without magnetic field concentrators and in Figure 10 – with concentrators. The color scale on the graphics is graduated according to the magnetic flux density, which is measured in Tesla.

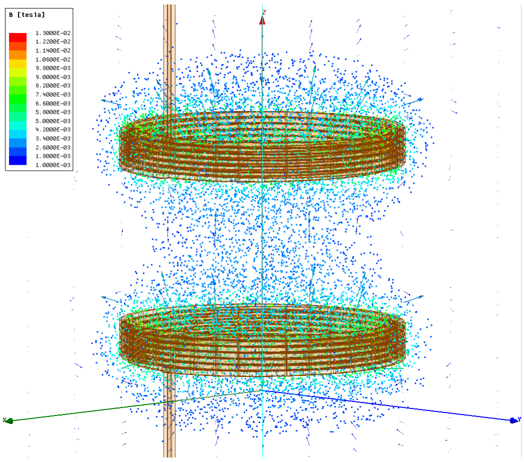

Figure 9. Magnetic flux for the coil set without ferrite concentrators

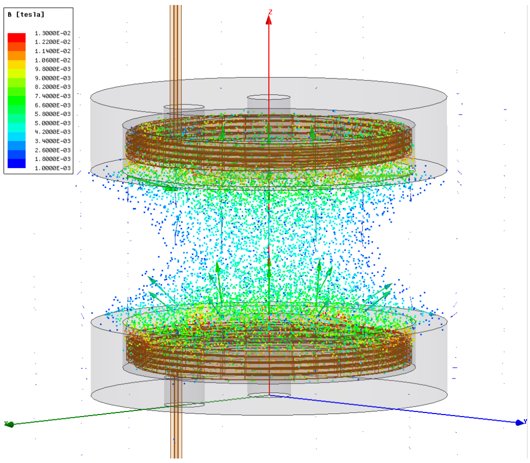

Figure 10. Magnetic flux for the coil set with ferrite concentrators

IV. Conclusions

The paper presented a study on the influence of magnetic concentrators on the design of the transmitter and receiver for an induction WPT system. Designing the system for the same self-inductance, two cases are compared based on coupling coefficient and magnetic field distribution. The introduction of a flux concentrator decreases the number of required turns for the same values of self-inductance and mutual coupling, but increases the quality factor, which results in increased electrical load on the resonant tank.

The magnetic field distribution is far more collimated when using magnetic field concentrators. This helps when IPT coils are near metal parts. In this case the losses will decrease significantly.

Magnetic field concentrators do not affect the coupling coefficient very much, when the gap between the coils is relatively large, but at small transmission distances they can increase the coupling coefficient. At very small gaps, the coupling coefficient can increase significantly.

As a final note, adding a concentrator has a very important role in reducing the leakage fields, thus helping in meeting the requirements for maximum permissible exposure [6]. This aspect is not discussed in this paper, but has very important implications on the design of the various flux concentrators.

Acknowledgment

The work presented in this paper is done with help provided from Technical University- Sofia, R&D sector thought project “Intelligent Electrical Drives for Small Transport Vehicles”, Project 181ПР0013-03.

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