Andreas FUCHS, Hans-Peter SCHMIDT

Technical University of Applied Sciences Amberg-Weiden, Germany

FEM analysis of couplers for inductive power transfer

***Abstract**. Couplers for inductive power transfer are studied via 3-D FEM analysis. Field and lumped parameter calculations are coupled and an N-port model is developed to describe the system. Applications of such couplers and systems are contact less charging units of electric vehicles, sensors or actors in factory automation and intra-logistics. Stray fields and shielding effects are considered. It is shown that an aluminium sheet metal may be beneficially used to reduced field levels in surrounding iron structures and to reduce losses.*

***Streszczenie.** W artykule zaprezentowano analizę metodą elementów skończonych przesyłu mocy indukcyjnej. Obliczenia parametrów polowych i skupionych są sprzężone i do opisania tego systemu opracowano N-wejściowy model. Takie sprzęgacze i systemy znajdują zastosowanie w bezdotykowym ładowaniu pojazdów elektrycznych, sensorach i aktuatorach w automatyce przemysłowej oraz w logistyce. Rozważono pole rozproszenia i efekty ekranowania. Zostało pokazane, że blacha aluminiowa może być skutecznie użyta do redukcji poziomu pola w elementach konstrukcyjnych ferromagnetycznych, a co za tym idzie do zmniejszenia strat. (**Analiza sprzęgaczy dla transferu mocy indukcyjnej metodą elementów skończonych**).*

Keywords: FEM Analysis; Inductive Power Transfer; Contactless Charging;
Słowa kluczowe: analiza metodą elementów skończonych, transfer mocy indukcyjnej, ładowanie bezkontaktowe

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Introduction

We consider the contact less power supply and data transfer [1] for multiple loads that are distributed across some area and are not moving [2]. Such loads are charging units of electric vehicles (EV) at car parks or adjustable speed drives, which are widespread in manufacturing and in conveyer systems [3,4]. The main components of such systems are a power electronics unit for converting the 50/60Hz power grid frequency to the inductive power transfer (IPT) frequency, some rectifying, control circuitry and couplers [4,5]. In this part of our work, we study the coupler design for such stationary apparatus with respect to shielding surrounding iron structures. This extends the work of other groups [4-10].

Frequencies for such IPT applications range from 20 kHz to 140 kHz and power levels vary from a few hundred watts to some ten kilowatts. Couplers dimension are typically some 10mm to a few 100mm. In this study we apply 140kH for power levels of 10-20kW, which are transferred via a 3phase system [11].

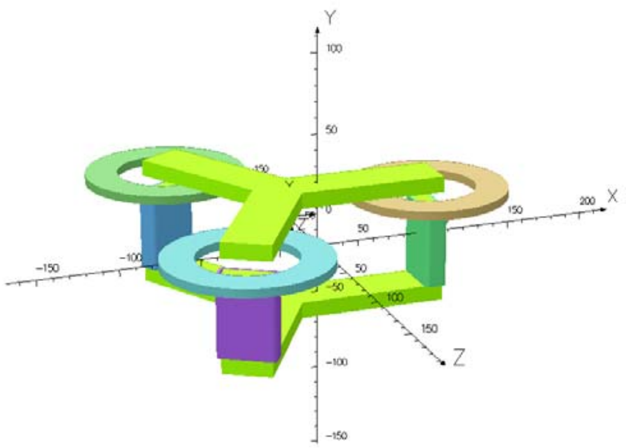

Fig.1. Schematic view of a three phase coupler for EV applications with preliminary dimensions given in mm. Ferrites are given in green

Coupler Design and Model

For the design, we consider commonly used ferrite material for the core and litz wire for the windings. The ferrite material exhibits an overall height of 10mm and a width of 30mm and an according cross-section of 300mm². The actual litz wire cross-section is approximately 5.4mm². For the study we allow for none or mild saturation of the core material.

Therefore, we solve the harmonic equation of magneto - quasi statics for a slightly complex geometry. We use OPERA 3D, a commercial tool, for solving the governing equations. To study the shielding effects we consider aluminium sheets, which are modelled via an impedance boundary layer.

The aluminium sheet may be a deliberately placed sheet metal that covers the car-attached part of the coupler. Also we coupled the FEM equation to circuit calculations to find voltage, current and power levels. From an electrical point of view we use a star like connection and setup of coupler. Here we minimize the use of ferrite material via this three-phase setup. Reduced amount of ferrite implicates less cost and especially less weight for the car mounted part of coupler. An important design restraint. A sketch of such a coupler geometry can been seen in Fig. 1.

Furthermore, we adopted the variant with relatively small air gap. In EV application, such couplers consist of a fixed ground-mounted part and a movable part, which is mechanically shifted towards the car bodyfro actual charging. This design results in a small air gap. The actual gap size is some millimetres to some centimetres depending on the application. The winding of the ground mounted parts are tightly wound around the ferrite legs, while the receiving coils are placed annular at the lower secondary core surface. They are fixed by a nonmagnetic armature, which the schematic view of Fig. 1 does not show.

Electrical Circuit of the Simulation Model

The equivalent circuit that is coupled to FEM calculation is shown in Fig 2. Self- and mutual inductances are taken from FEM calculations. All circuit elements of the sending and receiving end of the coupler are symmetric and electrically connected to a delta setup. In preliminary simulation run, the inductances of the primary and secondary windings are determined. These values are needed for calculations of the required compensation capacitances. For a compensation of the primary inductances L_1, L_2 and L_3 we used a series compensation of C_1, C_2 and C_3 to avoid large currents in the case of resonance. For better voltage stability a parallel compensation consisting of C_4, C_5 and C_6 is used for the secondary windings inductances L_4, L_5 and L_6.

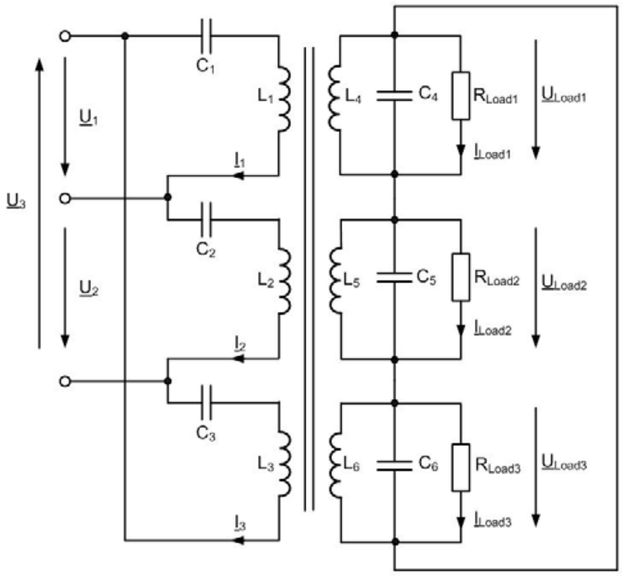

Fig. 2. Electrical circuit of the primary and secondary coupler

Using the FEM coupled model circuit all system voltages, currents and transferred power can be figured out by adjusting the supply voltage levels U_1, U_2 and U_3.

The coupling factor of 0.58 between the primary and secondary windings was readily calculated by two open circuit simulations. The dependency between the coupling factor and the variation of the air gap and amount of ferrite was studied in a other publication with a similar geometry [13].

Field distribution

As a typical result for such a coupler, the B field distribution is depicted in Fig. 3. B-field levels smaller than 20mT are shown. Levels above 20mT are whitened out. In Fig. 3a (left) no aluminium sheet is used where in Fig. 3b (right), a deliberately mounted aluminium plate sits above the coupler. The transferred power is 12kW for both cases.

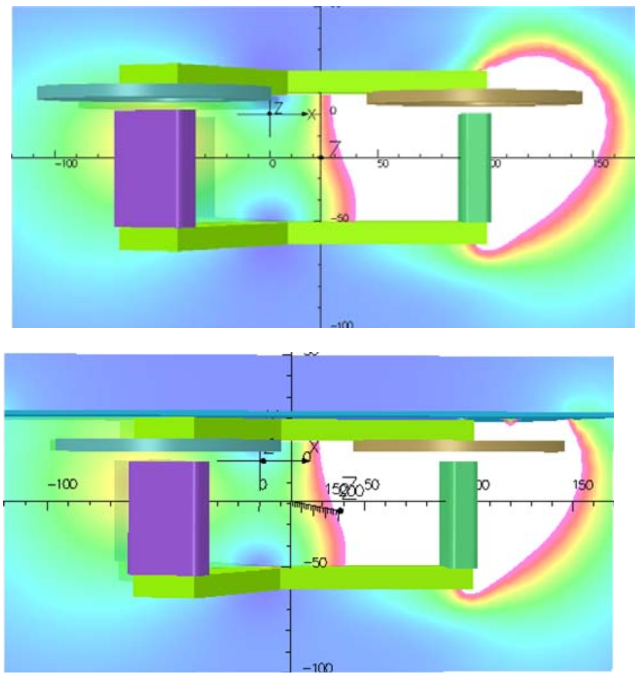

Fig. 3. B-Field distribution samller 20 mT with and without aluminium shield

Fig. 4a shows the corresponding 3D model of the magnetic coupler without and with aluminium sheet. The brownish line given here is the path where the field levels from Figure 4b are taken. This line is placed 10 mm above the ferrite structure.

At the start of the path, which relates to the center of the coupler, the level of flux densities is nearly the same for both structure: with or without aluminium sheet. Since the ferrite material channels the flux here quite effectively. Increasing the distance to the coupler center, the ferrite coverage4r of the area reduced rapidly and the increase in filed levels is much more pronounced in the case of no aluminium compared to case with aluminium sheet.

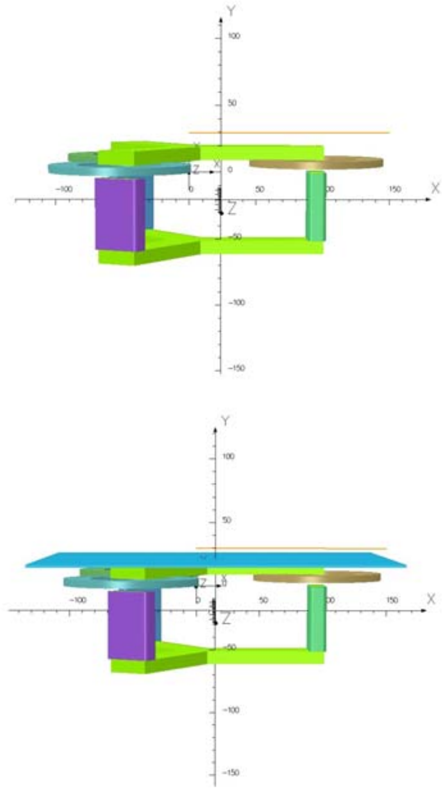

Fig. 4a. Model for the setup with and without aluminium sheet and indication of path

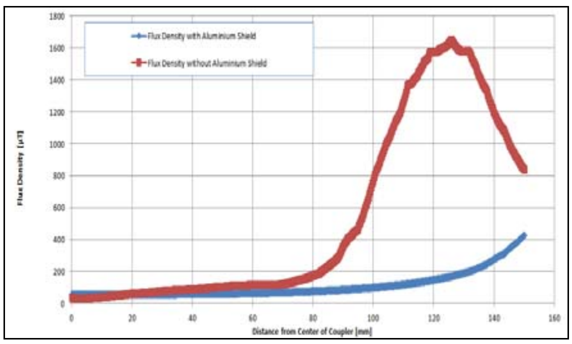

Fig. 4b. Magnetic flux density 10mm above the secondary ferrite with and without aluminium sheet

Conclusion and Outlook

A three phase magnetic coupler for electric vehicle charging has been simulated for assessing the shielding via additional aluminium sheets. A 3 D FEM model is solved for the magneto-quasi static case taking eddy currents into account. This FEM model is solved in conjunction with a

3phase equivalent circuit. This 3phase setup has been applied here to minimize the amount ferrite, which goes onto the car. This lowers not only cost but also weight of the coupler parts that attach to the car. We find that despite the aluminium shield theses ferrites are needed to channel the flux as not the produce excessive field levels in the aluminium and therefore to high losses within this sheet metal.

For identical power transfer we find the field levels in the vicinity of the coupler are markedly reduced, when an additional aluminium sheet is used. Therefore, such a thin aluminium plate may be beneficially used to lower the field levels and in turn the losses in surrounding iron structures. Where such structures may be the car body itself or gearbox/drive train housings, muffler, heat shield etc.

In a further work an experiment has to be carried out to validate the simulation results.

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***Authors**: Prof. Dr.-Ing. Hans-Peter Schmidt, Ostbayerische Technische Hochschule Amberg-Weiden, Kaiser-Wilhelm-Ring 23, 92224 Amberg, Germany, E-Mail: h.schmidt@oth-aw.de; M. Eng. Andreas Fuchs, Ostbayerische Technische Hochschule Amberg-Weiden, Kaiser-Wilhelm-Ring 23, 92224 Amberg, Germany, E-Mail: a.fuchs@oth-aw.de;*