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Design of Safe Wireless Power Transfer Systems for Electric Vehicles

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Abstract

Wireless charging of electric vehicles is convenient but in order to make it safe the exposure of humans to electromagnetic fields must be below acceptable limits. We have designed a prototype system that transmits 3 kW with an efficiency of 85% where the magnetic fields around and inside the vehicle are below the EU council recommendation of 6.25 µT at 85 kHz.

1. Introduction

Wireless power transfer can make battery charging more, convenient and reliable for electric or hybrid vehicles. In order to make it safe, the exposure of humans to electric and magnetic fields must be limited. In 1999 the EU Council [1] released a recommendation of the exposure of general population. This recommendation builds on the 1998 guidelines of ICNIRP [2].

We have designed a prototype wireless power transfer (WPT) system based on resonant circuits with four magnetically coupled coils. Motivated by the SAE standard [3], we have chosen an operational frequency of 85 kHz. As the available space underneath a vehicle is limited and a vehicle to ground clearance of about 20 cm is typical, four resonator circuits was selected as an appropriate design criterion to achieve high efficiency and power transfer capabilities given the rather low magnetic coupling [4, 5, 6]. Moreover, in [7] it was shown that the capacitance values of a four coil WPT design can be used for system tuning, which makes it possible to recover high-performance operation due to e.g. manufacturing tolerances or coil displacement. Further, the design goal was that the magnetic field strengths, at positions where humans may be present, should be limited to the reference values of ICNIRP [2], (which for 85 kHz is 6.25µT) at a transmitted power of 3 kW with an efficiency of 85%. These design goals were checked in simulation as well experimentally on a full-scale prototype.

ICNIRP [2] also gives reference values on the electric field strength, which is dependent of the AC potential of the body of the car. In this state of the project the prototype system was not integrated in a car, so the actual electric fields could not be determined, however this is an important factor for the final design.

2. Model of Wireless Power Transfer System

The WPT system design consists of four magnetically coupled resonators, two located on the transmitter side in the ground and two on the receiver side in the vehicle. The transmitter is fed by a square wave power supply and the receiver is connected to a full-bridge rectifier, low-pass filter and a resistive load as shown in Figure 1. Here, the resistive load has been selected to 27 Ω. The coil inductance and the connected capacitance values were chosen such that a power transfer of at least 5 kW could be realized in a time-domain circuit simulation where the voltages and currents in the circuit were subject to a set of suitable constraints to prevent component breakdown as presented in [7].

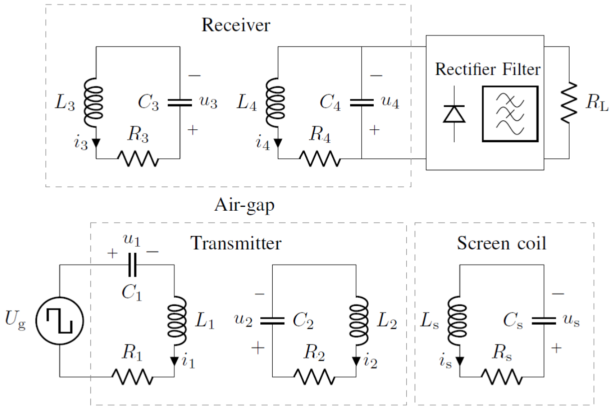

Figure 1. Circuit diagram of the wireless power transfer system prototype which consist of four magnetically coupled resonators, square wave generator, rectifier, filter, resistive load and an optional screen coil circuit.

A schematic model of the transmitter and receiver units of the WPT system is shown in Figure 2 with design parameters in Table 1. The coils are constructed using Litz-wire with 1050 individual copper strands of diameter 0.1 mm to reduce resistive losses. The metal sheet is used for structural stability in the transmitter unit and is assumed to be part of the vehicle bottom plate in the receiver unit. A 1.5 cm thick ferrite block with relative permeability of approximately 2100 is used to guide the magnetic fields around the coils and reduce eddy current losses in the metal parts. On the transmitter unit, a steel plate can be attached to mimic that a large ground plate is located underneath the vehicle. If no ground plate is attached, a rectangular "screening" coil was placed around the transmitter unit with 5 turns and an average side length of 0,89 m.

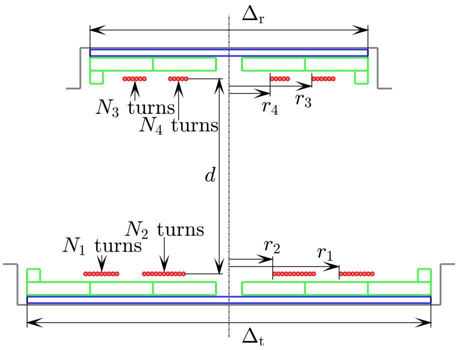

Figure 2. Schematic model of the transmitter (bottom) and the receiver (top) including a metal sheet frame, acrylic glass separation layer, ferrite plates and coils.

Table 1. Coil model parameters as shown in Figure 2. The number of coil turns are 9, 11, 6 and 5.

Parameter	(m)
r_1	0,204
r_2	0,099
r_3	0,151
r_4	0,099
Δ_r	0,46
Δ_t	0,68
d	0,215

The COMSOL Multiphysics® model shown in Figure 3 used to compute the coil inductances and coupling coefficients and it shows in addition to the transmit and receive units the vehicle plate and screen coil. In the model, the coils are simulated using a multi-turn coil feature with a simplified coil geometry that does not resolve the individual turns. The metal sheets are modelled using an impedance boundary condition and the computational domain is truncated using infinite elements. The COMSOL model is also used to simulate the magnetic field strength around the prototype system given simulated or measured coil currents.

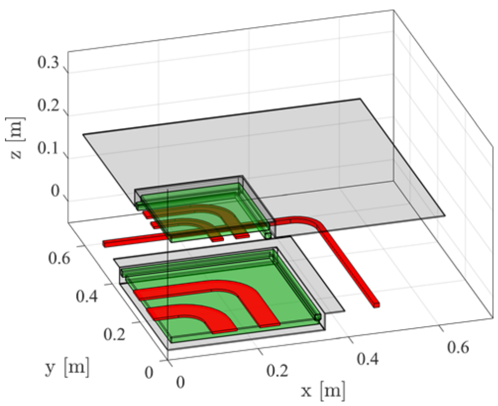

Figure 3. Computational model showing a quarter of the prototype system with transmit and receive units with coils and ferrite material, vehicle plate and a screen coil.

The screen coil shown in Figure 3 is located rather close to the transmitter coils and, consequently, a current is induced in the screen coil during power transfer. The magnitude of the induced current is highly dependent on the capacitance of the connected capacitor due to the resonant nature of the power transfer system. In simulation, we found that the magnetic field strength just outside the vehicle plate could be reduced by a factor of 2 by selecting C_s such that the resonance frequency $f_s = 1/2\pi\sqrt{L_s C_s}$ of the screen coil circuit was approximately 10% lower than the operating frequency of the WPT system without adverse effect on the power transfer or system efficiency.

Manufacturing tolerances or coil displacement may yield significant deviations from the nominal design determined by the simulation. Consequently, a system identification procedure followed by capacitance tuning as described in [7] may be required for the assembled prototype system. In this work, we use five capacitance banks (one for each coil) that are possible to tune to a few discrete values each, similarly as presented in [7]. After system assembly, we measure the inductances and coupling coefficients of the coils and the results of the measurement compared to the Comsol model are shown in Table 2. Next, all realizable capacitance values where analyzed in simulation and their performance compared. The capacitance values presented in Table 3 was selected as an appropriate tuning.

Table 2. Measured and simulated inductances for the WPT system with a screen coil.

Parameter (µH, %)	Measured	Comsol Model
L_1	146,9	149,4
L_2	95,9	96,0
L_3	49,6	49,3
L_4	24,1	21,3
L_s	62,6	65,4
k_{12}	26,07	25,33
k_{13}	10,48	11,25
k_{14}	7,33	7,99
k_{1s}	1,77	2,44
k_{23}	10,30	10,57
k_{24}	8,45	8,88
k_{2s}	1,37	0,97
k_{34}	33,22	34,29
k_{3s}	0,78	0,83
k_{4s}	1,12	0,52

Table 3. Selected capacitance values with the corresponding resonance frequencies for each of the individual LC-circuits.

Capacitance	(nF)	Resonance frequency	(kHz)
C_1	26,1	f_1	81,4
C_2	31,2	f_2	92,0
C_3	67,6	f_3	87,0
C_4	122	f_4	92,9
C_s	65,4	f_s	78,7

3. Measurement on Prototype

An experimental setup was used for measuring the transferred power, efficiency as well as the magnetic field around the WPT system. Two different setups were used for evaluating the prototype WPT system. In case 1 a steel sheet, (“ground”-plate) was placed in the plane of the transmitter coil to simulate that the transmitter coil is placed in the ground under a car. Another steel sheet, “vehicle”-plate, was placed in the plane of the receiver coil in order to simulate the body of a car. This sheet marks the minimum area occupied by a car so that a user is always outside the sheet. Holes were cut in the sheets in the area of the transmitter and receiver coils. In case 2 the “ground”-plate was removed and a screen coil was placed so that it encloses the transmitter coil. A capacitor was connected to the screen coil in order to adjust the induced current.

The transmitter coil was placed 0.5 m above the floor on a wooden stand and the receiver coil was placed 0.2 m straight above the transmitter coil. The magnetic field strength was measured with a magnetic field meter, Narda ELT-400 with 100 cm^2 and 3 cm^2 probes. The instrument measures the RMS-value of the magnetic field vector. It also has analog outputs that can be used for observing the waveform of the measured field on an oscilloscope. The accuracy of the instrument is 4 % but it is difficult to determine the position of the probe in the setup with better precision then 10 – 20 mm. Since the field strength varies rapidly with position this can cause errors of 10-20 %.

The magnetic field strength was measured in positions where persons can be expected to be during normal use of a WPT system.

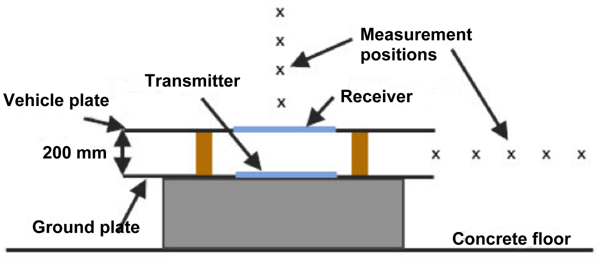

Figure 4. Setup with measuring positions.

This is in the passenger compartment of the car and directly outside the car but not under it. The measuring positions were placed vertically straight above the receiver coil and horizontally at the side of the WPT system according to Figure 4. The background level of magnetic fields in the room was less than 0.06 µT.

The WPT system transferred 3.1 kW with an efficiency of 85% after adjustment of the capacitor values as described above. This is very close to the simulated results of 2.9 kW at 88% efficiency. This power and efficiency was achieved for both the ground-plate and screen coil systems.

3.1 Measurement of magnetic field strength

The magnetic fields around the system are almost sinusoidal (Figure 5) and can therefore be directly compared to the reference values.

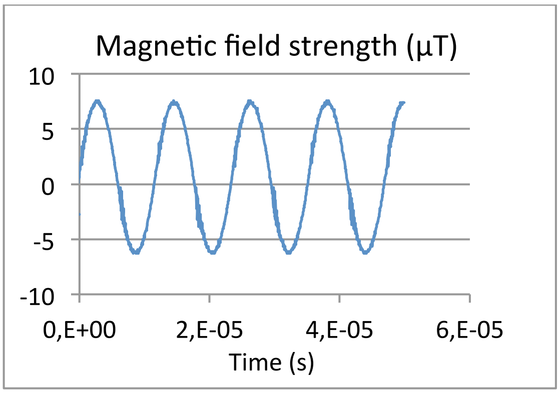

Figure 5. Waveform of the measured magnetic field outside the vehicle plate. It is sinusoidal with a frequency of 85 kHz.

Table 4 and Table 5 shows the measurement results for the system with ground-plate (case 1). The measurements show that the field strength is below the reference value for exposure of the general public (6,25 µT) except at the edge of the ground-plate.

Table 4. Measurement of magnetic field in horizontal direction for ground-plate system (case 1) for a power transfer of 3.1 kW.

Distance from center (m)	Magnetic field B (µT RMS)
0.61 (edge of ground-plate)	7.2
0.76	1.5
1.01	0.39
1.16	0.15
1.31	0.08

Table 5. Measurement of magnetic field in vertical direction for ground-plate system (case 1) for a power transfer of 3.1 kW.

Height above receiver coil (m)	Magnetic field B (µT RMS)
0.15	3.2
0.30	1.4
0.45	0.68
0.60	0.38

For the system with screen coil (case 2) all the measured magnetic field values where found to be below the reference value, see Table 6.

Figure 6 shows a comparison between the simulated and measured magnetic field strength for the WPT system with screen coil (red) and without screen coil (blue). Measured values are marked with circles and simulated values by dashed lines.

Table 6. Measurement of magnetic field in horizontal direction for screen coil system (case 2) for a power transfer of 3.1 kW.

Distance from center (m)	Magnetic field B (μT RMS)
0.61 (edge of ground-plate)	5.3
0.71	2.5
0.81	1.4
0.91	0.84
1.01	0.57

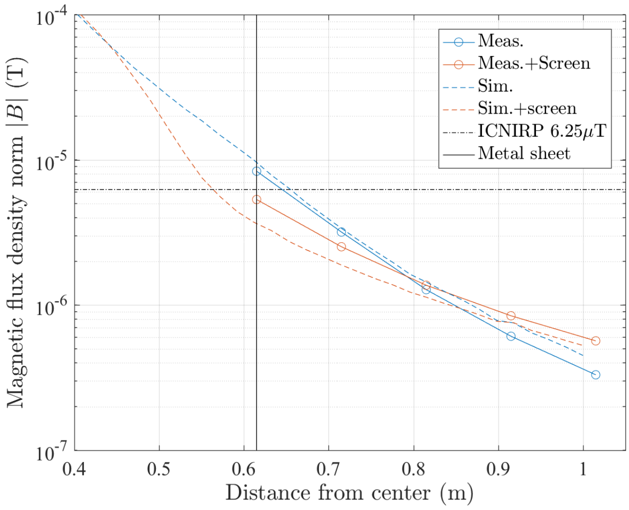

Figure 6. Simulated and measured magnetic field strength for the WPT system with or without the screen coil.

In the area between the plates the field strength increases rapidly towards the center. The reference value for occupational exposure (100 μT) was reached at a distance of 0.38 m from the coil center. The presence of humans or animals must be restricted in the space between the coils or detected so that the WPT system is turned off to avoid exposure above the limits.

When performing the measurements, we noted that there was a voltage difference between the "vehicle"-plate and the "ground"-plate. This will in turn cause an electrical field around the car since the car in general will not be connected to ground. There will also be a contact current when a person touches the car. Both these quantities have to be limited to safe levels when implementing a WPT system in a car.

4. Discussion and Conclusions

The project achieved the goal of transferring 3 kW at 85% efficiency with magnetic leakage fields lower than 6.25 μT. Measurement on the prototype system shows very good agreement between simulated and measured values of efficiency, power transfer and magnetic field strength. The electrical fields and contact current must also be considered be when designing a WPT system.

5. Acknowledgements

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6. References

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