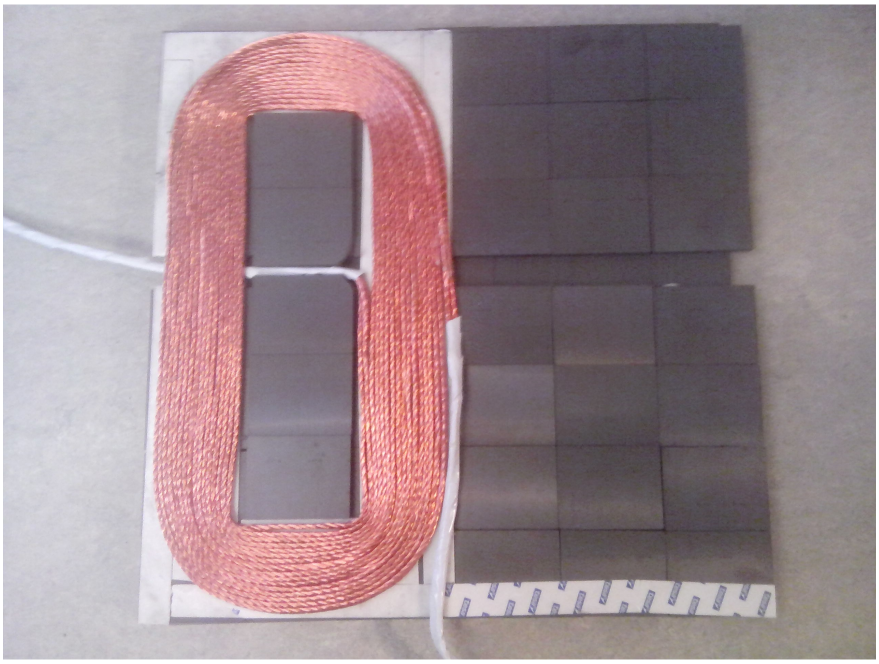
CHALMERS

Energimyndigheten

Svenskt Hybridfordonscentrum

www.hybridfordonscentrum.se



Coils for wireless charging of vehicles using a resonant auxiliary winding

MIKAEL ALATALO

Department of Energy and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden

Wireless charging using a resonant auxiliary winding

Technical report 2015:3
Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Gothenburg
Sweden, 2015

Cover page: An experimental DD-coil.

Abstract

The project has investigated different types of inductive power transfer coils and also the possibility of adding an extra winding to the system. The extra winding is connected to a capacitor and by means of resonance or near resonance the reactive power that is needed comes from this extra winding. This report mainly deals with different coils and the magnetic behaviour of the coils.

The best type of the investigated coils is the so called DD-coil which has low leakage field and can be used with larger air gaps compared to a circular or square coil. The bar type which has been used in a student project at CTH has been tested and works fine, but the leakage flux is higher compared to the DD-coil and it will be harder to shield the passenger compartment from high flux density. A DD-coil with the size of 400 * 400 * 20 mm can handle the power of 6 kW. A work done by Qualcomm indicates that the size may be lowered by 40 % at the same power level.

The efficiency of the magnetic parts will be high at 85 kHz, in the range of 97-98 % if the airgap is 100 mm. The three winding concept will not increase the efficiency perhaps make it more robust to big airgaps, but the cost of the device will increase.

During the project, methods for analysing the system has been developed. The methods includes algebraic calculation, FEM-analysis, time domain simulations and to some extent laboratory work. It should be possible for skilled staff to follow the work flow.

Next step could be to develop a working system out of specifications from an automotive manufacturer. Suggested is to use a DD-coil and two windings with series coupled capacitors and an attractive solution is to use SiC-components to minimise losses.

The technology has a potential to make it easier to use electro mobility. The plug-in cars that will soon come to the market have small batteries and the need for easy and convenient charging will be high in these vehicles.

Preface

This report is a part of the SHC-project, 'Wireless charging using a resonant auxiliary winding' In the project several participants have been engaged and the project has covered topics such as resonant windings, control strategy, coil geometries and also methods for analysis. One article have been published in March at EVER 2015 and one more is coming as an IEEE-article. Beside this report there will be a report concluding E.Palmberg's efforts together with articles made by Eva and Saeid Haghbin.

Thanks to prof. Torbjörn Thiringer for valuable discussions and comments on the text. Sonja Lundmark has helped me with reports and administration of the project. Robert Karlsson has guided students in a project that worked on a charger for a go-cart. The findings in their work have been useful for analysis and verifications. Eva Palmberg have thoroughly looked into resonant circuits and the use of Comsol for analysing the coils. Saeid Haghbin have worked on the control of the device and guided a master of thesis worker Ivan Salcovice who also been active in the laboratory.

Mats Josefsson from Volvo Cars has participated and guided in the reference group. Many thanks for sharing your good knowledge with us and providing very valuable comments and suggestions. Maria Grahn, Ellen Olausson, Roy Andersson and all the participants of the workshop made the workshop to a nice and rewarding event.

The financial support of Svenskt Hybridfordonscentrum and participating companies is gratefully acknowledged.

Mikael Alatalo

Gothenburg, Sweden, 2015

Content

1. Introduction

Inductive charging, inductive power transfer and wireless charging of an electric vehicle is more or less the same. It's about delivering power over a distance from the ground to the under body of the vehicle. The situation may be static and standstill at a parking place, [1], or it may be done when the vehicle is moving, so called dynamic charging. At standstill it is beneficial to move one of the coils in order to minimize the air gap. If nothing is done to decrease the air gap the air gap between the sending and the receiving coil will be rather long, so in this case there is a need for transferring power over a distance of 10-20 cm depending on technology and vehicle.

For the time being inductive chargers as a home charge device will be an option to the plug-in and electric vehicles in a couple of years. Audi Q7 e-tron are planned for inductive charging using a system that lifts the ground coil towards the car. The planning is for the 2016 model and the power rating is 3.6 kW [16].

It is also likely that it will be an option for city buses, where a lot of test activity is ongoing. In Gumi South Korea a semi-commercial line of buses, OLEV, is already in use.

The need for convenient charging differs depending on the vehicle. As an example a plug-in hybrid (PHEV) where the battery needs to be charged every 30 minutes or less, it has to be convenient to charge the vehicle. Otherwise it is a risk that the car owner skips the electric energy and of pure laziness waits for the combustion engine to take over the propulsion work. For purely battery electric vehicles (BEV) it's probably no need for inductive charging, but of course this is depending on range and use. When an electric vehicle has a range of 300 km or more it's probably enough for the average car owner to stop and have a pause and in the mean time charge the car at a fast charger. It might be reasonable that a charge every third day is enough in average every day use, if the plans from the big auto makers will come true. In that case the handling of a cable twice or three times a week is not so much of a problem. If the battery energy content will increase it will also be necessary to increase the charge power at home. A wall box could be a convenient choice where the user take the plug out of the wall box and connects it to the car. A manoeuvre of less than a minute.

At longer trips the car can be handled as an ordinary car and be charged at a fast charger. If this scenario will become reality we will need fast chargers with higher power rating than the normal 50 kW level that is the Chademo and CCS-standard. The Chademo-association is looking for an increase to 100 kW, which means that it may charge a driving range of 120 km in 15 minutes.

There is of course a possibility that inductive charging could be the main technology for delivering energy to the cars. A scenario is that electric roads will be realised to power trucks and if the cars could utilise the same technology, then it will be an option where the cars will have small batteries and will be powered from the roads. But it's also likely that the trucks will be powered by conductive overhead technique and in that case it may be tricky to find a solution where the cars can benefit from the same equipment.

So it's quite important to predict the future scenario. A case with a massive increase of plug-in vehicles could benefit of inductive charging technology. On the other hand a massive investment in inductive chargers along highways could be wasted money if the batteries will develop and the era of plug-in hybrids will be short. Compared to a BEV, the PHEV is a much more complicated technology with electric system, internal combustion engine, automatic gear box and ultimately with equipment for inductive charging.

The most important factor is the battery cost, which is somewhere around 250 $/ kWh, [2], and it is on it's way to 200 $/kWh in year 2020. It is predicted in [3] that at 150 $/kWh the battery electric car will take over the market and combustion engines will be history. At least for passenger cars, the situation is different for trucks and other heavier vehicles.

2. Dynamic and convenient

The incentives to use an inductive charger are two.

It's convenient to have an inductive charger at home, you just park the car above the primary coil and the charging starts automatically. No need for cables and it could be a key technology for making the electric vehicles popular. When a standard have been decided the technology can be used at parking lots and at stores where people stops, do their business and returns to a charged car.

The other incentive is to charge the car while driving, so called dynamic charging. This ability isn't so much of a focus in this report but it could be a way to extend the range of the electric vehicle. How should this work to be competitive to the solution with a big battery and fast chargers?

This might be illustrated with a highly simplified case of a hypothetical journey of let us say 300 km. A number of cars with a small battery with a range of 50 km, and a usable energy content of 7.5 kWh, starts with fully charged batteries. The other alternative is that the cars can have different starting SOC's but with a big battery. A rather normal energy consumption figure is 15-20 kWh / 100 km if the car travels at 100 km/h, i.e. 45-60 kWh for the whole trip. This is equivalent to a mean power of 15-20 kW.

In the case of a small battery the car will have enough energy for the first 50 km but after this we have to deliver 15-20 kW continuously for the rest of the journey. In order to manage hills and overtaking the peak power should be higher for a highway car. A fully depleted battery and a long hill with a 6 % gradient will result in 60 kW for a high way car, [18]. In the case of an inductive solution there has to be a primary coil and supporting feeders for 250 km that continuously deliver 15-20 kW and with a peak power that corresponds to the ability to climb hills at a certain speed. I.e. the secondary coil and circuitry inside the car shall also be dimensioned for this power capability. There should also be a margin power that charges the battery if the final destination lies some 50 km off the high way.

Another view point is if we compare the system with a car that travels 50 km and then use a fast charger with 50 kW for charging needs something like 10 minutes for charging. If a dedicated charging lane is available every 50 km it has to be 16 km in length and have a power rating of 65 kW. The power shall cover 50 kW of charging power and also the propulsion power.

Furthermore the primary coil will not always have a load if it isn't so long that it covers the whole distance between the cars. The best in terms of efficiency is if the primary coil is as big as the secondary coil and it magnetise the secondary winding in the car when it pass. This will however need a system that continuously monitor the car position and start the right primary coil. Quite possible to manage but overall a system that is utilised in a very low manner. A major part of the primary coils will thus be inactive.

On the electric grid side we have to have feeding points to the road that delivers the power for all the cars that are on the road. If the road is heavily used there will be a car every 100 m, which is equivalent to 2500 cars that needs power. (The first 50 km doesn't need powering). And the total power is 37.5 MW, which should be distributed along the road.

It has been argued that fast chargers along the high way is a waste of money, [16], and in the article it is argued that long trip travels with electric cars is of no interest. Tesla has proven the opposite and my opinion is that the car buyer will probably buy a car for short trips inside cities but if the car can be used on some occasions to make longer trips it could be an even more attractive alternative to buy an electric car.

In the case where the battery energy content is 45 kWh and as in the previous example the mean power is 15 kW for propulsion of the car in 100 km/h for 300 km. Some of the cars will manage the whole trip and at arrival will charge over night, some will stop and charge during the trip. A simple assumption is that 50 % of the cars will stop half way and charge at a charger with 100 kW and they charge 70 % of the battery energy content. That is they need 31.5 kWh which should be possible to charge in 20 minutes. Every 8 s a car arrives (every second car) that need a charger and we will need 150 chargers that can handle this. We have a point where we feed 15 MW to the cars that has stopped for charging. This is of course a heavy load on a single grid point but it should be quite obvious that this is a more attractive solution from the point of grid owners. There is a single point that needs high power. Compared to fast chargers, making inductive coils for 37.5 MW and distribute them along the roads shouldn't be cheaper than a set of fast chargers for 15 MW. The cars also have to have a lot of equipment in the inductive charging case. Figure 1, shows the SOC (state of charge) in the different cars. The blue line corresponds to a car with a small battery and the SOC-level might increase during the trip if surplus energy is charged to the car. I.e. if the driver wants to travel an extra distance at the end of this electrified high way.

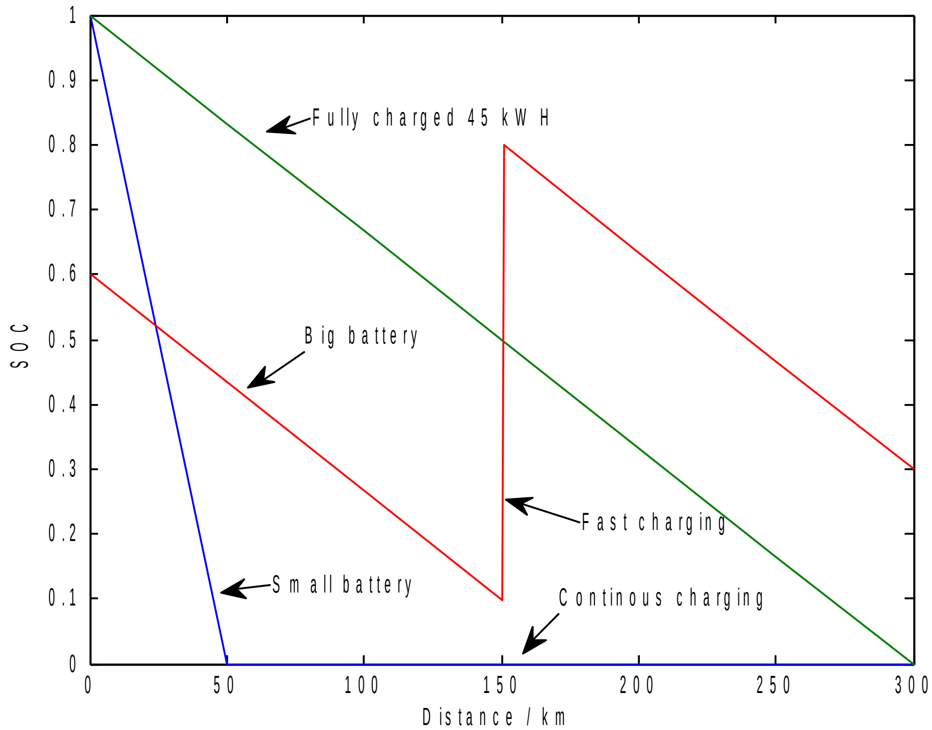


Figure 1. SOC-levels of the travelling cars.

The drawback of fast chargers and big batteries are of course the battery cost but one big important fact is that we will need storage capacity in the future when electricity is produced by renewable energy sources as wind and solar power. If the batteries are big it will be possible to charge at night and at times when there is a surplus of renewable energy. Smart grid techniques could be available and make the charging a benefit to the grid system. It's smarter to use the batteries that are available in the cars compared to buy dedicated batteries just for grid stabilisation.

Furthermore if the EV's that are produced behave more like ICE-cars the acceptance from the costumer will be higher and the market can start and grow instantly. When aiming towards a system with small batteries no costumers will buy an electric vehicle unless the charging system are at place.

As stated earlier the example is very much simplified and in reality the SOC-level will be more or less random at the start, which means that in the case of big batteries and fast chargers it is necessary to distribute the chargers along the highway and in that way we can handle different starting conditions. A scenario with big battery cars will need an infrastructure similar to the petrol stations we have today but the number of fast chargers have to be higher than the petrol pumps as the charging takes longer time than the average filling up of a car. These problem how the charging influence the grid and how many chargers that is needed is a research study in it self.

3. Examples of core and coil shape

An overall demand of the coil system (transformer) with a long air gap is that it should provide a good coupling between the coils. The leakage flux should be low or at least decay to low values in a short distance from the coils. The amount of material in the coil will be the most critical factor when production of these devices starts. It should be easy to integrate into the vehicle and the efficiency should be comparable to conductive chargers.

A lot of work has been done at the University of Auckland New Zeeland, [5], in which they have compared the DD-coil, see Figure 2a and b, to a circular coil. The coil is less sensitive to position error compared to a circular coil. In the receiving part an extra 'Q-coil' can make the coil even more tolerant to misalignment. The Q-coil is the same as an extra circular coil and placed in such a way that the sending DD-coil magnetise the Q-coil when the receiving DD-coil is misaligned. Just an addition of functionality.

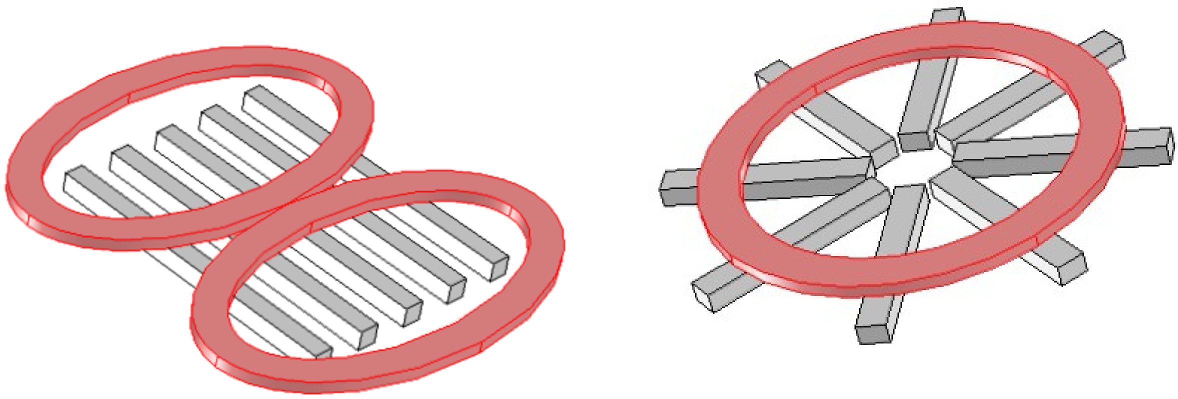


Figure 2a. DD-coil, Auckland [5]. 2b. Circular coil. Grey-ferrite red-copper

They have moreover compared the flux pipe construction in Figure 3 with a circular coil and found an increased coupling factor with the flux pipe type. The flux pipe is also named bar type and solenoid type in the literature. In this report 'bar type' is used. The circular type can have a rectangular shape but is nevertheless called 'circular type'.

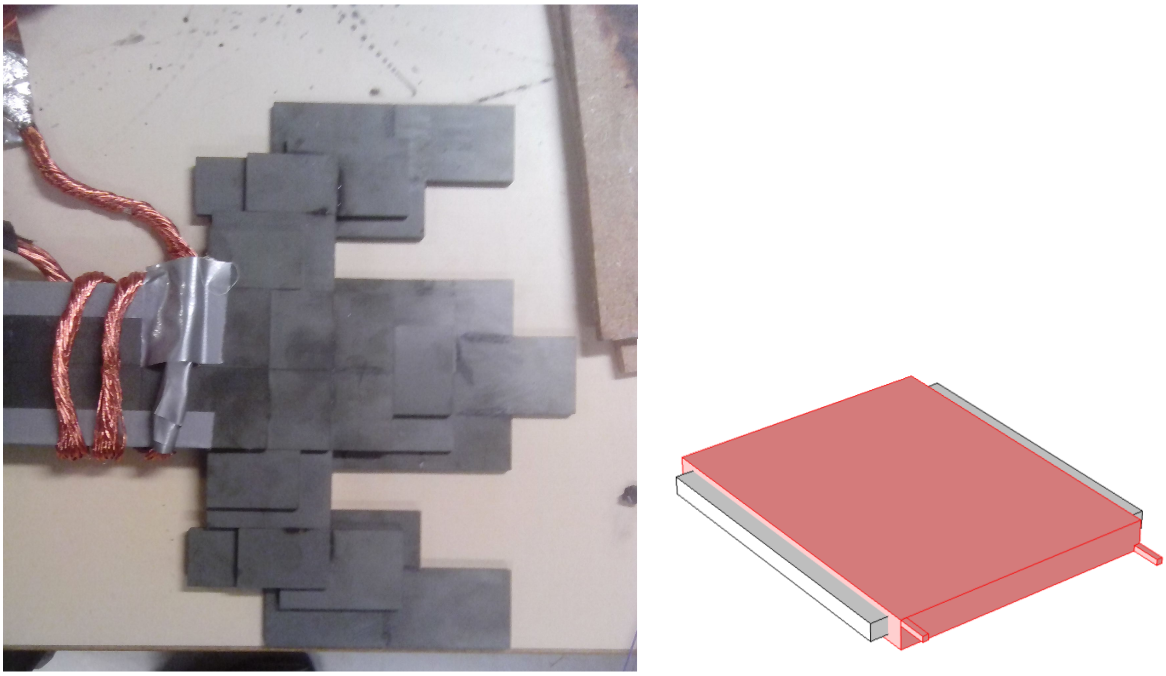


Figure 3. Bar type from Chalmers. One side of one of the coils and alternative construction

KAIST is a Korean university that has done a lot in this area. They use rather long E-type cores on the primary side. The primary coil is shown in Figure 4.

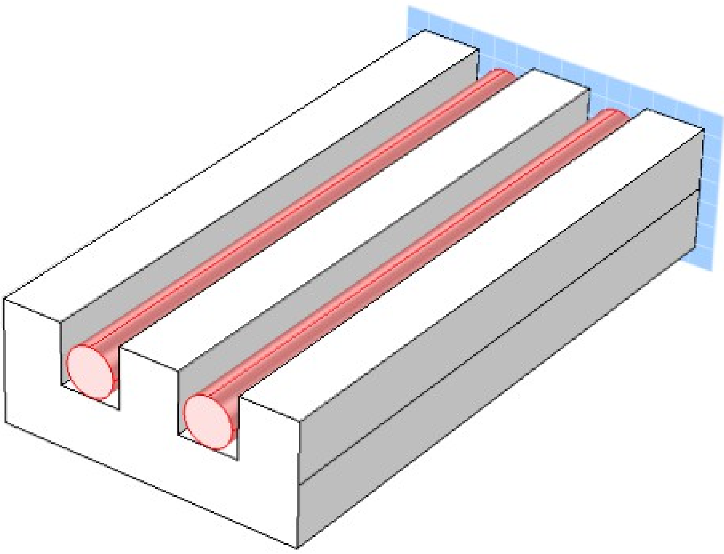


Figure 4. E-type primary coil

A team from QUALCOMM have studied the interoperability of different coils, [14]. They suggest a DD- sending coil with rather big size and the best choice for the receiving coil is a DD coil with smaller dimension than the sending coil. The sending side is almost three times as big as the receiving coil. See Figure 5 where the receiving coil is shown. It is sometimes mentioned as bi-polar but we use 'DD-type' in this report. The coils are directed in a way that produce a flux into one of the coil and out of the other.

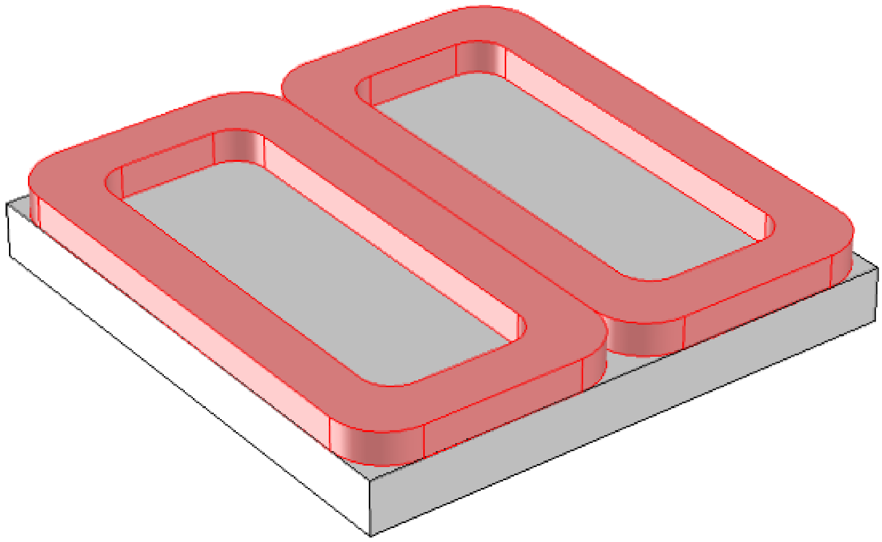


Figure 5. DD-coil.

The receiving coil of DD-type has the dimension of 340*270*20 mm at the power level of 6 kW, which is sufficient for home charging. To use a big sending coil is a matter of making the system more robust to misalignment but it can also be seen in the light of a system where the primary coil is made for higher power than what is actually drawn from the secondary side. This is the case when the road system are made for heavy vehicles and the cars try to benefit from the same system.

Turki et al. [17] have made a comprehensive article in this area and have studied coil shapes, control options and also how to connect resonance capacitors. The result points towards DD-coils on the primary side and a bar type on the secondary side. The capacitors should be connected in series on the primary side and a control method where a number of pulses are fed to the primary coil is used. The power level can be controlled from the primary side via pulse skipping. The intention in their work is to minimise the coil on the secondary side and 3 kW is transferred to a secondary coil with the dimensions 185*210 mm and an efficiency from DC to DC-link of 92-94 % at an air gap length 120-140 mm.

3.1 Fundamental of a coil and induced voltage.

The coil system shall transmit as much power as possible without producing leakage flux. The power of a transformer is the current in the winding multiplied by the induced voltage considering the phase angle between current and voltage. The amount of current in a winding is the current density multiplied by the cross-sectional area and current density is limited by thermal properties of the construction. High power loss in the core may also result a high temperature, which should be considered.

The area of the winding is proportional to the flux that is enveloped by the coil and we may produce a figure of merit of the coil material divided by the power, see Figure 6.

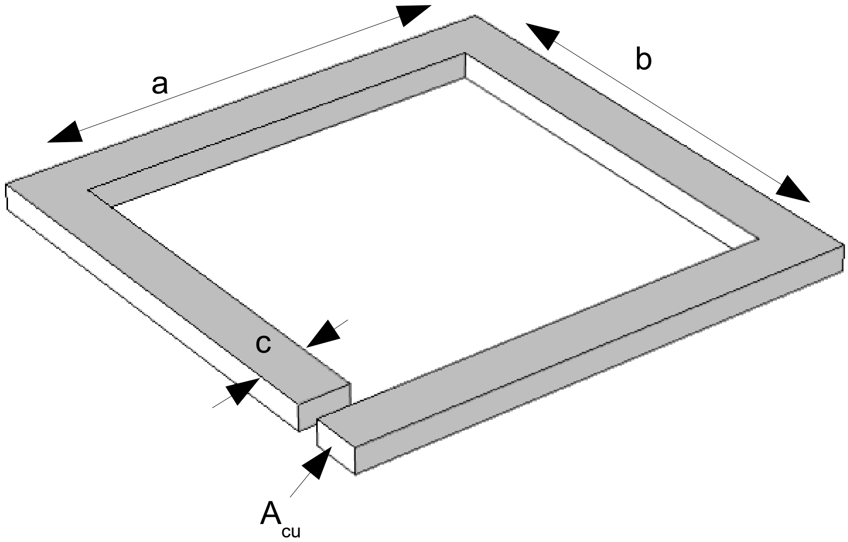


Figure 6. Coil and definitions.

The area of the coil is,

$$A = ab \tag{1}$$

where a and b is the side length of the rectangular coil. The amount of material in the coil is,

$$V_{cu} = A_{cu}\left(2\left(a + 2\mathrm{c}\right) + 2\mathrm{b}\right) \quad , \tag{2}$$

here is c the width of the winding and A_{cu} is the cross-sectional area of the winding. The power of a one turn coil is,

$$P = k_w J_{cu} A_{cu} A\, \omega\, B_d \cos(\varphi) \tag{3}$$

J_{cu}: Current density (A/m^2)

B_{d}: Average of flux density (T)

φ: Phase angle

ω: Frequency (rad/s)

$k_{\mathrm{w:}}$ Constant depending on winding shape and finally a figure of merit, ξ, is,

$$\xi=\frac{P}{V_{cu}}=\frac{k_w J_{cu} A_{cu} A B_d \omega\cos(\varphi)}{A_{cu}(2(a+2c)+2b)}=\frac{k_w J_{cu} ab B_d \omega\cos(\varphi)}{2(a+2c)+2b}=k_{phys}\frac{ab}{2(a+2c)+2b} \qquad (4)$$

, where $k_{phys}=k_w J_{cu} B_d \omega\cos(\varphi)$ is a constant depending on physical factors as flux density and current density. In a case where a=b and c<<a, we get:

$$\xi=k_{phys}\frac{a}{4} \quad . \qquad (5)$$

Thus as long as the physical constant is unchanged the output power compared to the material use increases with the side length of the coil. I.e. it's better to have one large coil than several small coils and even individual turns of the coil shall have as large width as possible. The figure of merit is also coupled to the frequency, but with this parameter there are issues with loss density in the different materials.

The magnetic flux has to have a return path, which can be solved in different ways. See Figure 7 where different constructions are shown. The bar type has the ability to concentrate the flux to a central part, which can minimise the copper used in the winding.

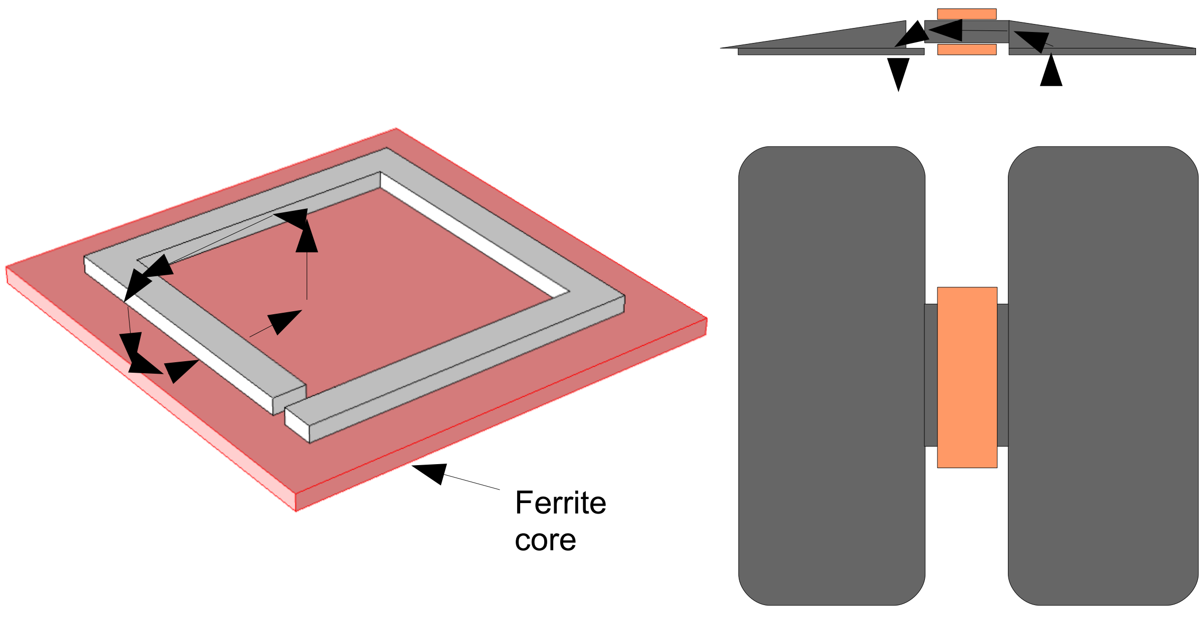


Figure 7a. Return path via ferrite core, circular coil. 7b. Return path via centre concentrated winding, bar type coil.

Mixes of the two is also possible for instance a sending DD-coil in Figure 4 can have a receiving coil of the type in Figure 7b.

The difference between the coils have been evaluated by Budhia et.al, [6]. The type in Figure 7a have a weak spot in that the distance between sending and receiving coil should be lower than one quarter of the side, a. The other type in Figure 7b. have flux lines that embrace the whole distance from one end of the bar type to the other end and it should be able to work on a distance that is lower than half of the side, a.

In the latter construction a significant flux leaks from one pad to the other, according to Figure 8. There is a leakage flux path above the sending coil and also under the coil. Of that reason Budhia et.al suggests a divided coil that lowers the leakage flux. The length, l_1, of the central part also contributes to a lowered leakage.

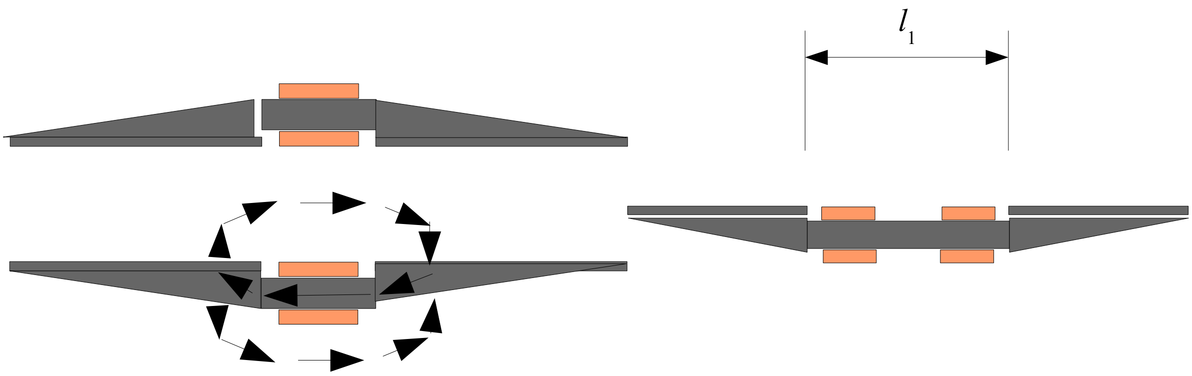


Figure 8a. Leakage flux paths. 8b. Divided coil.

At a first glimpse the DD-coil seems to have a disadvantage compared to the circular coil, the coil is divided in two and would have lower coupling factor. In fact the circular coil cannot use more than half of the ferrite area making the coil more or less the same as the size of the DD-coils. The DD-coil can also be made with an increased distance between the poles of the sending coil. The flux lines are shown in Figure 9. Further on the DD-coil hasn't the disadvantage of producing leakage outside of the coil as the bar type.

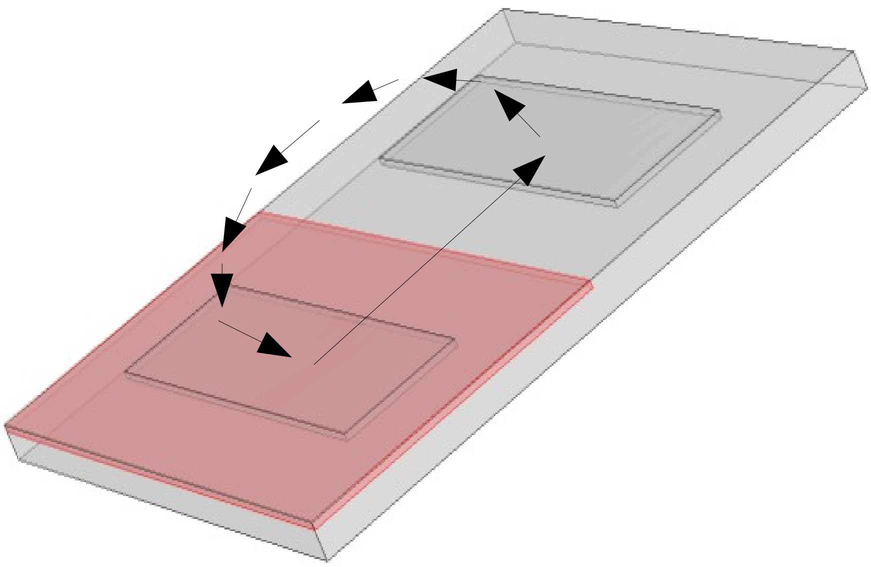


Figure 9. DD-coil.

3.2 2D analysis

Two dimensional analysis is used as a start. And the first question is how the flux transfer from the primary to the secondary. We may start with the construction in Figure 4, the KAIST construction. How much flux that is transferred using two similar E-cores is investigated. The total current in the primary coil is constant and the flux that is transferred to the secondary coil is evaluated.

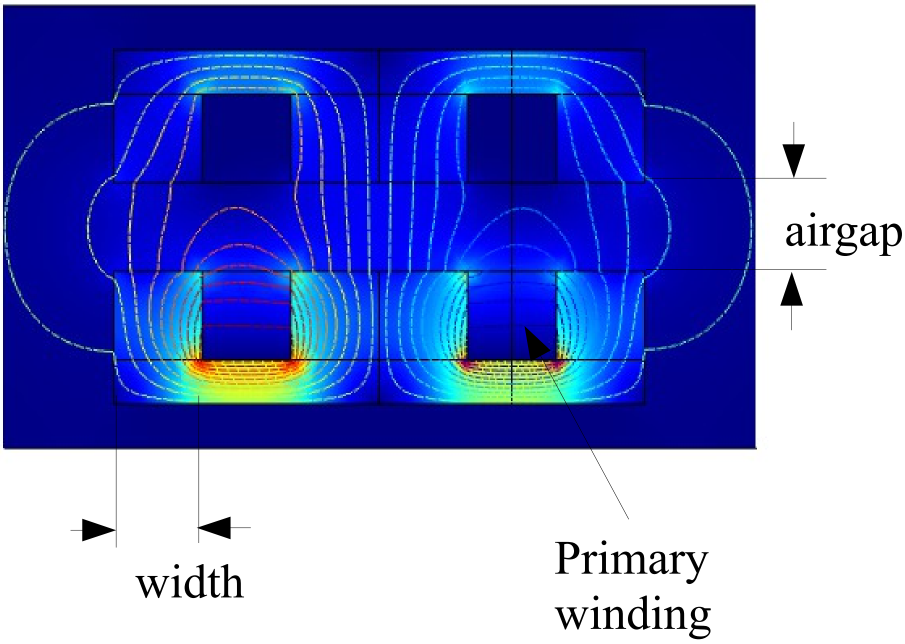


Figure 10. E-cores and primary winding.

With a fixed air gap length the width of the core is varied and also the width of the winding. The depth of the winding is changed so that there is the same amount of copper in all the calculations and the current density is constant.

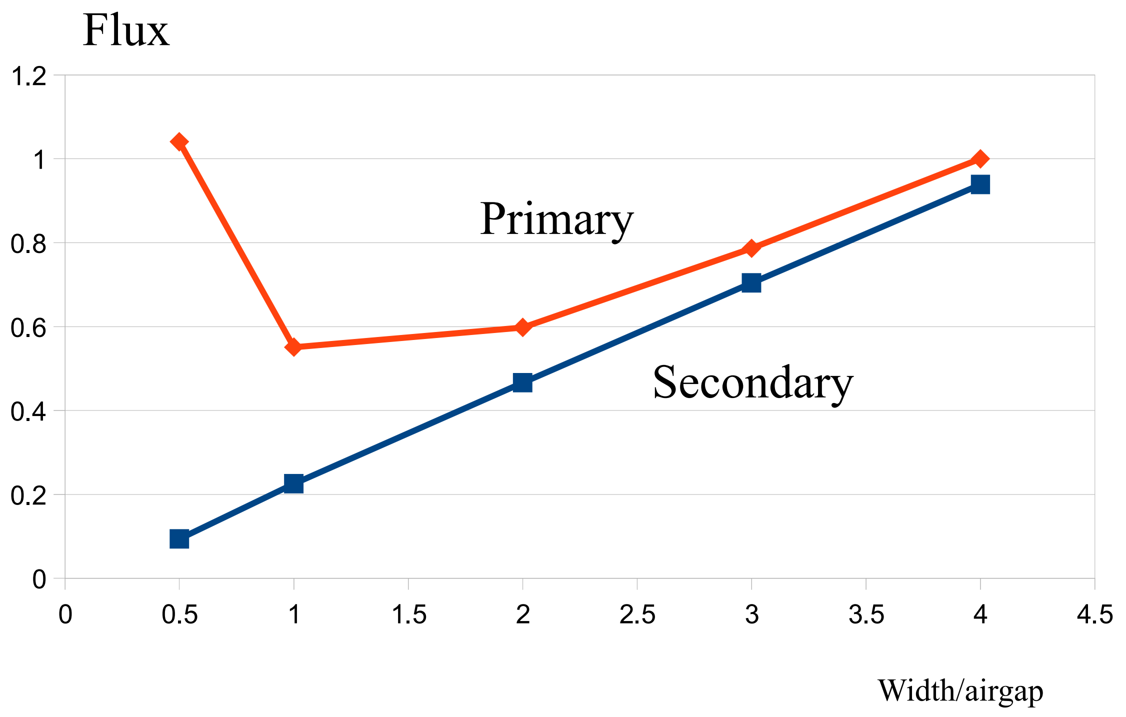


Figure 11. Relative flux vs relative width of the core, b_w, normalised with the air gap length.

As seen in Figure 11, the flux in the secondary coil increases almost linearly with the width of the core. An important factor is also that the flux in the primary coil will converge towards the flux in the secondary coil. I.e. the relative leakage will decrease with a wider coil.

The leakage flux density is evaluated at a point that is three airgap lengths outside of the coil. The flux density is divided by the flux density in the middle of the air gap. When increasing the width, the total flux in the secondary coil increases with a factor of 10 and in the same time the leakage flux density increases with a factor of two. This means that the relative disturbance to the surroundings will decrease if the core is flat and wide.

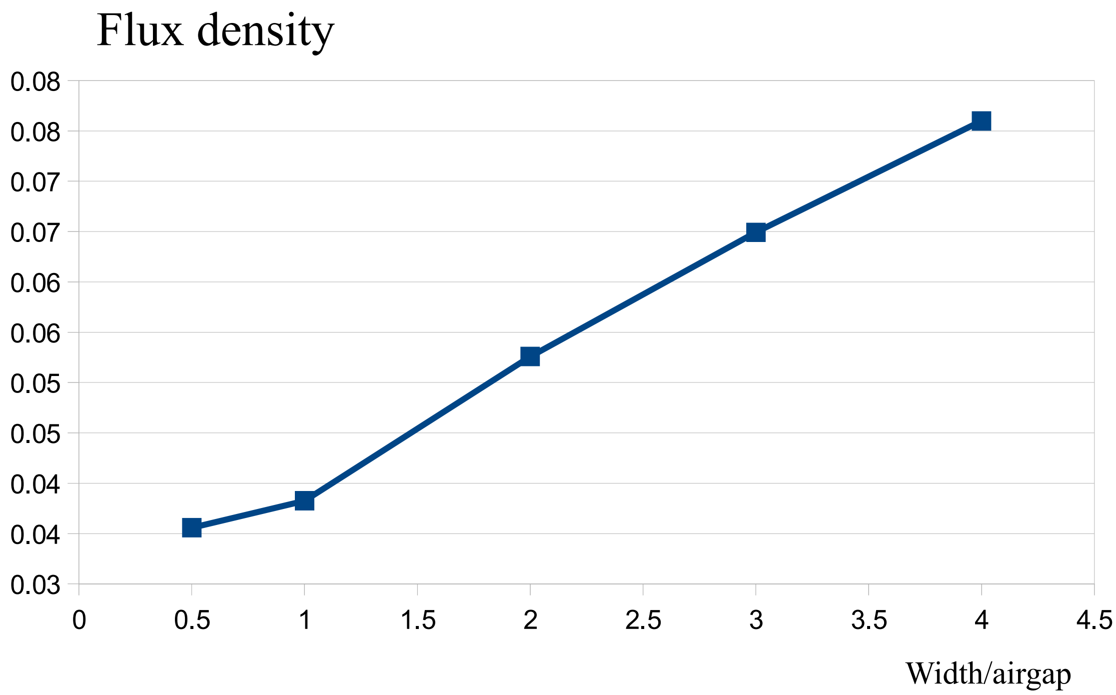


Figure 12. Relative flux density three air gap lengths from the core, flux density normalised to maximum air gap flux density.

The conclusion of this is that a core with long air gap shall be constructed as a flat structure and a thin and distributed winding. The 3D-version of the E-core is the circular coil where the winding is thin and the core is wide and flat.

3.3. Resulting flux density from a 3D case

A surface of one square meter is studied for three different coil types, and the distance between the coils is varied between 10 cm and 20 cm. The coil geometry is shown in Table 1. The resulting flux density is shown in Figure 13, 14 and 15, when the primary coil is excited with a total current of 150 A.

Table 1. Coil geometry.

	Circular	Bar type	DD-coil
Core side	1 m	1 m	1 m
Coil side, a * b	0.71 * 0.71 m		1*0.5 m
Center length, l_1		0,15	
Winding cross section	1 * 20 cm^2	20 cm^2	2*10 cm^2

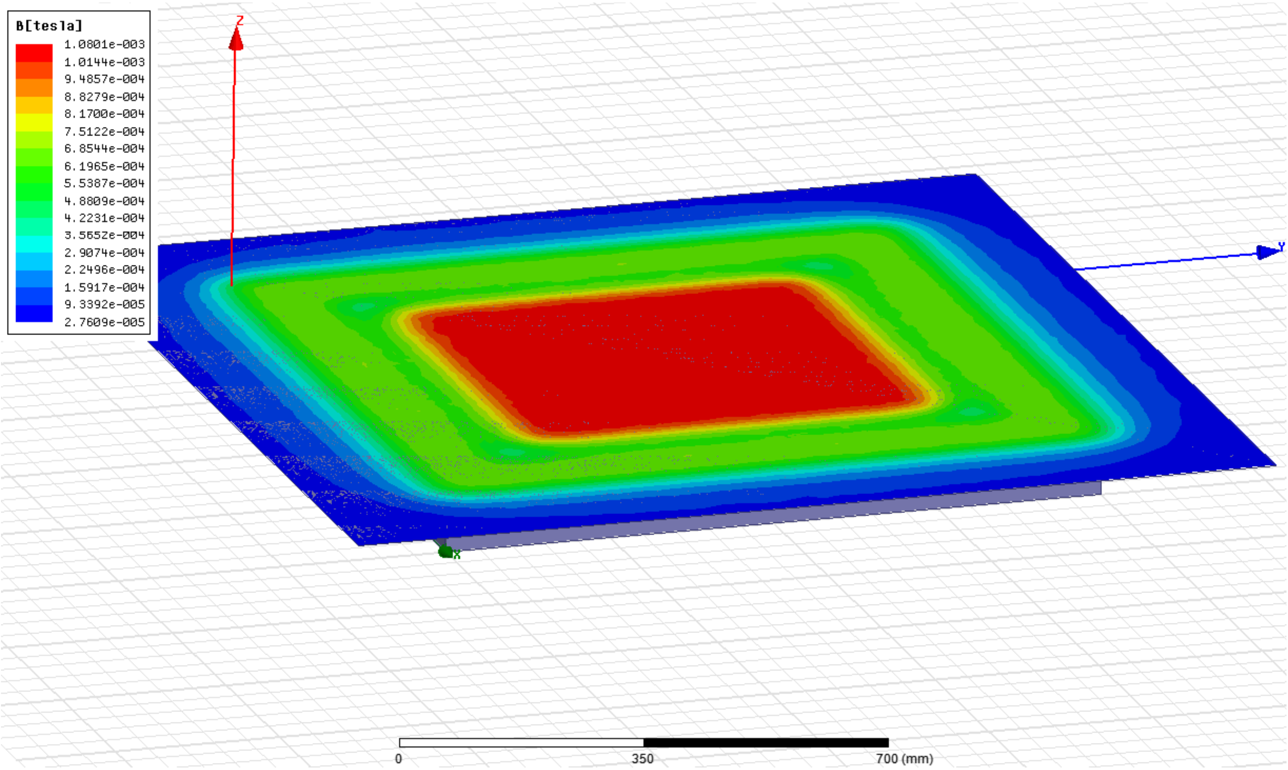


Figure 13. Resulting absolute flux density from a circular coil in the middle of the air gap, current in the sending coil is 150 A. Number of turns is one.

The flux density resembles the coil shape which in the circular coil case is quadratic, in the centre of the coil the flux density is 10 mT but it decays towards the periphery of the ferrite. It should be possible to increase the size of the winding but this will increase the leakage flux.

The bar type produces two poles of flux with a spot of high flux density just outside of the central winding part, see Figure 14.

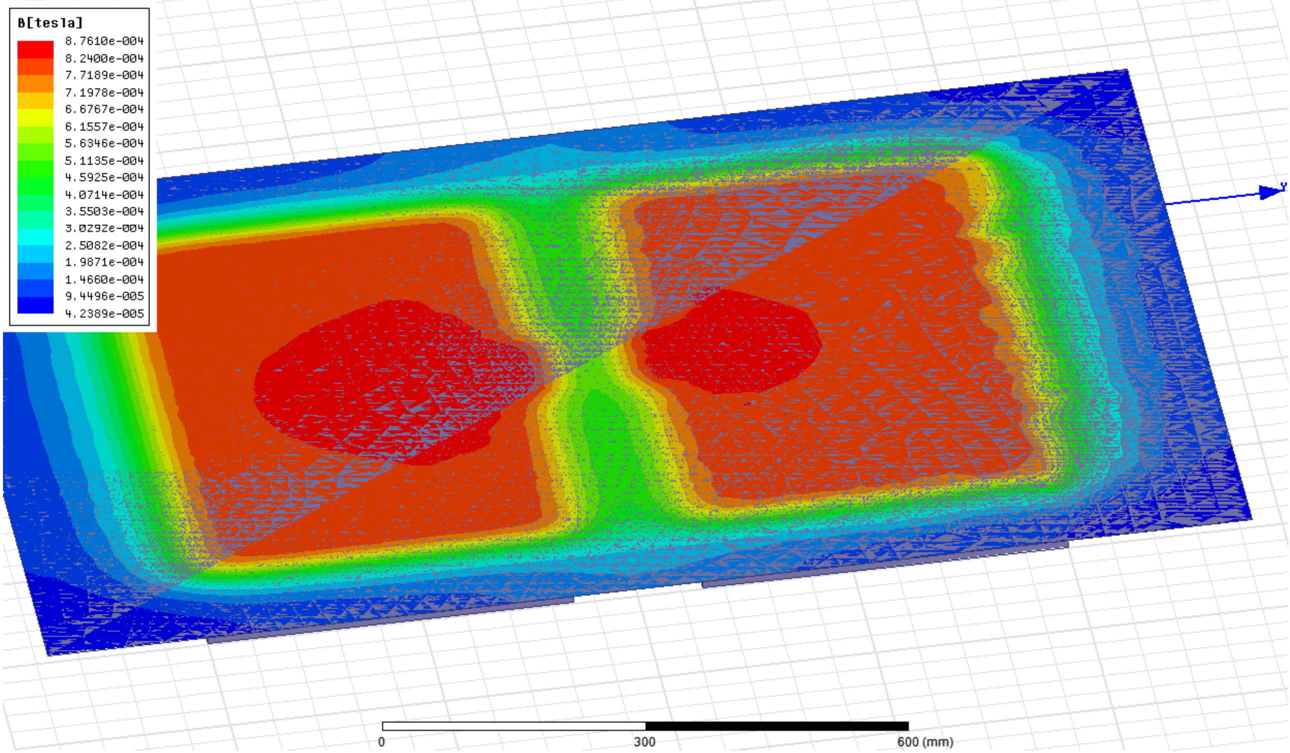


Figure 14. Flux density in the middle of the airgap of a bar design. Current is 150 A.

The flux density from the DD-coil is shown in Figure 15 and it also produces two poles with higher flux density than in the circular type, due to coils that work in the same direction. Compared to the bar type the flux density decays faster outside of the coils.

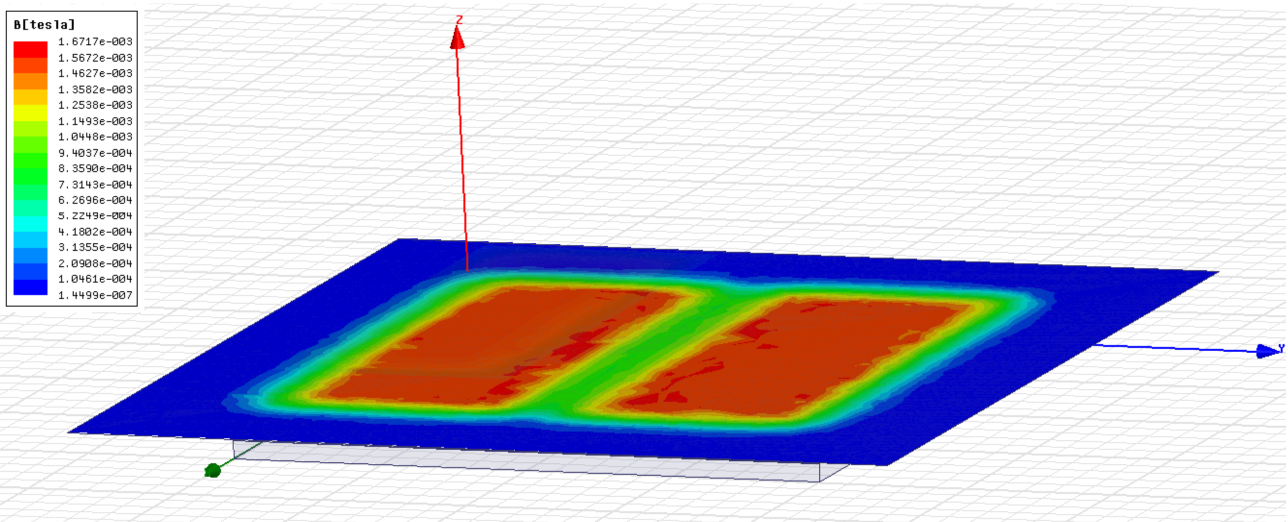


Figure 15. Flux density in the middle of the air gap from the DD-coil

The resulting data of the different coils are displayed in Table 2. The coupling factor k_{13} is defined by,

$$k_{13}=\frac{M_{13}}{\sqrt{(L_1 L_3)}}=\frac{M_{13} I}{\sqrt{(L_1 I L_3 I)}}=\frac{\psi_{13}}{\sqrt{\psi_1 \psi_3}}=\frac{\psi_{13}}{\psi_1} \quad (6)$$

, where I is an arbitrary current and it is assumed that the coils have the same shape so that $\psi_1 = \psi_3$ when excited with the same current. We may rewrite the figure of merit,

$$\xi=\frac{P}{V_{cu}}=\frac{k_w J_{cu} A_{cu} A B_d \omega \cos(\varphi)}{V_{cu}}=\frac{I \psi_{13} \omega \cos(\varphi)}{V_{cu}} \quad (7)$$

In this case we assume that the frequency, ω, and phase factor, $\cos(\varphi)$, is unity.

Table 2. Resulting data from calculations, DC-current in the primary coil.

	Square/circular		Bar type		DD-coil	
Distance	100 mm	200 mm	100 mm	200 mm	100 mm	200 mm
Secondary flux/ mWb	0,4	0,17	0,44	0,24	0,43	0,19
Primary flux/ mWb	0,55	0,41	0,66	0,49	0,57	0,41
Flux density 200 mm from coil/uT	27	31	60	200	25 and 6 dep. On dir.	50 and 20
k13	0,73	0,41	0,67	0,49	0,75	0,46
Winding cross section	20 cm^2	20 cm^2	20 cm^2	20 cm^2	10+10 cm^2	10+10 cm^2
Applied total current / A	140	140	140	140	140	140
Copper volume receiving part	2,80E-003	2,80E-003	6,76E-004	6,76E-004	2,60E-003	2,60E-003
$\xi(\omega=1, \cos(\varphi)=1)$	20	8,5	91	50	23,2	10,3

According to Table 2, we get a slightly better coupling, k_{13}, using the bar type coil compared to the flat coils when the distance is high. At shorter distance the coupling is the lowest with the bar type coil The figure of merits is very much better for the bar type coil but the downside is the leakage flux, which is higher when using the bar type coil.

The flux density decreases rapidly with distance, but the limit for long term exposure is 27 uT, (ICNIRP) and sometimes 6.25 uT is also used as a limit. In order to not exceeding the latter value nobody can approach a Circular type coil closer than 500 mm. I.e. the flux density in between the coils should be in the range of 1 mT and the distance to the coil should be greater than 200 mm in the case of 27 uT and 500 mm for not exceeding 6.25 uT.

4. Work flow

To construct a resonant device is not so straight forward as a normal transformer dimensioning.

Some parts may be linearised and approximated but a full understanding of the device needs the following steps:

1. Analysis of inductance and coupling of a coil
2. Calculate the operating point, number of turns and capacitors using sinusoidal assumption.
3. Analyse power losses and that no part of the coil is saturated assuming the operating point.
4. Thermal analysis of the device

Iterate 1-4 until a reasonable dimensioning is done.

5. The operating point is calculated once more using converter voltage, or data from time-domain simulation. The recorded current wave-shape could be used in a new analysis and power loss calculation.
6. Thermal analysis with power losses from step 5.
7. Eventual shielding

The shielding isn't taken care of in this report but it might be a tricky and important part of the dimensioning.

The first step is a FEM-analysis of the device and the second can be made out of algebraic solution of the equations,

$$
\begin{aligned}
U_1 &= j\omega L_1 I_1 + R_1 I_1 + \frac{I_1}{j\omega C_1} + j\omega M_{12} I_2 + j\omega M_{13} I_3 + \ldots + j\omega M_{1\mathrm{n}} I_n \\
U_2 &= j\omega L_2 I_2 + R_2 I_2 + \frac{I_2}{j\omega C_2} + j\omega M_{12} I_1 + j\omega M_{23} I_3 + \ldots + j\omega M_{2\mathrm{n}} I_n \\
&\;\;\vdots \\
U_n &= j\omega L_n I_n + R_n I_n + \frac{I_n}{j\omega C_n} + j\omega M_{1\mathrm{n}} I_1 + j\omega M_{2\mathrm{n}} I_2 + \ldots + j\omega M_{n-1\mathrm{n}} I_{n-1}
\end{aligned}
\tag{8}
$$

n: is the number of windings.

U: voltage

A thorough analysis of this have been made by Eva Palmberg, [8].

Point 3 and 4 is preferably done with a multi-physics tool and in this report Ansys-Maxwell and Comsol has been used. It's necessary with a program that can make good calculations of the iron core losses and it is preferred that the geometry can be built up with parameters. In this way it's easy to change and optimise the geometry.

Time-domain simulations may be done with Simulink or similar tools. A representation in Simulink is shown in Figure 16, where building blocks from the Toolbox SimPowerSystems are included. With such a tool, control algorithms can also be evaluated.

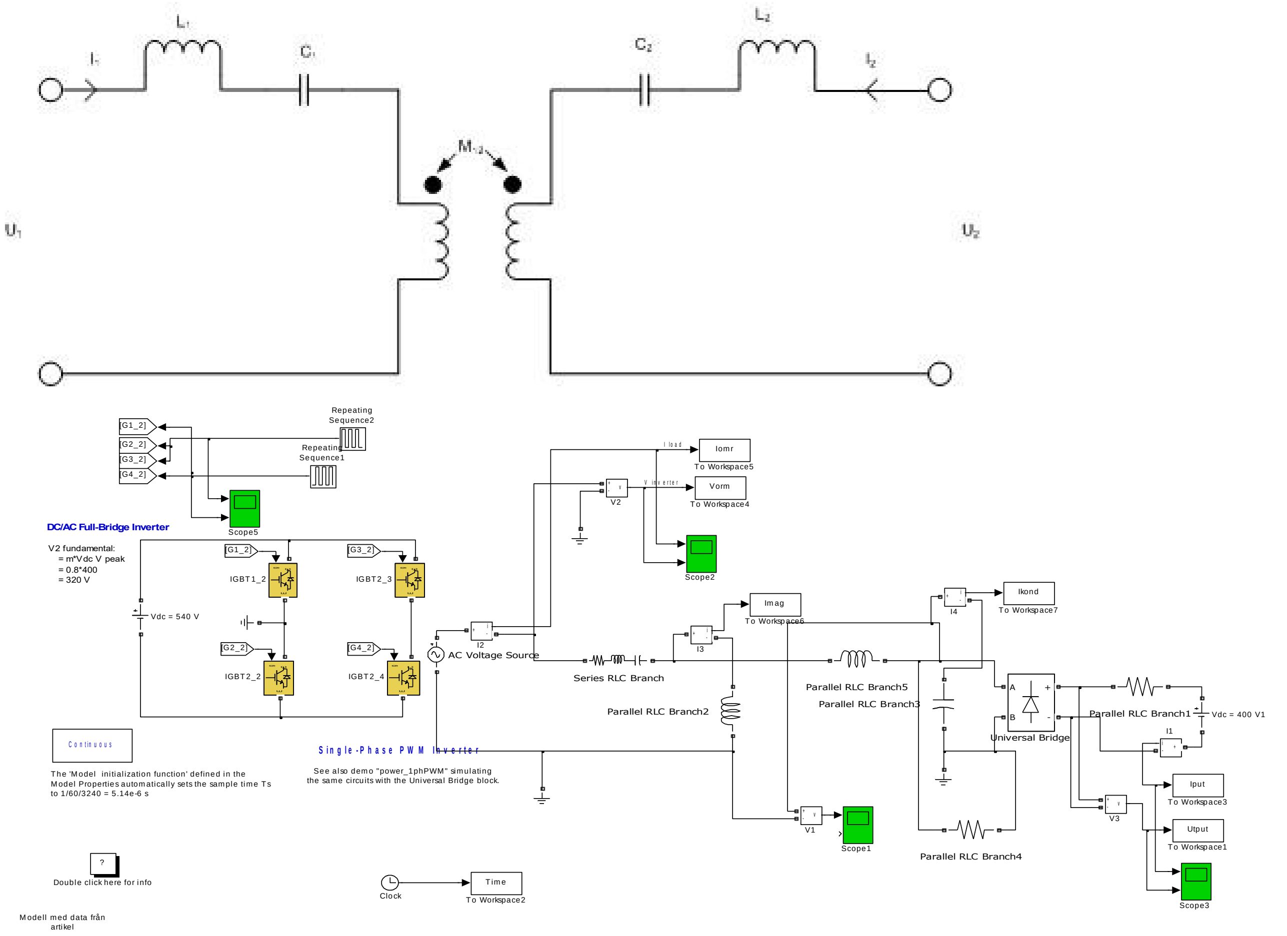


Figure 16. Two winding circuit and a representation in Simulink.

In this report it is assumed that the capacitors that is forming the resonant circuit is connected in series with the winding. In the primary circuit it blocks DC-current and in the secondary circuit it makes it possible to operate with a passive DC-rectifier. A possible third winding will only have the capacitor.

5. A qualitative discussion of the three winding coil

Of practical reasons the best is to place the extra coil close to the sending coil, as we don't want any extra material in the air gap and we should place as low amount of material as possible inside the vehicle. If the primary coil and the extra coil are close together the receiving coil will interact with the sum of the flux produced by the two sending coils. If the currents in the two coils is in phase with each other they would add flux to each other but this is not the case.

In a two-winding case the current in the secondary coil is shifted 90 degrees to the current in the first coil and this is almost true in the three winding case. The current in the extra winding is around 90 degrees from the first coil and the receiving coil is shifted to 180 degrees, i.e. completely out of phase from the sending coil. The current in the extra coil is dominating which means that it also dominates the flux to the receiving coil. The receiving coil interacts with this flux and produces voltage and current to the load

When producing secondary flux from two coils that are not in phase shouldn't be more effective than having just one sending coil.

6. Shielding

Shielding of the device can be done with aluminium parts in which the leakage flux can induce currents that will lower the penetrated flux.

The shielding works with the principle that the flux is decreasing by an opposing current which is large enough so that the resulting flux is suppressed. The current induced in the aluminium will produce losses in the shielding material.

One example is KAIST, [19], where metal shielding is used beside the primary coil and on the vehicle short circuit conductors hangs between the ground and the vehicle in order to lower the flux density to 6.25 uT outside of the vehicle. In their case the secondary coil directs flux horisontally which in this case result in a need for shielding.

The best is of course if the coil has low leakage as a starting point.

7. Frequency

Generally it's a good idea to increase the frequency of the feeding electronics. We may see from the figure of merit that the power increase with the frequency. At a certain power level the amount of material will be lower and the capacitors can also be smaller. A high frequency will however be more demanding on the power electronic devices and the coil material. Switching losses will be higher and EMI-disturbance will be more severe. Figure 17 and figure 18 shows the losses of the TDK/Epcos material N87, [13]. The power losses increase in the material but an increased frequency can be compensated for with more material and lower flux density. A lower flux density limits the power losses and makes it thermally feasible.

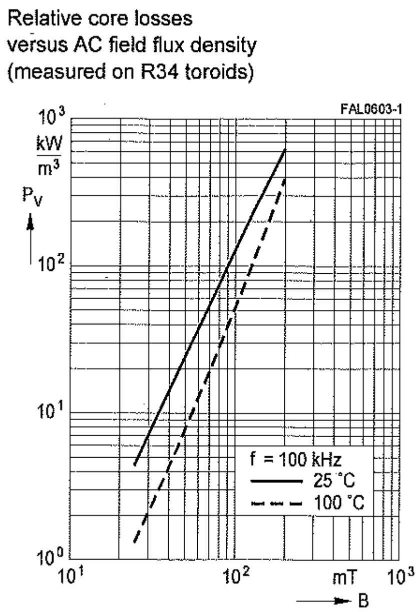


Figure 17. Core losses of N87 vs flux density at 100 kHz.

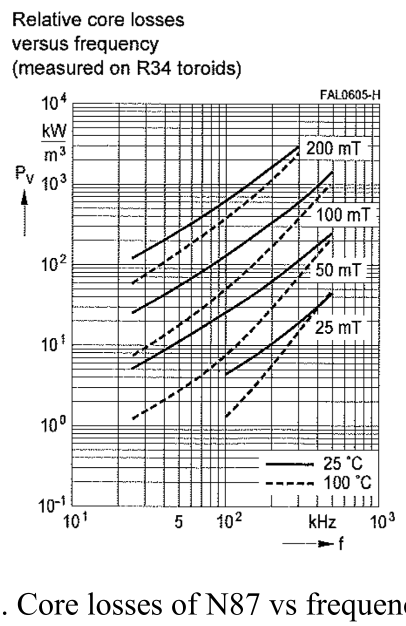


Figure 18. Core losses of N87 vs frequency.

The switching losses of the power electronic components can be avoided or lowered by means of capacitors that allows the component to switch off at low voltage. Another way is to use SiC-components that are faster than silicon components. They have also better thermal characteristics and can operate at higher temperature. For the time being they are more expensive but the general opinion is that the next generation of vehicle electronics will incorporate these devices.

Due to flux that originates from the winding and are directed through the winding the losses in the conductors will increase, even if the conductors are divided in thin individual parts. Litz-wire are ideal for this application but the power losses in the winding due to leakage flux has to be evaluated. The proximity effect, [15], is calculated as

$$\begin{aligned} P(t) &= \pi l \frac{d^4}{64\rho}\left(\frac{dB}{dt}\right)^2 \\ P_{av} &= \pi l \frac{d^4}{128\rho}\omega^2 B_p^2 = V_{cu}\frac{d^2}{32\rho}\omega^2 B_p^2 \end{aligned} \tag{9}$$

where l is the conductor length, d conductor diameter, B_p is the peak flux density penetrating the conductor.

8. A core with fingers

In this report most evaluated cores are solid but it may be divided in smaller pieces as in Figure 2. Ferrite material is brittle and cannot be thin without breaking so it may be necessary to use thicker parts that leads the flux. In order to save material there can be space between the ferrite pieces. In this case where the air gap is long the division of the core doesn't influence the total flux so heavily. A 3D-analysis of a structure with solid core and a core with fingers, as displayed in Figure 19, showed that just 1 % of the flux is lost when the core is divided.

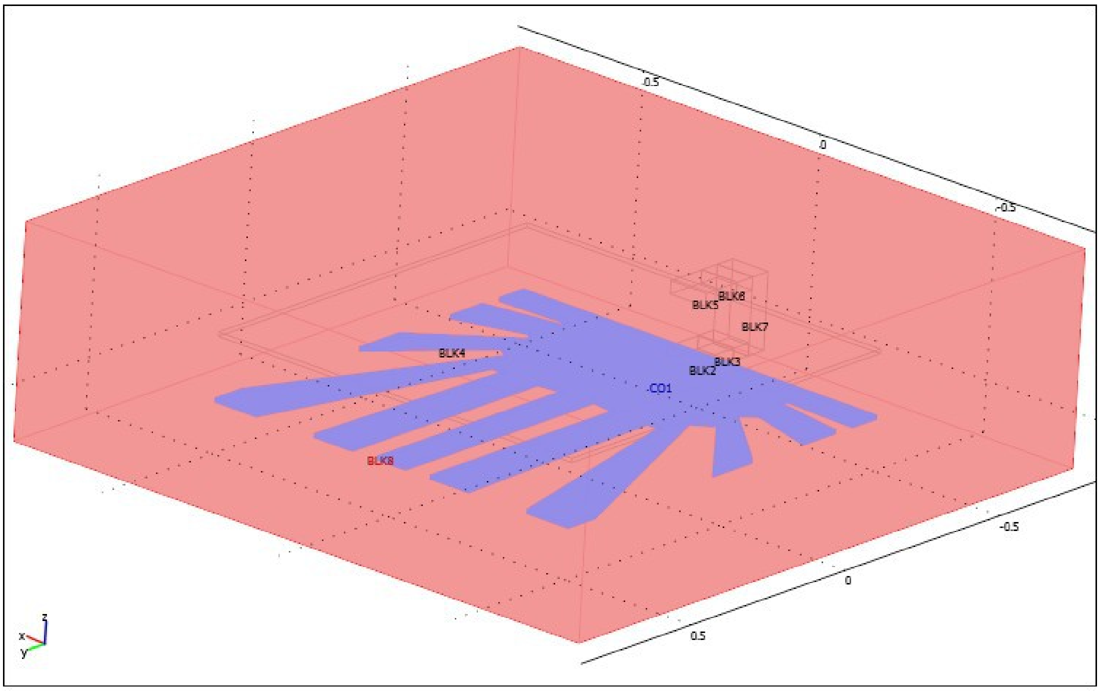


Figure 19. Core with 'fingers'.

When using this technique it should be evaluated how the leakage flux is changed compared to a solid core.

9. Case study

A square or circular coil and a DD-coil are evaluated with the same size as the student project coil . The area of the student project coil is:

A=0.27*0.54 m^2= 0.146 m^2

A square or almost square structure with the same are, i.e. the side of the coil is 0.38 m, see Figure 20.

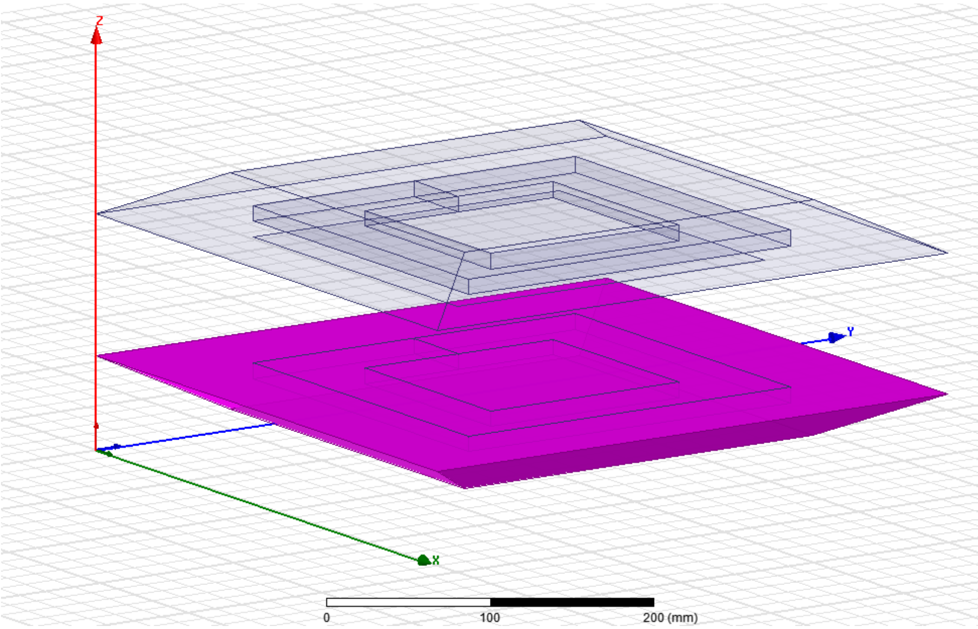


Figure 20. Analysed coil with a ferrite core and embedded winding.

The distance between the primary and the secondary coil is 100 mm.

The ferrite core material used is N87 and the winding is made with Litz-wire using 0.2 mm individual conductors. The skin depth of copper at 20 kHz is 0.46 mm so it is assumed that the DC-resistance value can be used. The proximity effect is however evaluated and cannot be neglected. The material-data, see Figure 17 and 18, are used as input to Maxwell and an approximation is done of the core losses. The approximation is shown in Figure 21.

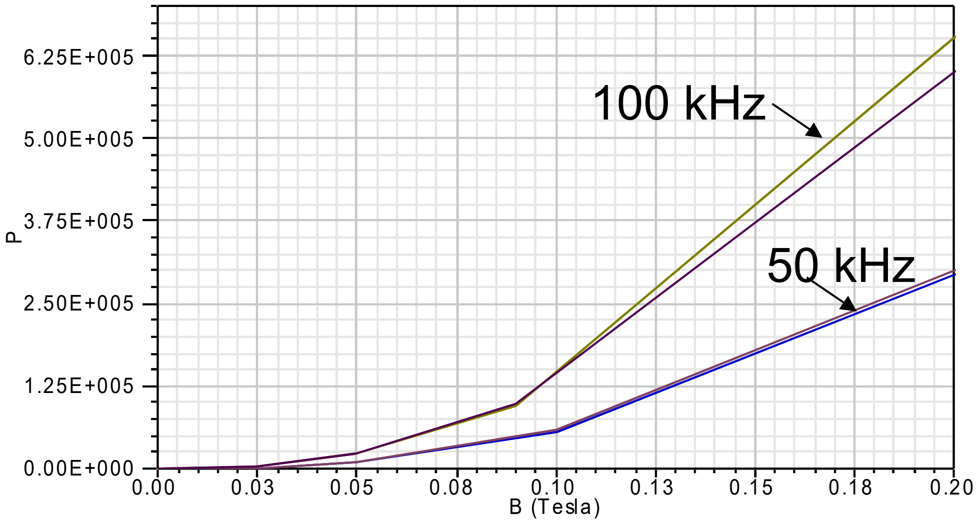


Figure 21. Core losses/W/m^3 as function of flux density approximated in Maxwell.

Figure 22 shows the simulated result of an operating point of 6.0 kW. The battery voltage is assumed to be 300 V. As can be seen the transformer and capacitors filter form the currents into an almost sinusoidal shape. The resulting currents are

$I_{1rms} = 40.6$ A / 18 ^{o}

$I_{2rms} = 24.7$ A / 114 ^{o}

In the simulation it is assumed that the number of turns is the same in the coils and it is assumed that a change of turns just scales the voltage and current. The same operating point have been used for both types of coils. It's not perfectly true but the impedance are quite well adapted to 120 uH for the primary current. The coupling factor differs slightly.

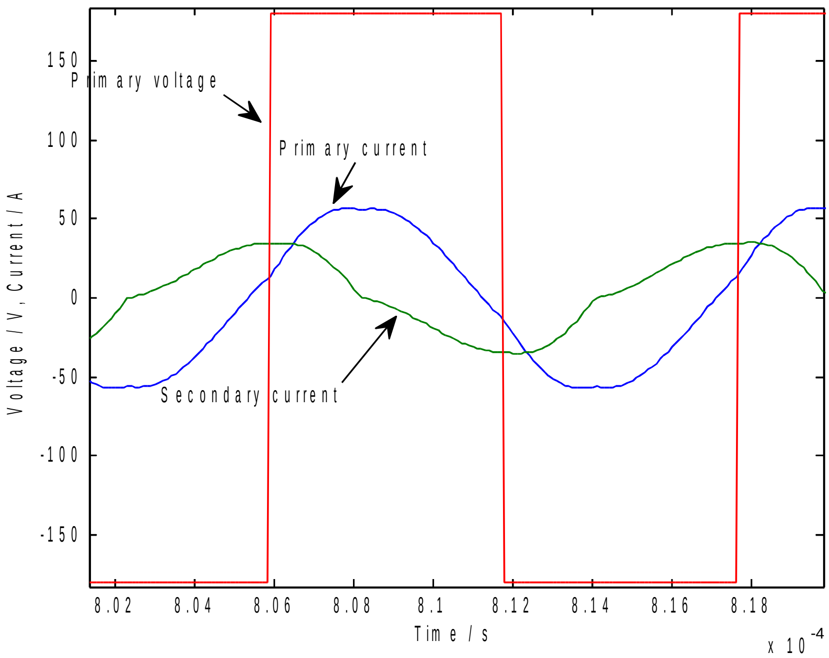


Figure 22. Simulated voltage and current to the coil.

When using the simulated currents the resulting flux density is calculated in Maxwell and the result is shown in Figure 23.

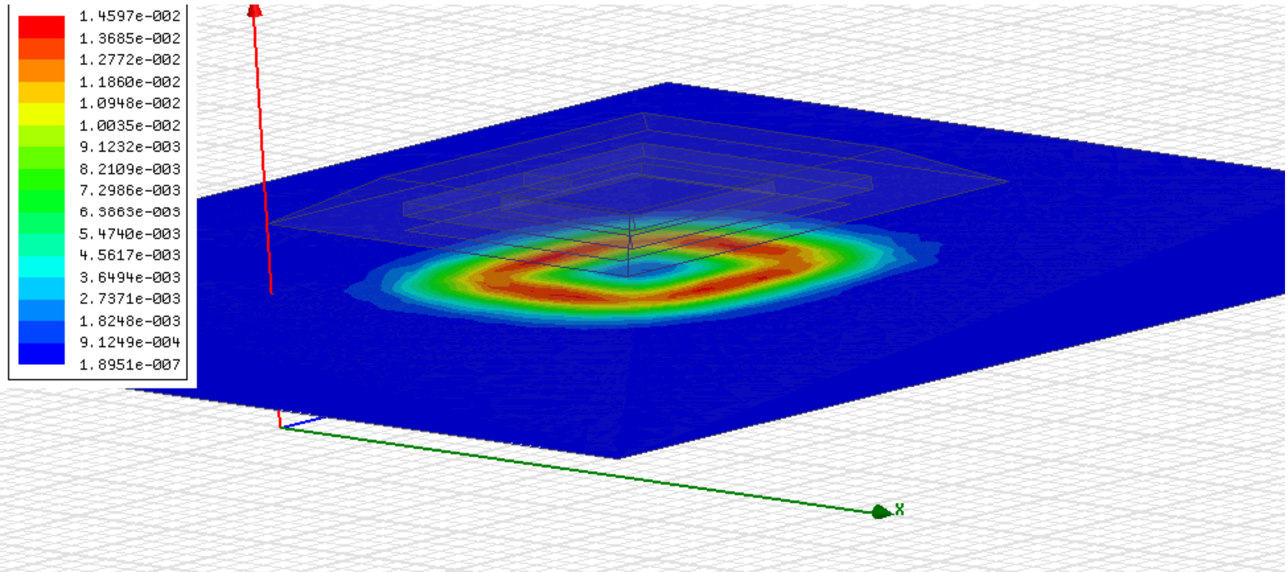


Figure 23. Flux density in the middle of the air gap of the Circular/Square coils.

The main difference between the evaluated coils is that the bar type concentrates the flux to a small ferrite volume. In that center core the flux density is high and also the power losses. Regarding the core losses in the other two types the flux density in the evaluated cores is rather low and hence the power losses. The copper losses is however higher which was expected but it is anyway rather low compared to the core losses of the bar type.

The core losses of the DD-coil is lower compared to the circular coil but the proximity losses are higher so overall they are quite similar. Earlier result showed better coupling factor with the DD-coil which is not the case.

Table 5. Resulting figures for simulated Circular/Square type and DD-coil. Power is 6 kW.

	Circular/Square type	DD-coil	Bar type / measurement
Air gap	100 mm	100 mm	50 mm
Frequency	20 kHz	20 kHz	20 kHz
Power	6 kW	6 kW	6 kW
Primary turns	15	9+9	11
Secondary turns	7	4+4	5
Copper weight	3.4 kg	4.8 kg	

Ferrite weight	26 kg	24 kg	
L1	121 uH	122 uH	114 uH
L12p*	56 uH	46 uH	44 uH
L2p*	121 uH	122 uH	114 uH
K13	0.46	0.38	0.39
Rs1/DC	24 mΩ	17 mΩ	4.2 mΩ
Rs2/DC	5.2 mΩ	4.9 mΩ	1.9 mΩ
C1	0.53 uF	0.53 uF	
C2	2.43 uF	2.68 uF	
Primary current	40.6	40.6	
Secondary current	52,9	55,6	
Copper losses	50	56	19
Ferrite losses	12	6,8	129+237
Proximity losses**	13 W(5 mT)	27 W (6 mT)	
Sum of losses	75 W	90 W	385 W

* Normalised to the same number of turns as primary winding

** Aproximative and assumed diameter 0.2 mm.

If we scale the result to a situation with 85 kHz, the winding has to be adjusted to 4.25 less turns which means that the conductor cross-sectional area increases with a factor of 18. The voltage and current will be the same which means lower flux density in the core and also lower current density in the winding. i.e. the losses will be reduced except for the proximity losses that increase with a factor of 18 if the amount of copper is the same. This may well be compensated for if the conductor diameter is lowered to 0.1 mm.

A shielding of an aluminium plate with the thickness of 5 mm and dimension of 1*1 m results in very low losses as long as the coils have the same dimensions and are perfectly aligned. As a result of a bigger sending coil and the shielding on the receiver side, the losses in the aluminium plate increase to 17 W at 20 kHz and 25 W at 85 kHz. A bigger sending coil is used to exaggerate the tolerance to misalignment and to minimise the coil on the receiving side.

A thinner core than in this example can be used, which will result in higher losses. The weight of the device will decrease, which is desireable. However mechanical considerations, such as mechanical strength and thermal behaviour, has to be taken into account.

9.1 Three winding case

The circular coil is evaluated using two and three windings. It is also found that the Powersim module 'Rectifier' produce some error that result in 3kW from the secondary winding and 6 kW on the DC-side so we use resistive load.

The resulting operational points in the two respective three-winding case is displayed in Table 6.

Positive current result in positive flux in the coils and as we can see from this example the current in the first coil(primary) is lower and have better phase factor in the three winding case. The current and voltage in the third (secondary) winding is almost the same. The copper losses of the windings are in this case the current squared times the resistance. It is assumed that the three windings have the same volume and number of turns so th resistance is the same. The last columns is the sum of the currents with a power of two, i.e. the copper losses are the sum times resistance in each winding.

Table 6. Operational points at resistive load and sinusoidal excitation, RMS-values

Case	Current 1	Voltage 1	Current 2	Voltage 2	Current 3	Voltage 3	Sum
Two-wind	29/0	212 / 0º			29/-90º	496/25º	1682
Three-wind	14.8/30.6º	475/ 0º	33/-90º	493/-180º	29/-149º	489/-34º	2149

The copper losses are 28% higher in the three winding case and a more complicated solution with three winding and extra capacitor.

10. Thermal evaluation

A calculation of the temperature of the circular coil is done. The losses are assumed to 90 W and it is assumed that an aluminium plate supports the ferrite and is mounted to a rather large steel area. One surface is facing air with the temperature of 40 degrees and an assumed convection constant of α=5 W/m^{2}K is used.

The resulting temperature is shown in Figure 24, calculated in Comsol. It is assumed that the backside has the temperature of 25 ºC and that the losses is 7 W in the core and the winding losses are 83 W. The front side has a convection cooling of 5 W/m2K.

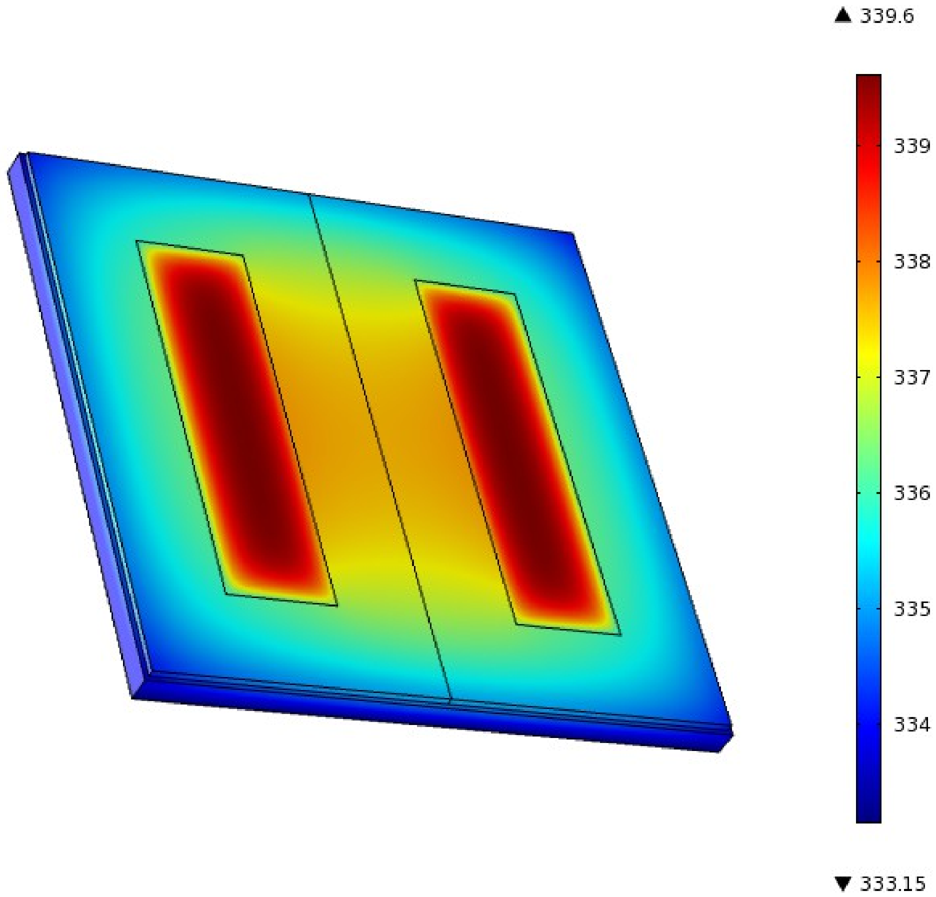


Figure 24. Resulting temperature /K at 90 W losses. Cooling of backside.

The result indicates 70 C, but the backside cooling is important especially when extra material covers the winding in order to protect it. The protection must withstand stones and other stuff that might bounce up towards the under body. If the backside isn't cooled, the temperature will be too high, which indicates that there might be a cooling problem of the devices. At least there has to be an aluminium sheet that both acts as a shield and as thermal energy transport to the chassis of the car. And the best is of course if chassi parts with some thickness can be thermally connected to the receiving coil. The electronics need also some conduction parts.

11. Measurement on lab device

A prototype of the DD-coil is manufacture and the inductance of the device is measured using a Wayne Kerr Automatic LCR-meter. It is measured to 48.4 uH (10 kHz). The value is almost constant in the frequency interval of 1 - 100 kHz, 48.6-48.3 uH.

The measured value differs also compared to the calculated value of 41 uH, (the coil has half of the turns in Table 5), which possibly can be more accurate if the extra quarter of turn is taken into account and also the connection cables. The latter will add some uH but the rest of the added inductance must come from the first turn and inlet of the cable which is not so well constructed, with ferrite almost surrounding the inlet cable. A topic for further investigation.

As another verification the induced voltage is measured in one measuring turn of the secondary circuit. The induced voltage on the secondary side is 10 mVt (Volts / turn) when 19 mVt is fed to the primary coil. The measured coupling factor is k13=0.53 and the calculated value is 0.52 i.e. rather good compliance.

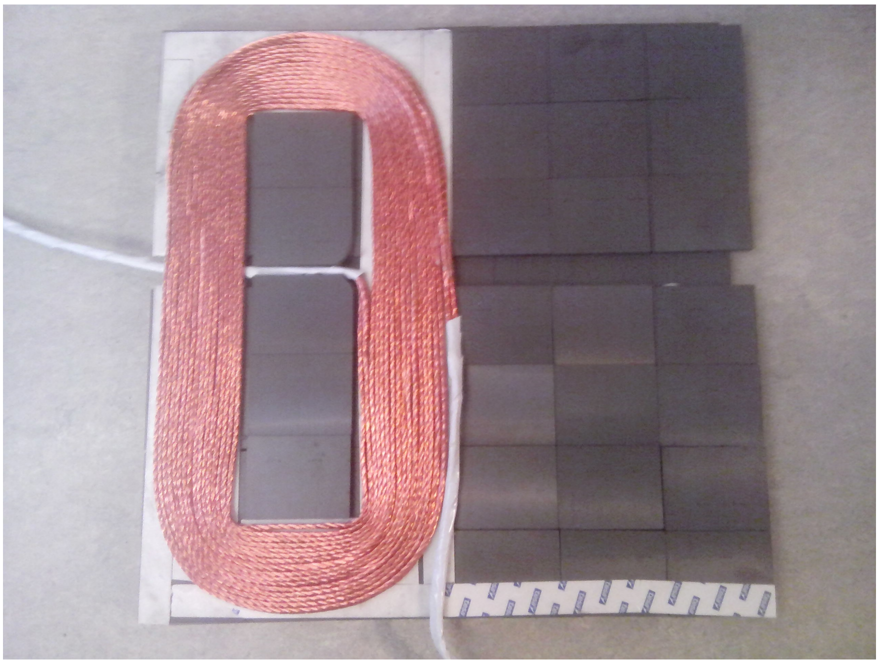


Figure 25. Prototype DD-coil.

12. Conclusion

Inductive charging is a convenient choice for home charging and if standardised an alternative to charge cars at parking lots. Using this technique for dynamic charging or propulsion of vehicles looks as a more expensive and complicated method than fast chargers. If we just regard the charging infrastructure of cars we need very much higher total power rating in the system compared to fast chargers. If the dynamic charging shall be able to coupe with hills and peak power to the cars the peak power should be 60 kW for an ordinary car. In the inductive charging case we also need a lot of expensive equipment in the vehicle.

Of the analysed coil types there is no big difference between the DD-coil and the square / circular type. Both has high coupling factor on the same time as the leakage flux is low. The efficiency the bar type coil seems rather good, but it has the draw back of high leakage flux.

The calculated efficiency of the magnetic devices are in the range of 97-98.5 % and the efficiency at 85 kHz is higher than at 20 kHz. It is in the same range as calculated by Ombach, [14], for the magnetic part. In order to make an even better prediction the leakage flux and shielding should be evaluated as well. Calculation on the losses in the shielding results in neglible losses as long as the coils are symmetrical and made as DD-coils or circular coils. A sending coil bigger than the receiver will result in losses in the shielding.

Heat dissipation looks as no problem as long as the receiving coil is mounted to a fairly good thermal conductor and the power rating is 6 kW. A steel sheet of 1 mm isn't good enough for cooling of 90 W but if the receiving coil can be fixed to thicker parts then there is good chance of cooling the coil. The size of such device is 380 mm times 380 mm.

A three coil solution needs more copper than a two coil solution in the studied cases. This result in a more expensive and heavier construction than the two coil solution.

13. Reference

[1] http://www.greencarcongress.com/2014/07/20140731-fraunhofer.html

[2] http://www.greencarcongress.com/2014/09/anderman-report-on-teslas-battery-prospects-with-the-gigafactory.html

[3] Tony Seba, 'Clean disruption of energy and transportation', ISBN9780692210536

[4] *Gruber et al., '*Global Lithium Availability and Electric Vehicles', *Journal of Industrial Ecology*

[5] Budhia, Boys, Covic, Huang, 'Development of a Single-Sided Flux Magnetic Coupler for Electric Vehicle IPT Charging Systems', IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 60, NO. 1, JANUARY 2013

[6] Budhia, Boys, Covic, 'A New IPT Magnetic Coupler for Electric Vehicle Charging Systems',

[7] Lee et.al., 'On-Line Electric Vehicle using Inductive Power Transfer System', ECCE IEEE 2010

[8] Eva Palmberg, 'Investigations on an inductive power transfer coupler with two or three windings', CTH 2015, report No. 2015:4

[9] Ivan Salkovic, Saeid Haghbin and Torbjörn Thiringer, 'The control design and practical measurement of a wireless power transfer system with an auxiliary transformer winding,' will be submitted to IEEE International Conference on Renewable Energy Research and Applications (ICRERA) 2015, Italy.

[10] Elgström et.al. 'Induktiv högeffektsladdare till elfordon', Chalmers University of Technology 2014.

[11] Ivan Šalković , 'Wireless charging using a separate third winding for reactive power supply', Master of thesis report, CTH 2015

[12] Cicnrp vad är tillåtet som nivå av flödestäthet?

[13] Data sheet for TDK/Epcos N87, http://en.tdk.eu/blob/528882/download/4/pdf-n87.pdf

[14] Ombach et.al., 'Optimum magnetic solution for interoperable system for stationary wireless EV charging.' 2015 EVER.

[15] R. Sullivan,'Computationally Efficient Winding Loss Calculationwith Multiple Windings, Arbitrary Waveforms, and Two-Dimensional or Three-Dimensional Field Geometry', IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 16

[16] Ny Teknik,' http://www.nyteknik.se/asikter/debatt/article3758280.ece' Camilla Stålstad, Viktoria ICT

[17] Turki, Körner, Tlatlik, Brown, ' Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles' , SAE International Journal of Alternative Powertrains, 05/2014, Volume 3, Issue 1

[18] Grunditz E. 'BEV Powertrain Component Sizing With Respect to Performance, Energy Consumption and Driving Patterns', Chalmers University of Technology, 2014.

[19] Seungyoung Ahn, Joungho Kim 'Magnetic Field Design for High Efficient and Low EMF Wireless Power Transfer in On-Line Electric Vehicle', Wireless Power Transfer Conference (WPTC), 2015 IEEE