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Coil Topologies for Inductive Power Transfer in Automotive Applications

Katharina Knaisch, Markus Springmann, Peter Gratzfeld

Karlsruhe Institute of Technology, Institute of Vehicle System Technology, Rail System Technology
Rintheimer Querallee 2, Bldg. 70.04, 76131 Karlsruhe, katharina.knaisch@kit.edu

Summary

Inductive charging of battery electric vehicles became increasingly popular in recent years, as this wireless charging technology provides for a comfortable, hands-free, safe, and reliable way to charge. In this work, current research results relating to various coil topologies are transferred and applied to specific automotive applications. Two different cases of application are investigated in this paper: Small and inexpensive minicars and large sport utility vehicles (SUVs) with higher ground clearance. First, topologies that are particularly appropriate for the respective vehicle segment are selected and designed. A subsequent optimization considers the key requirement of the automobile manufacturers of a lightweight, compact, and small inductive charging system.

Keywords: BEV (battery electric vehicle), inductive charger, optimization, simulation, wireless charging

1 Introduction

Inductive power transfer (IPT) systems developed rapidly in recent years, as they are driver-friendly, reliable, and safe. Presently, they are widely used in a broad range of applications, for example in consumer electronics, biomedical implants, automatic guided vehicles, electric vehicles, or busses [1–3].

IPT systems use an electromagnetic field to transfer energy through air between two coils by electromagnetic induction. The primary coil as stationary coil is implemented in the ground. The secondary receiver coil is placed in the vehicle underbody.

At the moment, various coil topologies are applied in IPT systems. An appropriate structure of the magnetic coupler system has to be selected depending on the specific application. As there is a broad range of different vehicles, the coil systems have to meet special requirements, such as power level, costs, system size, ground clearance, and many more. So far, however, only partial comparisons of the various topologies have been reported, for example in [4–7]. In [8, 9] a comprehensive comparison of air cored coils as well as of entire coil systems is made, but specific applications have not been considered in these studies.

In this paper, latest research results for various coil topologies are applied to specific automotive applications, or vehicle segments. Focus of this paper is the key requirement of automobile manufacturers of a light-weight, compact, and small charging system.

This paper is organized in the following way: In Chapter II, the requirements on the coil system are defined from the automobile manufacturer's point of view. Two different applications are selected, for which the coil systems subsequently are designed and optimized. Chapter III discusses the selection of optimal coupler topologies for the two previously defined vehicle segments. In Chapter IV, specific dimensions of the reference models are defined and the particular characteristics of each topology are analyzed. A following optimization of both secondary topologies in Chapter V reduces the weight of the charging systems. For this purpose, one-factor-at-a-time variations of the geometrical variables are examined first. On the basis of these results, the coil system then is optimized iteratively. Numerical 3D simulations with the software tool ANSYS Maxwell are used in this work to analyze the IPT systems. [10]. This software uses the finite element method to solve the electromagnetic fields. As all simulations are based on numerical approximate solutions, the simulation results are validated and verified in Chapter VI. The final chapter summarizes the main findings of this work.

2 Automotive Applications and Boundary Conditions

The selection of representative automotive applications the coil systems are designed for is based on the vehicle segments loosely defined by the German Federal Motor Transport Authority [11] and the EU-Commission [12]. The vehicles are classified in different categories according to various criteria, such as size/weight, motorization/engine power, trunk/seating capacity, and other. In this work, the vehicle segments "Minicar" (segmentation A) and "SUV" (segmentation J) are selected, which are the most contrasting segments according to the previously introduced classifications.

2.1 Minicars

Minicars are small, lightweight, and inexpensive vehicles. They are mainly used for short distances, such as urban trips. According to [11], the five top-selling minicars in 2015 in Germany were: Hyundai i10, Smart ForTwo, Opel Adam, Fiat 500, and VW Up.

The average length of these five vehicles is about 3.4 m. The average vehicle width without side mirrors is 1.66 m. The Fiat 500 is the most narrow vehicle in this group, with a width of 1627 mm [13].

2.2 SUV

Sport Utility Vehicles (SUVs) are large vehicles with higher ground clearance. Within the last years, SUV sales are growing: compared to 2014 the new registrations of SUVs in 2015 in Germany increased above-average by 15.2 % [11]. The five top-selling SUVs in 2015 in Germany were: Hyundai ix35, Nissan Qashqai, Ford Kuga, Opel Mokka und VW Tiguan [11].

The average length of these vehicles is 4.4 m, the width is 1.8 m on the average (without side mirrors). The SUVs have a ground clearance between 170 mm and 200 mm.

2.3 Derivation of Requirements on the Coil System

The requirements on the coil systems can be derived from the characteristics of the previously introduced vehicles. These requirements are listed in 1.

1) Limitation of the maximum size of the coil system is based on the installation space available in the minicar, or SUV. The track width minus the tires section width of minicars is about 1.27 m, which is only slightly smaller than that of the SUVs with 1.35 m. When deducting the space needed for cornering, a maximum available installation space of 1 m × 1 m results for both vehicle systems.
2) The air gap of the IPT system implemented in a minicar is defined based on the ground clearance demanded by the Technical Inspection Agency (TÜV) of 110 mm [14]. The air gap of the coil system of a SUV is 200 mm, as this represents the largest ground clearance of the five vehicles mentioned above.
3) According to the requirements of the ICNIRP guideline (International Commission on Non-Ionizing Radiation Protection) 2010 [15], the magnetic stray field has to be lower than 27 µT at the vehicle body in order to prevent against known adverse health effects by exposure to electromagnetic fields. The Fiat 500, as the most narrow car of the five top-selling minicars, is taken as a basis with a vehicle width of 1627 mm [13]. Furthermore, a side clearance is taken into account, as passengers always pass the vehicle with a small distance to the vehicle body. For the minicars, the magnetic flux is measured at a distance of 850 mm from the secondary coil center. For the vehicle segment "SUV", the measuring

plane is defined analogously to the minicars: Of the five presented SUVs, the Opel Mokka has the smallest width with 1780 mm [16], which is why the magnetic flux density is measured at 950 mm lateral distance to the secondary coil center.

4) Referring to the current guideline of the International Electrotechnical Commission (IEC) [17], the required positioning tolerance is a circular offset with a radius of 150 mm.
5) The power to be transmitted in nominal position (i.e. without lateral misalignment between the coils) also is defined based on the current activities of standardization [17]. For minicars, an IPT system of power class WPT3 (wireless power transfer) with 22 kW is implemented. As SUVs are significantly larger than minicars and used for longer distances, accumulators implemented in SUVs have a considerably higher capacity. Thus, an IPT system of power class WPT4 with a power of 50 kW is used for SUVs.
6) In case of a maximum lateral misalignment of the coils, the efficiency still has to exceed 80 % according to [17]. As a fully compensated system is assumed in this paper, a maximum loss of power of 20 % is accepted.
7) The frequency is 85 kHz, as discussed by the bodies of standardization [17].
8) For the simulation model, currents have to be defined. Based on the experiments of the prototype in [8, 9], the primary current is set to 60 A for the WPT3 system. As power transmitted in a WPT4 system is almost twice as high, a primary current of 120 A is imposed in this case.
9) In this study, a constant transferred power is assumed. Therefore, the secondary current is limited and the output power is then calculated. A current density of 2.4 A/mm² at nominal position and a maximum permissible current density of 4.8 A/mm² are assumed. This results in a maximum secondary current of 120 A for coil systems implemented in minicars and of 240 A for systems in SUVs.

Table 1: Requirements on the Coil System

	Requirement	Minicars		SUV	
(1)	Maximum size in y-direction	1000	mm	1000	mm
(2)	Air gap	110	mm	200	mm
(3)	Distance of coil center from the ICNIRP measuring point in y-direction	850	mm	950	mm
(4)	Positioning tolerance in x-y-direction	150	mm	150	mm
(5)	Power to be transferred at nominal position	22	kW	50	kW
(6)	Power to be transferred with maximum lateral misalignment	17.6	kW	40	kW
(7)	Frequency	85	kHz	85	kHz
(8)	Primary current	60	A	120	A
(9)	Maximum secondary current	120	A	240	A

3 Selection of Coils for Particular Applications

In this chapter, optimal coil topologies are selected for the previously introduced cases of application (minicar and SUV). The selection of particularly suitable coils for the respective vehicle segments is based on the results of [8, 9].

For the minicar segment, a geometry with a magnetic field perpendicular to the surface (also called non-polarized) is applied. Non-polarized couplers are comparatively simple and inexpensive [8], which corresponds to the characteristics of minicars. Moreover, the group of non-polarized topologies is suitable for applications with a relatively small installation space. Compared to IPT systems used in SUVs, the transferred power is significantly lower and, consequently, currents also are lower. For this reason, the unfavorable characteristic of a large magnetic stray field is of minor significance. Based on the results of [8], a circular geometry (CP) is selected from the group of non-polarized geometries. The CP coil has a good score in total, a simple structure, and a very low weight. The reference design of a CP coil is illustrated in the left image of Figure 1. Usually, a conventional magnetic circuit consists of copper windings (black) made of litz wire in order to reduce losses due to skin and proximity effects. A soft-magnetic material, such as ferrite (dark gray), guides and contains the fields and a material for shielding, such as aluminum (light gray), shields the magnetic fields.

As regards to the application of an SUV, a polarized geometry is chosen. Polarized couplers are characterized by a high power transfer over large air gaps. Due to the requirements of a large air gap and a high power to be transferred, a coil system with a small leakage field has to be used. According to [8], DD and DDQ topologies perform particularly well. In this study, the DD design is selected as primary coil implemented in the ground. It is well-known that DD coils interoperate with various geometries [1, 5, 6, 17, 18].

However, a combination of a primary DD coil and a secondary DD coil has a fundamental x-axis tolerance limit, see [4]. Hence, a DDQ topology is applied on the secondary side in combination with a DD design on the primary side. The quadrature coil is magnetically decoupled from the DD coil and can be tuned separately without affecting the other coil.

The DD-DDQ system applied in SUVs is shown on the right side of Figure 1.

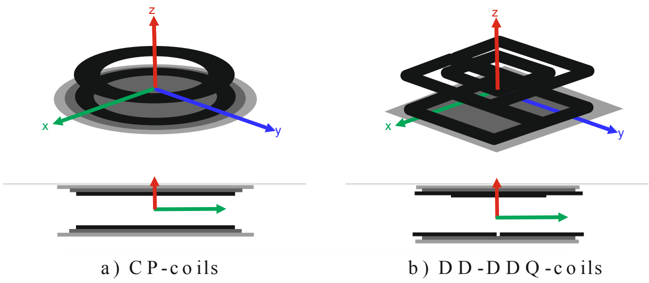


Figure 1: Reference designs of CP and DD-DDQ coils in dimetric projection (without secondary ferrite plate and secondary aluminum plates for reasons of clarity) and sectional view in plane x-z.

4 Characteristics of Selected Coils

In this chapter, both reference systems are defined. In order to obtain a first impression of the system behaviors, the coil systems are analyzed in nominal position as well as in cases of lateral misalignment.

4.1 Dimensions of the Coils

The dimensions of the reference systems are based on the requirements previously explained, see Chapter II and 1. Table *2* summarizes the geometrical variables of the coil systems and the dimensions defined.

Table 2: Dimension of the Reference Coil Systems

Variable	Minicars	SUV
Size of coil system [mm]	Ø 800	900 × 900
Cross section of coil [mm²]	50	100
Number of turns [ ]	5	5
Distance between windings [mm]	20	10
Distance between sub-coils [mm]	-	10
Size of quadrature coil [mm]	-	500 × 500
Number of turns quadrature [ ]	-	3
Ferrite size [mm]	Ø 900	800 × 800
Ferrite height [mm]	5	5
Aluminum size [mm]	Ø 1000	1000 × 1000
Aluminum height [mm]	5	5
Vehicle underbody [mm]	Ø 1500	Ø 1600
Air gap [mm]	110	200
Lateral misalignment in x-y-direction [mm]	150	150

It is assumed that the maximum permissible size of coil system is equivalent to the installation space available. For the size of the coils, the maximum permissible size is chosen. This allows for the best transmission characteristics, such as high transferred power and a large positioning tolerance.

The size of the vehicle underbody is set to 90 % of the vehicle width. The cross section of the coils for WPT4 systems is twice as large as for WPT3 systems, as also currents are twice as high.

4.2 Characteristics of the Coils

The reference system of the circular coil (CP) defined in Table *2* is characterized by self-inductances of 47 µH and a mutual inductance of 26.9 µH. Hence, the coupling factor in nominal position (without lateral misalignment of the coils) is 0.56. The magnetic flux density on the vehicle body is 2.42 µT and the secondary pad has a weight of about 41 kg.

The characteristics of the circular coil system with lateral misalignment in x-direction, y-direction, and x-y-direction is depicted in Figure 2. In case of lateral misalignment, the coupling factor decreases to values between 0.35 and 0.54, compared to a coupling factor of 0.56 in nominal position. For a circular system, the direction of the offset is irrelevant, as it is rotationally symmetric.

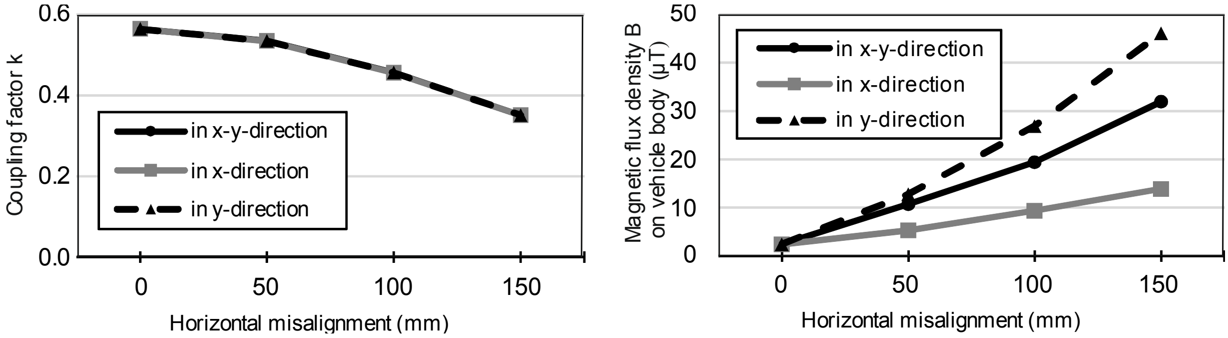


Figure 2: Characteristics of the circular coil system.

Even in case of a maximum lateral misalignment, the required power of 22 kW can be transmitted. With a radial offset of 150 mm, the limit given in the ICNIRP guideline of 27 µT [15] is exceeded slightly with a magnetic flux density on the vehicle body of 31.9 µT. In y-direction, an offset of up to 100 mm is possible without exceeding the ICNIRP guideline limit.

The IPT system with DD-DDQ coils applied in SUVs has self-inductances of L1 = 112.5 µH and L2 = 117.2 µH. Together with a mutual inductance of 45.1 µH, a coupling factor of 0.38 is resulting. The magnetic flux density on the vehicle body of 45.4 µT exceeds the maximum permissible limit of the ICNIRP guideline of 2010 in nominal position already. The secondary side weighs about 47 kg.

The behavior of the DD-DDQ system with lateral misalignment is illustrated in Figure 3.

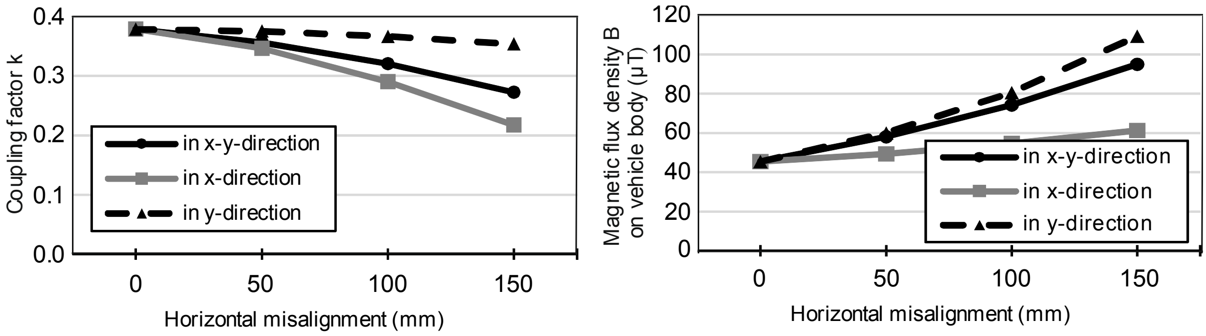


Figure 3: Characteristics of the DD-DDQ coil system.

It is obvious that the coupling factor is significantly lower than that of the CP system. However, it is to be considered that the air gap for the DD-DDQ system also is significantly larger. Similar to the CP system, the maximum transferred power can be transmitted even in case of a maximum offset. But at no time can the requirements of the ICNIRP 2010 be met.

To sum up it can be said that both topologies operate with the highest performance at any time. As, only a transferred power of 80 % of the nominal power is required in case of maximum offset, there is some room left for an optimization of the system.

For this reason, the following chapter analyzes possible reduction of the secondary coil system size. By reducing the size, the automobile manufacturers' demand for a lightweight and small system can be met. Moreover, a smaller secondary IPT system results in a larger distance between the coil center and the vehicle body. Thus, the magnetic flux densities on the vehicle body decrease and the limits defined in the ICNIRP guidelines can possibly be complied with.

5 Weight Optimization of the Secondary Coils

At first, the secondary side of the IPT system is optimized, as the vehicle manufacturers prefer a secondary coil system that is as small and light-weight as possible. The primary coil system is kept constant for now as it is not relevant to the weight from the manufacturer's point of view. Furthermore, keeping the primary system large allows for a good positioning tolerance. If necessary, the primary side is adapted afterwards in order to meet the previously defined requirements (such as magnetic stray field on the vehicle body).

For weight optimization of the secondary side, all parameters having a significant effect on the secondary weight are varied and optimized.

The most important objective function of optimization is minimization of weight. At the same time, though, a sufficiently high coupling factor has to be ensured. Moreover, the previously defined boundary conditions have to be fulfilled: Minimum positioning tolerance of a radius of 150 mm, compliance with the ICNIRP guidelines on the vehicle body, and transmission of 80 % of the nominal power in case of maximum lateral misalignment.

To take all these requirements into account, all following studies are conducted for the worst case of lateral misalignment. As can be seen from Figure 3, on the one hand an offset in x-direction is critical for the coupling factor, and on the other hand an offset in y-direction is critical for the magnetic stray field. A lateral misalignment in diagonal direction represents the worst case for both target values. Thus, in this study the system is optimized for lateral misalignment in x-y-direction.

5.1 Optimization of the CP Coil

5.1.1 Parameter Variations

For the circular coil design, the following parameter variations are studied:

- Decreasing the coil size. Ferrite and aluminum plates are scaled down accordingly in order to keep the proportion of the pad constant.
- Decreasing the number of turns. A current density of 3 A/mm² and a copper fill factor of 0.5 are assumed. Hence, a reduction in number of turns with a consistently magnetic field strength requires higher currents and, thus an enlargement of the cross sections of coils.
- Changing the geometry of the ferrite plate. As already discussed in literature, for example in [19], the ferrite plate can be replaced by radially arranged ferrite bars. Although ferrite bars have considerable advantages in weight, their transmission characteristics are comparable those of a ferrite plate. In this work, the number, the width, and the length of the ferrite bars are varied. The reference model has 8 bars with a width of 60 mm each and a length of 900 mm.

5.1.2 Results of the Parameter Variations

As an example of all parameter variations, the two main results of the parameter study are highlighted in Figure 4. For a clearer representation, all values are normalized to the initial values of the reference model.

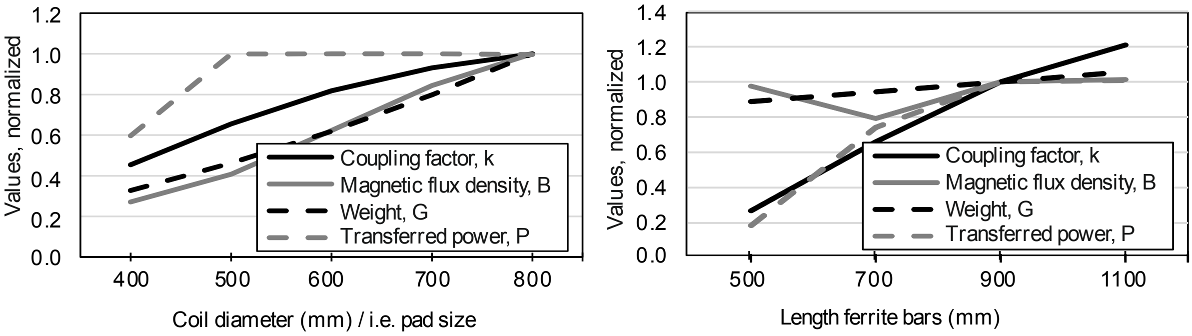


Figure 4: Selected parameter variations of the CP coil.

As illustrated in the left diagram of Figure 4, a reduction in pad size results in a decrease in magnetic flux density and in weight at the same time. When reducing the pad size to 500 mm, the coupling factor decreases to 0.23, the weight reduces to 19.1 kg, and the magnetic flux density on the vehicle body decreases to 13 µT. With a pad smaller than 500 mm, the required power transfer of more than 80 % of 22 kW is no longer possible.

Furthermore, the parameter variations revealed that a variation in number of turns has a negligible effect on the weight, but increasing the number of turns results in a slightly higher coupling factor.

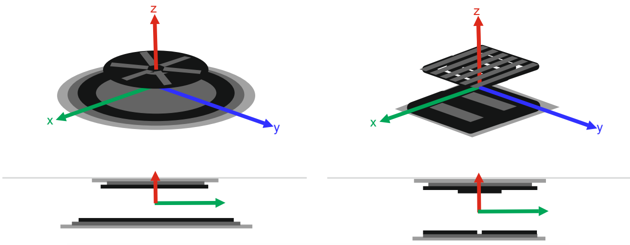
Replacing the ferrite plate by ferrite bars also reduces the weight and the magnetic stray field. A trade-off is needed between the minimization of weight and the maximization of coupling factor. As illustrated in the right diagram of Figure 4, the length of the ferrite bars has to be slightly smaller than the outer radius of the coils in order to transmit the power required. The weight can be reduced further by varying the width and the number of the ferrite bars. Nevertheless, this reduction in weight also has to be traded off against a sufficient coupling factor.

5.1.3 Optimized CP Coil

Based on the previous findings, an optimal CP design can be defined for minicars. According to Figure 4, the coil size is set to 550 mm. This allows for a significant reduction in weight, a good coupling factor, and a sufficient transferred power at the same time. In order to increase the coupling factor of the coil system, the number of windings is increased from 5 to 8.

The length of the ferrite bars is slightly smaller than the outer radius of the coil. In that case, the magnetic flux density has a local minimum, as is seen in Figure 4. Furthermore, the parameter variations revealed that the selection of 6 ferrite bars with a width of 40 mm each results in a good system behavior.

The design of the optimized circular coil is shown in the left picture of Figure 5, its specific dimensions are listed in Table *3*.



a) CP-coils b) DD-DDQ-coils

Figure 5: Optimized designs of CP and DD-DDQ coil systems in dimetric projection (without secondary aluminum plates for reasons of clarity) and sectional view in plane x-z.

The results of the optimization compared to the characteristics of the reference model are depicted in Figure 6. The coupling factor decreases from 0.35 to 0.18 in case of lateral misalignment. Despite this decrease in coupling, the requirement of a transferred power of at least 80 % of nominal power can be met with a power of 19.2 kW. In case of lateral misalignment, the magnetic flux density decreases from 31.94 µT to 5.75 µT.

This means that the ICNIRP guidelines now are fully met. The weight of the secondary coil system is reduced by more than 75 % to 9.8 kg.

Table 3: Dimension of Optimized Secondary Coils

Variable	Minicars	SUV
Size of coil system [mm]	Ø 550	600 × 450
Cross section of coil [mm²]	110	120
Number of turns [ ]	8	6
Distance between windings [mm]	20	10
Distance between sub-coils [mm]	-	10
Size of quadrature coil [mm]	-	200 × 300
Number of turns quadrature [ ]	-	2
Number of ferrite bars [ ]	6	6
Width of ferrite bars [mm]	40	40
Ferrite size [mm]	Ø 500	500 × 450
Ferrite height [mm]	5	5
Aluminum size [mm]	Ø 650	700 × 700
Aluminum height [mm]	5	5
Vehicle underbody [mm]	Ø 1500	Ø 1600

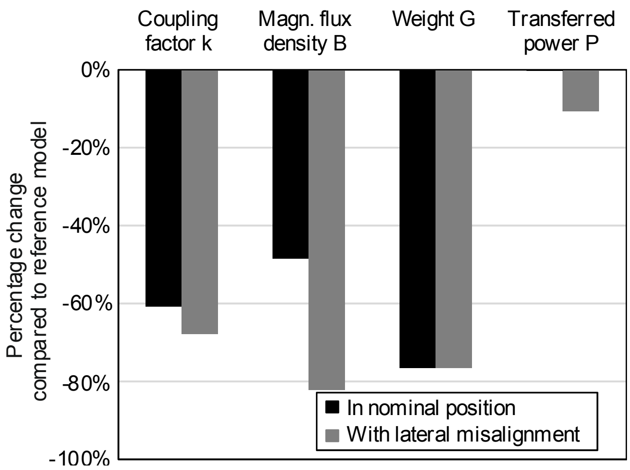


Figure 6: Optimization results of the CP coil.

The following optimization of the DD-DDQ coil system is carried out analogously to the optimization of the CP coil system.

5.2 Optimization of the DD-DDQ Coil

5.2.1 Parameter Variations

The parameter variations studied for the DD-DDQ coil are listed below:

- Decreasing the coil size. Analogously to the CP coil, the coil size is decreased together with the ferrite and the aluminum plate.
- Decreasing the number of turns. Similarly to the CP coil, the number of turns together with the cross section of coils is varied. Here again, a current density of 3 A/mm² and a copper fill factor of 0.5 are assumed.
- Varying the size of the quadrature coil.
- Varying the number of turns of the quadrature coil.

- Changing the geometry of the ferrite plate. As already mentioned above, the ferrite plate is replaced by ferrite bars. The parameter study comprises the variation of number, width, and length of the ferrite bars. The reference model has 8 bars with a width of 60 mm and a length of 900 mm each.

5.2.2 Results of the Parameter Variations

Selected results of the parameter variations of the DD-DDQ coils are highlighted in Figure 7. The values are normalized to the initial values of the reference model.

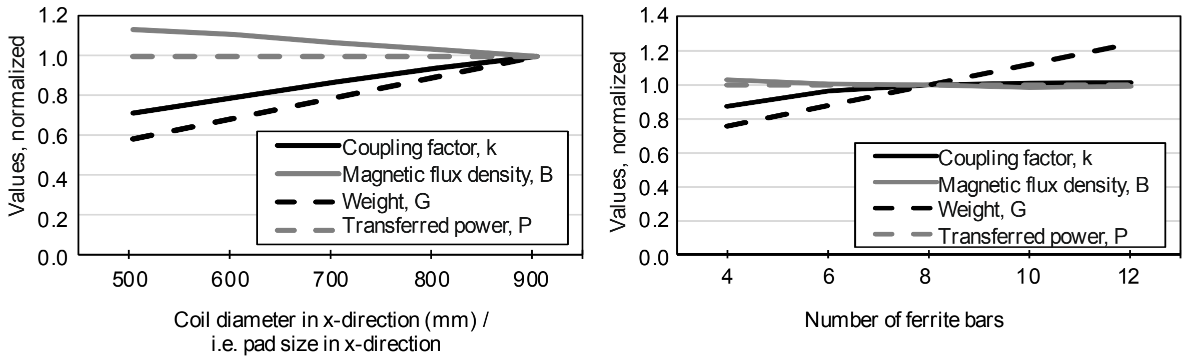


Figure 7: Selected parameter variations of the DD-DDQ coil.

A reduction of the pad size in x-direction results in both a decrease in weight and in coupling factor. In contrast to this, a decrease in size of the pad in y-direction only affects the weight. Consequently, the pad is made smaller in y-direction than in x-direction. As can be seen in the right diagram of Figure 7, the number of ferrite bars can be reduced to a certain extent without affecting the coupling factor or the transferred power. This can also be observed for the variation of the ferrite bar width.

Moreover, the parameter study shows that a variation of the geometrical degrees of freedom of the quadrature coil has a negligible effect on the target values.

Overall, it can be concluded that no parameter variation results in significant decrease of the magnetic flux density on the vehicle body. This means that the ICNIRP guidelines are not met in any of these cases. In order to meet these guidelines nevertheless, the primary system is adapted based on the previous findings of the parameter variations: The size of the primary coil system is reduced to 600 mm × 600 mm, the number of turns is increased to 6. The ferrite plate also has an edge length of 600 mm and the aluminum plate is reduced to 700 mm × 700 mm.

Despite the change in size of the primary side, the qualitative results of the previous parameter variations remain valid for the adapted primary coil. Beyond that, the conclusions drawn from Figure 7 also can be transferred qualitatively to the new system.

5.2.3 Optimized DD-DDQ Coil

The specific dimensions of the optimized DD-DDQ coil are listed in Table *3*. The right picture of Figure 5 shows the final design of the optimized DD-DDQ coil.

The coil size is smaller in y-direction than in x-direction, as already shown in Figure 7 (600 mm × 500 mm). As the number of turns only has a small impact on the weight, the number is increased slightly from 5 to 7 in order to reduce the winding losses.

As trade-off between a high coupling factor and a low weight, 6 ferrite bars with a width of 40 mm each are chosen. The total size of the ferrite can be reduced to 400 mm × 450 mm.

The results of the optimization are compared to the reference model in Figure 8. The coupling factor decreases from 0.27 to 0.11 in case of lateral misalignment. Even in the worst case, a power of 50 kW can be transferred. The magnetic flux density on the vehicle body can be reduced by more than 50 % to 26.8 µT. Hence, the requirements of the ICNIRP 2010 are now fulfilled. The weight of the secondary coil system is decreased by more than 70 % to 14.2 kg.

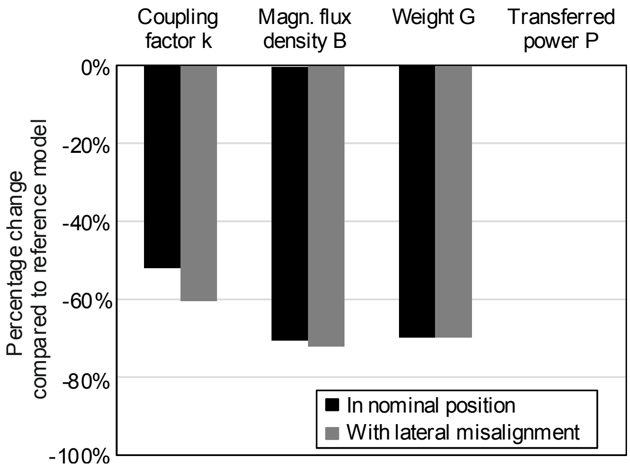


Figure 8: Optimization results of the DD-DDQ coil.

6 Validation and Verification

The results of this work are of approximate character only, as they are based on numerical solutions of partial differential equations. This is why an extensive verification and validation is made for the simulation model used. The procedure of validation and verification is explained in detail in [8, 9].

Verification ensures that the simulation model is built correctly [20]. It quantifies the numerical error made in determining the approximate solution by the use of several quality criteria for the mesh and for the most important system parameters. For the inductances, a maximum permissible deviation of 1 % is defined. The convergence of the total energy has to be lower than 0.5 % [8, 9].

Validation examines whether the right model is built [20]. This model error is estimated by comparing experimental measurements of an IPT prototype with the results of the simulation model. The prototype built is shown in Figure 9.

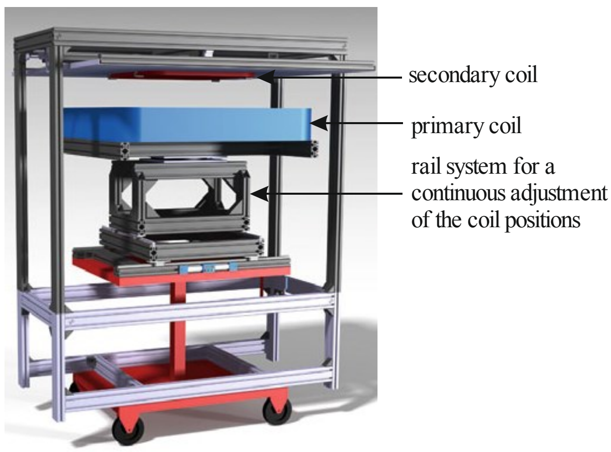


Figure 9: Experimental prototype, [21, 22]

The deviations between simulated and measured target values always are well below 10 %. Furthermore, the standard deviations for all quantities are small. [8, 9]

Thus, it can be stated that all simulations conducted in this paper are based on validated and verified simulation models.

7 Conclusion

In this study, two IPT systems are selected, analyzed, and optimized for application in two different vehicle segments. These vehicle segments comprise on the one hand small and inexpensive vehicles, so called minicars, and on the other hand large vehicles with raised ground clearance, SUVs. The requirements on the coil systems investigated are derived from the characteristics of the five top-selling vehicles in Germany in each segment for 2015.

Taking these requirements into account, coil topologies particularly appropriate for the respective application are selected. For the segment of minicars, a circular topology is selected; a DD-DDQ-topology is analyzed for SUVs. Afterwards, reference systems are defined for each design and analyzed regarding their specific characteristics.

Based on these findings, the secondary coil systems are optimized in order to meet the automobile manufacturer's key requirement of a lightweight and small inductive charging system. This also enhances flexibility for mounting and packaging. In addition, the optimized IPT systems fulfill further demands: They allow for a positioning tolerance with a radius of 150 mm, the radiated magnetic stray field on the vehicle body complies with the ICNIRP guideline of 2010, and a power of at least 80 % of the nominal power can be transferred.

Compared to the reference system, the weight of the secondary coil systems is reduced by 75 %, and 70 %, respectively.

The simulation models used in this work are validated and verified. The numerical error of the simulation is estimated by defining and analyzing several quality criteria for the meshing. For the estimation of the model error, an experimental prototype of the IPT system was built. Comparison of the measured data and the simulation results shows a good agreement.

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Authors

Katharina Knaisch received her Mechanical Engineering diploma in 2013 from the Karlsruhe Institute of Technology (KIT). She now is a PhD student at the Institute of Vehicle System Technology at the KIT. Her research areas include the design and optimization of coil topologies for inductive power transfer for electric vehicles with high power.

Markus Springmann is chief engineer at the Institute of Vehicle System Technology at the Karlsruhe Institute of Technology (KIT). He studied electrical engineering at the University Karlsruhe and received his PhD degree in mechanical engineering in 2015 from the KIT. He also succeeded an industrial training in industrial electronics.

Peter Gratzfeld is full professor at the Institute of Vehicle System Technology at the Karlsruhe Institute of Technology (KIT). He received his PhD degree in electrical engineering from the RWTH Aachen University. From 1986 to 2008, he held several leading positions within the rail industry at Bombardier Transportation and its predecessor companies.