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Contactless Energy Transfer for Charging Electric and Hybrid Electric Vehicles

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Abstract

This paper presents the state of the art in contactless inductive energy transfer systems for charging batteries that are integrated in electric or hybrid electric vehicles. Therefore the paper is divided into the three main categories principle of function, coil arrangements and power electronics together with compensation. After a detailed analytic explanation of the principles several types of coil arrangements are analyzed and compared. To charge batteries with contactless energy transfer systems an overview of recommended compensation typologies is given. Further on different usable power electronics are presented respectively to their use case.

Index terms: wireless charging, inductive charger, resonant converter, research, power, reactive power compensation

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1 Introduction

Since the beginning of the process of electrification over than 100 years ago and the development of electromechanical energy converters in combination with the introduction of computers, the number of the so called mechatronic systems has been continuously increased. Examples for mechatronic systems robots and power tools as well as electric or hybrid electric vehicles (EV).

A problem that arises here is the supplying of electrical devices in these systems, which will be done with cables and contacts. Cables and contacts, like for example slip rings, are a critical component, which reduce the reliability, durability and especially in electric vehicles the usability of the entire system. In addition cables need space and reduce the degree of freedom. Thus many innovative concepts, like dynamic charging of electric vehicles, could not be realized due to the cables staying in the way. As a result wireless charging of EV, also known as contactless energy transfer (CET) is becoming more and more popular [1]–[3]. This paper yields a comprehensive overview about CET-systems.

2 Principle of Function of Contactless Energy Transfer

In this chapter physical principles enabling a contactless transfer of energy and a deep insight into energy transferring using magnetic field are presented. In addition characteristics, setup and components as well as the limiting parameters of such systems are described. Existing systems are divided into two major types. First type of existing applications are stationary or so called point to point systems. Second type are dynamic systems, which are further divided by the amount of freedom degrees. Nowadays stationary systems and dynamic systems with one degree of freedom are state of the art [4]–[6]. Current research focuses on systems with multiple degrees of freedom. Therefore a distinction is made between systems which allow supplying EV's during operation, for example at traffic lights, and systems which supply

EV during movement. In this article a comprehensive overview of point to point stationary systems is given. Basis for analytical calculation are the transformer equations with the mutual inductance M. In the further calculations of this article all losses like skin, proximity effect and copper are neglected.

$$\begin{matrix} \underline{U}_{L_1} \\ \underline{U}_{L_2} \end{matrix} = \begin{pmatrix} L_1 & M \\ M & L_2 \end{pmatrix} \cdot \begin{matrix} \underline{I}_{L_1} \\ \underline{I}_{L_2} \end{matrix} \tag{1}$$

To describe the physical principles of CET-systems the equivalent circuit presented in Fig.1 is used. It describes the primary and secondary coils mutual coupling of a CET-system based on equation 1. The magnetic coupling k between the coils is less than 0.5 for CET-systems. That implies that less than $50\,\%$ of the flux created by the high alternating current in the primary coil permeates the secondary coil as well as the other way around. A huge amount is leakage flux, that needs to be compensated on both sides to reduce the reactive power in the overall system. The coupling factor k is described by the ratio of main to the total amount of flux for both sides with

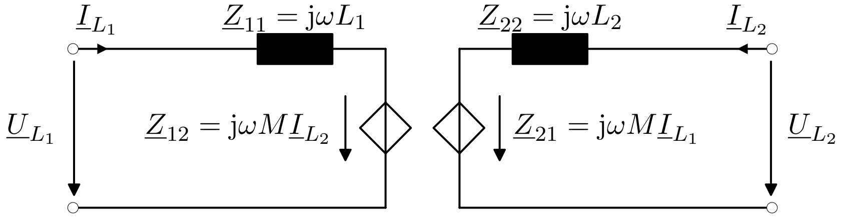


Figure 1: Primary and secondary coil of a CET-system represented with a two-port network

$$k = \sqrt{\underbrace{\boxed{\frac{\Phi_{12}}{\Phi_{1\sigma}+\Phi_{12}}}}_{k_{1,2}} \cdot \underbrace{\boxed{\frac{\Phi_{21}}{\Phi_{2\sigma}+\Phi_{21}}}}_{k_{2,1}}} \tag{2}$$

and the mutual inductance M is described with

$$M = k \cdot \sqrt{L_1 \cdot L_2} \quad , \tag{3}$$

whereas the index 1 corresponds to the primary and 2 to the secondary side. For technically practical and feasible operation of inductive charging, a coupling factor in the area between $0.1 \leq k \leq 0.4$ is a goal. A higher coupling factor leads to more harmonics, when the system is excited with a non sinusoidal voltage or current, as it is known from a transformer with $k \approx 1$. Lower coupling factors lead to high reactive currents or voltages in the system, which need more robust components [6]. To maintain an overall high efficiency with a weak coupling, a reactive power compensation is needed. The power losses in the system are not increasing significantly by a decreasing coupling factor, if the system is operated in resonant frequency, with a well designed compensation network and operating point. An overview on common compensation networks for CET-systems is presented in chapter 4.1. Basically for a reactive power compensation one capacitor on each side is used. For a serial interconnection of the capacitor with the coil, the system is designed to the frequency ω_d with

$$C_{1,\mathrm{s}} = \frac{1}{\omega_\mathrm{d}^2 L_1} \tag{4}$$

for the primary side and as well for the secondary side. With this approach and a total of four energy storages, two capacitors and two coils, three resonant frequencies are possible in a CET-system. These frequencies are calculated to

$$\omega_\mathrm{r0} = \omega_\mathrm{d} \tag{5}$$

and

$$\omega_\mathrm{r1,r2} = \frac{\omega_\mathrm{d}}{\sqrt{1 - \frac{R_2^2}{2\omega_\mathrm{d}^2 L_2^2} \pm \sqrt{\left(1 - \frac{R_2^2}{2\omega_\mathrm{d}^2 L_2^2}\right)^2 - (1-k^2)}}} \tag{6}$$

for a both side serial compensated system. As may surmised from equation 6 the resonant frequencies $\omega_\mathrm{r1,r2}$ are only valid in a specific operating area depending on the load resistance R_2. Further on for each resonant frequency different system behaviors are achieved. Beside both side serial compensation, three other possibilities to arrange the compensation are possible. Each has three resonant frequencies and two specific behaviors. A more detailed calculation of the four topologies, including the system behavior for each frequency in each topology, is done in [7].

3 Coil Arrangement

In this chapter three of the most common coil arrangements are presented regarding to their use case. A detailed comparison about circular and so called double-D together with 14 other flat coil arrangements is done in [8], [9]. The focus in this article lies on a short comprehension, with the aim to determine possible arrangements, which are sensible for charging electric vehicles. The three regarded coil setups, comprising circular, solenoid and double-D arrangements for a point to point system, are presented in Fig. 7. As shown in figure 7 the magnetic flux naturally spreads different. For example the magnetic flux of a circular coil proceeds orthogonal to coil surface in the middle, whereas a double-D or solenoid arrangement has a transversal flux component regarding to the coil surface in the middle. Because of this circumstances it is not useful to combine circular coils with double-D or solenoid. One possibility to combine double-D with circular is to use only one side of the double-D coil or to use multi-coil systems to achieve higher interoperability [10]. An overview of the nine different arrangement combinations is presented in table 1. On the one hand the arrangements with circular coils are not that compatible as described above. On the other hand circular coils have a high quality factor. Compared to a solenoid coil with losses in the ferrite rod the quality factor is better for circular and double-D coils. Considering the quality factor it is possible to determine an optimum design frequency ω_d for the coil system. The design frequency should be set as high as the quality factor is increased with a higher frequency [11]. Although boundaries of the systems power electronics have to be respected and are often a limiting factor.

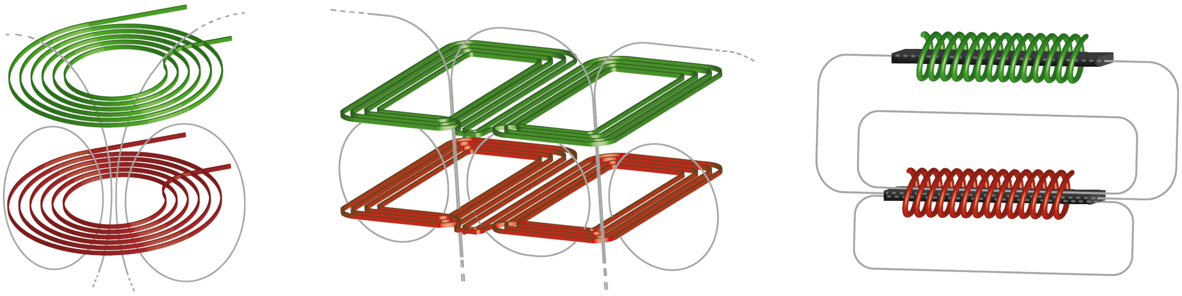

(a) Circular (b) Double D (c) Solenoid

Figure 2: Different coil arrangements with qualitative pattern of magnetic field lines

Table 1: Evaluation of different coil arrangement combinations

Primary	Circular	DoubleD	Solenoid
Secondary			
Circular	+	-	-
DoubleD	-	+	+
Solenoid	-	+	+

4 Power Electronics and Compensation

Besides the coil arrangement and magnetic parameters, advanced power electronics and compensation topologies are important for CET-systems. The components of a entire system for charging EV's are shown in Fig.3. Starting from the mains power supply a chain of transducers which convert the low frequency main voltage to a higher frequency voltage with the appropriate amplitude is needed. The used frequencies are in the range of 20 to 500 kHz and higher, whereas for charging electric vehicles a frequency of 85 kHz or 140 kHz is getting state of the art. With a higher frequency the system size is reduced compared to a constant transfered power. One advantage of 85 kHz is the higher limit of allowed field exposure for human beings compared to frequencies above 100 kHz [13], [14]. Returning to Fig.3 the secondary side includes also transducers to offer the appropriate voltage level and frequency to the user, for example a battery system. In this chapter the influence of compensation as well as two different power electronic typologies for both side parallel and both side serial compensated systems are presented in order to provide the fundamentals for the different setups.

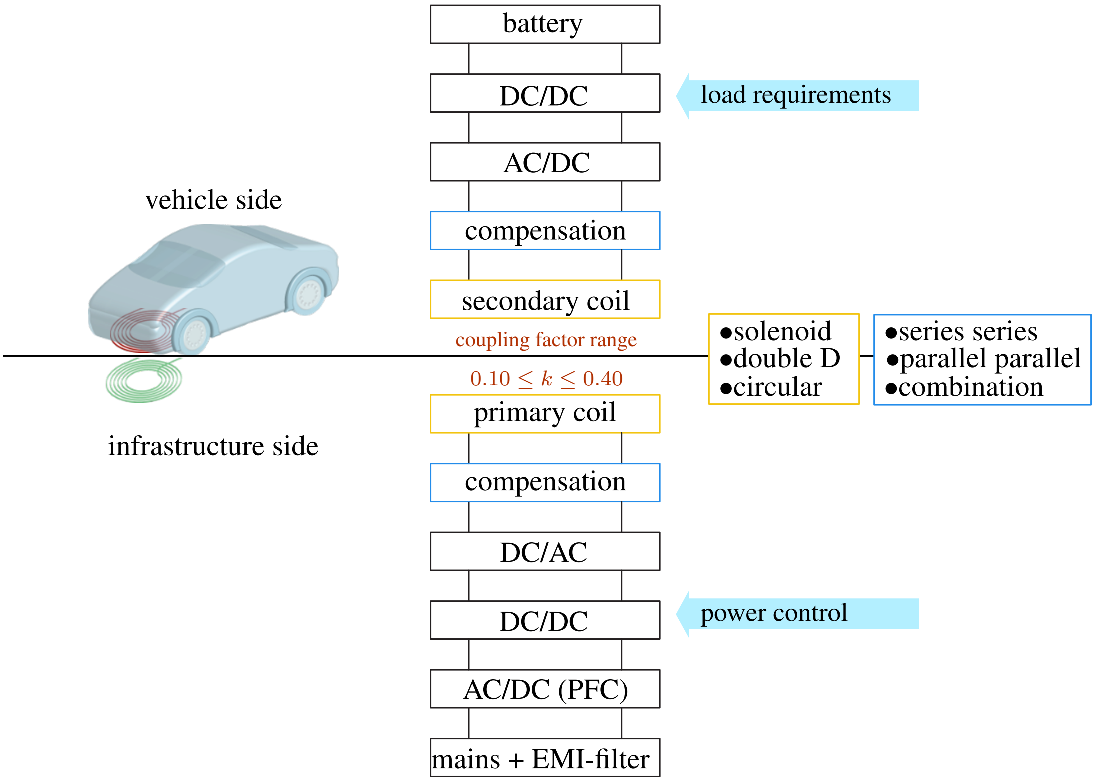
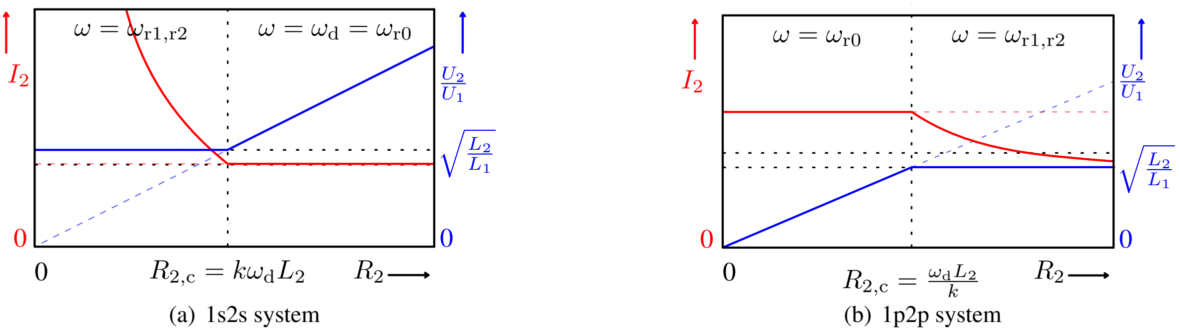


Figure 3: System overview of a CET-system for charging batteries[12]

4.1 Reactive Power Compensation

The efficiency of CET-systems is highly depending on the reactive power compensation. The measured efficiency without compensation is usually below $10\,\%$. In order to compensate the inductive reactive power, capacitors are used. Compensating the primary and secondary coil leads to an increased system efficiency, including the coil system with compensation, to values above $95\,\%$. The design of compensation has a high influence to system behavior. Especially voltage and current transfer function as well as resonant frequencies and system stability are strongly depending on the compensation topology [7]. In this article systems for two out of the four common compensation topologies are discussed. In Fig. 4 the output current and voltage transfer function of the both side serial and both side parallel system are presented. Concentrating on Fig.4(a) the discussed resonant frequencies of equation 5 and 6 are on the left and on the ride side. Depending on the load resistance the resonant frequencies $\omega_{\mathrm{r1,r2}}$ is only valid up to a characteristic resistance $R_{2,\mathrm{c}}$, which is defined for small coupling factors $k \leq 0.5$ with



(a) 1s2s system

(b) 1p2p system

Figure 4: Output current I_2 and voltage transfer function $\frac{U_2}{U_1}$ of 1p2p- and 1s2s compensated systems

$$R_{2,\mathrm{c}} \approx k \cdot \omega_{\mathrm{d}} \cdot L_2 \quad . \tag{7}$$

For values higher than $R_{2,\mathrm{c}}$ the both side serial compensated system has only one usable resonant frequency. The behavior changes, depending on the compensation as it can be seen in Fig. 4(b).
Is the system operated auto-resonant the frequency changes within a sweep of the load resistance from $\omega_{\mathrm{r1,r2}}$ to ω_{r0} automatically. Assuming a constant input voltage, magnetic parameters and compensation, the figure shows the behavior of the output current and voltage for different resistances R_2. As long as the quality factor of the coil is equal on the primary and secondary side, the operating point with the highest efficiency is at $R_{2,\mathrm{c}}$ [12]. To charge batteries of electric vehicles it is advisable to select a useful compensation topology. In the example of the both side serial compensated system the linear output voltage U_2 fits to the behavior of a battery, that is charged. Further on the charge mode equals to constant current charging within the frequency ω_{r0}. Charging is possible with other compensation topologies as well. Concentrating on the both side parallel compensation in Fig.4(b) a constant current (CC) and constant voltage (CV) mode is possible. Although it is difficult to design a both side parallel system, because the output voltage must fit to the battery voltage. On this account a more elaborate power electronic is needed for interoperability. As a conclusion a brief overview of the common four topologies is presented in table 2. Besides the above mentioned behavior a main difference between the compensation topologies is the safety. Primary side serial compensated systems need a permanent monitoring to operate it. It is not safe for a short and open circuit operation, as well when the secondary side is removed. In contrast primary side parallel compensated systems are safe for short and open circuit, if they are operated auto-resonant. Therefore parallel compensated systems need a more elaborate power electronic, which makes the system especially for a high power operation more expensive. This circumstances lead to a trade-off between serial and parallel compensated systems with an increasing power transfer. For low power systems a parallel compensated system is advisable, whereas the effort for a monitoring justifies the use of a serial compensated system for a high power transfer.

Table 2: Overview of different compensation topologies and behavior in auto-resonant operation[7]

Topology	1s2s[1]	1p2p[2]	1s2p[3]	1p2s[4]
Properties[5]				
Output power at $R_{2,\mathrm{c}}$	$P_2 \approx \frac{U_1^2}{k \cdot \omega_\mathrm{d} \cdot L_1}$	$P_2 \approx \frac{U_1^2 \cdot k}{\omega_\mathrm{d} \cdot L_1}$	$P_2 \approx \frac{U_1^2}{k \cdot \omega_\mathrm{d} \cdot L_1}$	$P_2 \approx \frac{U_1^2 \cdot k}{\omega_\mathrm{d} \cdot L_1}$
Short circuit behavior	$\lim_{R_2 \to 0} P_1\big\rvert_{\omega_{\mathrm{r1,r2}}} = \infty$ ✗	$\lim_{R_2 \to 0} P_1\big\rvert_{\omega_{\mathrm{r0}}} = 0$ ✓	$\lim_{R_2 \to 0} P_1\big\rvert_{\omega_{\mathrm{r0}}} = \infty$ ✗	$\lim_{R_2 \to 0} P_1\big\rvert_{\omega_{\mathrm{r1,r2}}} = 0$ ✓
Open circuit behavior	$\lim_{R_2 \to \infty} P_1\big\rvert_{\omega_{\mathrm{r0}}} = \infty$ ✗	$\lim_{R_2 \to \infty} P_1\big\rvert_{\omega_{\mathrm{r1,r2}}} = 0$ ✓	$\lim_{R_2 \to \infty} P_1\big\rvert_{\omega_{\mathrm{r1,r2}}} = \infty$ ✗	$\lim_{R_2 \to \infty} P_1\big\rvert_{\omega_{\mathrm{r0}}} = 0$ ✓
Advisable charge mode	CC	CC/CV	CC[6]	CC/CV[6]

[1] primary side serial and secondary side serial compensated system
[2] primary side parallel and secondary side parallel compensated system
[3] primary side serial and secondary side parallel compensated system
[4] primary side parallel and secondary side serial compensated system
[5] analytical calculation without losses
[6] output voltage and current depend on coupling factor

4.2 Power Electronics

In this chapter two power electronics are described. The first one shown in Fig.5 shows a 1s2s-system. To

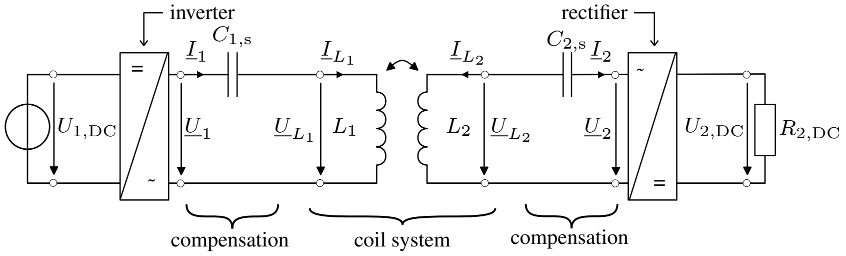


Figure 5: Overview of a 1p2p-system

fulfill system versatility it is possible to convert the rectifier from a full to half bridge with the integrated switch. Due to this conversion the secondary side can be used with different primary sides and different power levels. The system behavior is described by the inductance L_2 as seen in Fig.4(a) whereas the total power transfer is adjusted with L_1 and U_1. Through adjusting the number of turns and voltage levels on the primary side as well as switching the rectifier on the secondary it is possible to adjust the output power from 3 kW to 20 kW [15].
In contrast to the 1s2s-system, a 1p2p-system is presented in Fig. 6. As described in chapter 4.1 the system behavior indicates a charge controller. Another difference is the choke to emulate a current source, which is needed for parallel compensation. For the inverter it is advisable to use a royer converter, as described in [16] due to the simple structure. In addition is possible to transmit data with the royer converter using the same coil system [17]. Further on, the auto-resoant royer converter does not need any control or monitoring systems. For that reason it is a very cost effective inverter for a low power transfer. A major disadvantage for high power transfer are occurring high voltages, wherefore a solution is developed at the instutute of electrical energy conversion (iew).

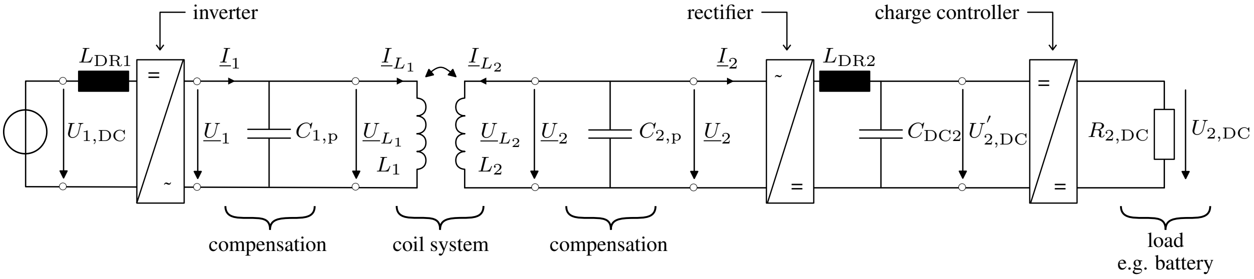


Figure 6: Overview of a 1p2p-system

5 Setups and Measurement

With the presented compensation topologies and power electronics some existing systems are already setup. An overview for both side serial and parallel compensations is shown in Table 3.

Table 3: Overview of different implemented systems

Project	StudKart	Bipol	Bipol+	CETeCar
Protoype	electro go-kart	EV1[3]	EV1[3]	EV2[4]
output power [W]	1000	3300	3000/20000	3000/12000
efficiency [%]	88[2]	90[2]	93[1]	92[2]
battery voltage [V]	48-57.6	90-100	290-410	259-394
coupling factor k	0.3	0.18	0.35	0.2-0.3
design frequency [kHz]	45	50	85	85
primary inductance [µH]	16.7	300	37.5	44
secondary inductance [µH]	16.7	35.4	33.5	35
compensation topology	1p2p	1s2s	1s2s	1s2s

[1] mains to battery at 3 kW
[2] DC to battery
[3] Smart
[4] BMW i3

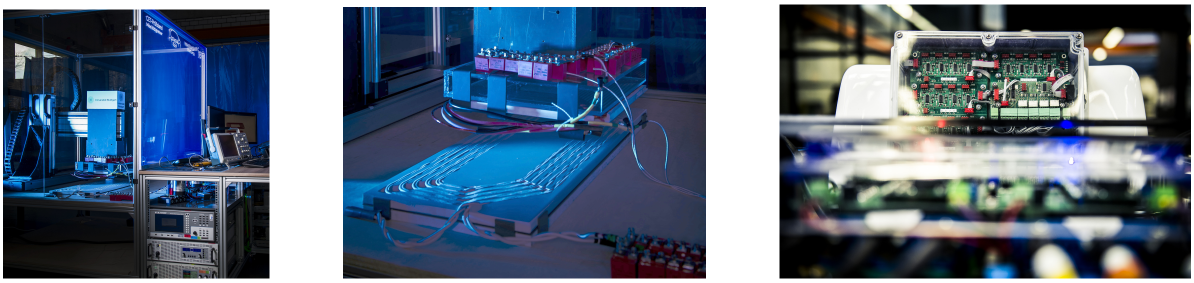

(a) Test Bench (b) Coil Setup (c) StudKart

Figure 7: Different coil arrangements

6 Conclusion

During the last five years inductive charging has more and more become a major topic of electro mobility. Contactless transfer of electrical energy offers comfortable and safe charging of electric and hybrid vehicles. Using an alternating magnetic field instead of wires, the charging system can completely be integrated into the infrastructure and is therefore safe from vandalisim and needs less maintenance. Inductive charging provides the possibility to charge electrical and hybrid vehicles both during parking and while driving. It also offers the possibility of automatic charging which leads to an increase of the range of the EVs and is advantageous for autonomous driving as well as integration of the EVs into smart grids. This paper provides an introduction to the principle of function of inductive energy transfer and describes the technical setup including coil arrangements, power electronics and reactive power compensation. In addition, different coil arrangement combinations and different compensation topologies are discussed and an overview on different implemented systems is given.The measurment results we achieved with our setups at the iew are very promising. Achieving efficiency values higher than 90% in combination with numerous advantages as mentioned above make inductive charging to the charging system of future EVs. Future research focus on multi-coil systems, systems with a less variable self inductance as well as a more constant coupling factor for different airgaps. Further, developing control algorithms for different compensation topologies and variably transferred power will be investigated, hereby preferably keeping the best operating point over the entire charging process and reducing the overall system complexity from the mains to battery.

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David Maier was born in Bühl in the Federal Republic of Germany, on November 7, 1990. He graduated from secondary school, Sasbach and completed his Bachelor degree at DHBW Stuttgart. Later he studied Electromobility at the University of Stuttgart from 2013 to 2015. Since 2016 he is with the Institute of Electrical Energy Conversion at the University of Stuttgart, Germany. He is currently perusing the Ph.D. degree in electrical engineering. Inductive charging of electric vehicles belongs to his special fields of interest.

Mike Böttigheimer completed his diploma degree in electrical engineering and information technology at the University of Stuttgart from 2007 to 2013. Since his graduation, he is participating in various research projects on contactless energy transfer as an academic employee at the Institute for Electrical Energy Conversion. Böttigheimer manages the research project Contactless Energy Transfer Electric Vehicle (CETeCAR) in which an existing electric vehicle is getting equipped with an inductive charging system. The focus of his PhD is on the detection of foreign objects (FOD) for the inductive energy transfer.