Concept Evaluation of an Inductive Charging System for Electric Vehicles

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Abstract
For the user acceptance of electric vehicles a simple, reliable and safe charging process is essential. An inductive charging system can fulfill this requirement and therefore contributes to the market integration of electric vehicles. This paper presents the results of the project "W-Charge" in which a contactless inductive charging system has been developed and evaluated.

1. Introduction

A major aim of the German energy concept is to reduce the CO_2-emissions by increasing the share of renewable energies as well as promoting electro mobility [1]. If charged from renewable energy sources, electric vehicles can contribute significantly to a reduction of CO_2-emissions. Additionally, they can be employed to store and balance the fluctuating energy production of renewable sources. Therefore, however, a high availability of electric vehicles in the grid has to be guaranteed.

Available charging systems for electric vehicles use cables to connect the vehicle to the grid, although this involves certain disadvantages such as vandalism and additional effort for the driver. Unplugged cables lead to uncharged batteries and loose or faulty cables are a safety risk. An alternative is wireless charging on the basis of inductive energy transfer. This technique allows for a simple, reliable and safe charging process. Therefore, it will improve the user acceptance and will contribute to the integration of electric vehicles into the market and thus increase the availability to the grid. As a consequence a higher degree of flexibility for the storage management is possible.

Within the project W-Charge the opportunities for wireless charging of electric vehicles are being analyzed. This paper presents the current results including the characteristics and functionality of the developed inductive charging system as well as the challenges towards vehicle integration. Furthermore, a higher integrated on-board converter for inductive as well as cable-based charging is described. Finally, an overview on the benefits for grid integration will be given.

2. Technical Description of the Inductive Charging System

The developed contactless inductive charging system, also called e-mobile contactless power supply (eCPS) is a reasonable alternative to the conventional vehicle charging via cable. It consists of an on-board unit (called “pick-up”), which is directly mounted on the vehicle underbody structure. To start the process of charging the vehicle has to be parked above the stationary unit, which can be placed at the central position of a parking lot, i.e. directly beneath the parked vehicle. By utilizing eCPS, several disadvantages of conductive charging systems are abolished: Its use is barrier-free (i.e. no insertion and withdrawal operations, no manual operations) and the probability of vandalism is reduced by far due to the lack of touchable cables. Furthermore, the deployment of eCPS causes a low deterioration compared to plug afflicted systems. The arrangement of the system at vehicle and parking lot is presented in Figure 1.

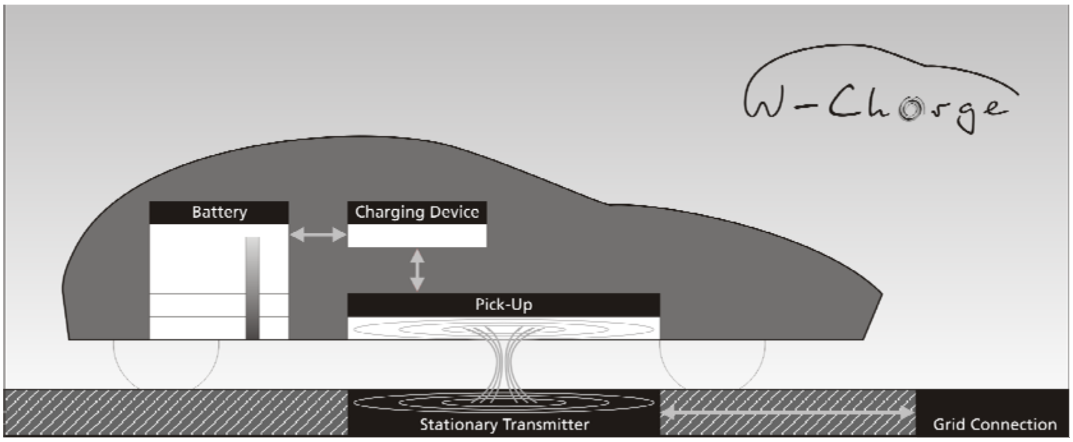

Figure 1 – Arrangement of the inductive charging system at the vehicle and parking lot

eCPS consists of several components. The power coupling between ground and vehicle is established by the stationary transmitter unit and the on-board receiver unit (“pick-up”) mentioned above. The transmitter is galvanically connected to the primary inverter unit. This unit converts the grid voltage to a high frequency alternating voltage with a nominal frequency of f = 140 kHz. The stationary power transmitter, also called primary part, generates a high frequency electromagnetic field. The outer dimensions of this primary part are presented in Table 1.

Dimensions Stationary Transmitter	
length	1089mm
width	1089mm
height	24mm
weight	approx. 49kg

Dimensions Pick-Up Unit	
length	825mm
width	825mm
height	16mm
weight	approx. 20kg

Table 1 – Dimensions of the stationary transmitter and the pick-up unit

It consists of a flat coil with several windings, which is mounted to a cover plate made of glass fibre reinforced plastic. This assembly group is directly placed above an aluminium plate populated with soft magnetic ferrites. Basically, the construction principle of the pick-up is the same. A difference between transmitter unit and receiver unit only exists in size, in number of windings, and in housing shape. The outer dimensions of the pick-up unit are presented in Table 1. The large dimensions of the inductive unit are caused by the safety limit value of the electromagnetic field defined in the German application guideline [2]. A schematic diagram of the inductive system's cross-section is shown in Figure 2 and a photographic illustration of that part is presented in Figure 3.

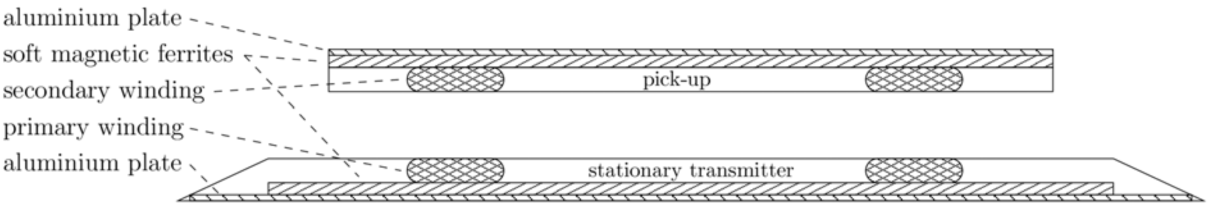

Figure 2 – Schematic diagram of the inductive system's cross section


Figure 3 – Stationary transmitter and pick-up of the inductive charging system

The high frequency electromagnetic field is coupled with the windings of the pick-up. The electrical transmission characteristic is described by a transformer equivalent circuit drawing. The flux leakage is very high, when compared to a conventional transformer. This is caused by the high air gap reluctance. This leads to a low coupling factor and with it to a small value for mutual reactance in comparison to primary leakage reactance.
To produce an appreciable part of active power in the on-board system, a compensation of the system's reactances is required. Therefore, the primary inverter unit is equipped with a capacitor assembly in series connection to the primary coil. A similar compensation is established at the on-board unit. The high frequent

alternating current of the pick-up is converted into a direct current by a high frequency (HF-) rectifier, to be connected to the on-board charging device (Figure 4).

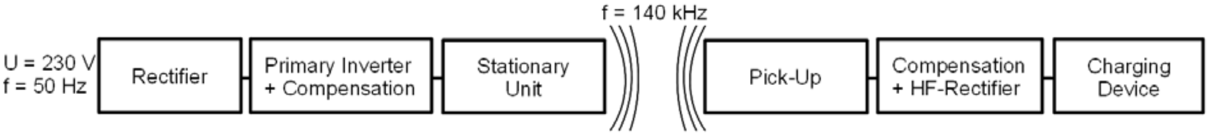

Figure 4 – Block diagram of the complete eCPS system

The nominal supply power of the system's on-board device is P=3,3kW. This power can be transmitted via an air gap of 60mm to 170mm. The greatest challenge in developing the contactless charging system is the design of a reliable primary inverter. Today, the 140kHz-technology is not state of the art in common power electronic systems within this power range. Therefore, the selection of reasonable components, the interaction between them and the ensuring of the electromagnetic compatibility are major requirements in the development work. Future development steps can obtain an easier and more inexpensive assembly and further efficiency improvements. However, laboratory measurements utilizing the existing system show a satisfying performance with an efficiency of η = 91% ascertained between grid and on-board charging device at an optimal placement.

3. Higher integrated on-board charging converter

The inductive charging system eCPs provides a variable DC output voltage dependant on the load condition, the air gap and the lateral offset between stationary and on-board transmission coil. As common battery chargers are not designed for these conditions, the usage of an inductive charging system also requires adaptations to the on-board charging device.
In order to achieve a maximum flexibility and comfort for the user of electric vehicles, the vehicle should offer the opportunity to be charged by diverse charging techniques and at different power levels. The inductive charging technique as the most user-friendly one is supposed to be the predominantly used method in the long term. Though, one cannot expect that inductive charging infrastructure is available everywhere, especially not within the early days of electro-mobility. Therefore the opportunity of cable-based charging is needed as a back-up. If a higher amount of energy is demanded within a short time range, a higher charging power is recommended. This can be realized by 3-phase connection or DC fast charging.

At present, most charging infrastructures in electric vehicles are able to charge from a 1- and 3-phase connection point via cable. Current developments have also generated chargers that can feed energy from the vehicle battery back into the grid

[3][4]. Though, all those charging concepts do not provide an appropriate interface for inductive charging systems. If DC-charging is offered, this is usually realized by a DC/DC converter in addition to the generally integrated battery charger.
This reveals that a higher integrated power electronic for charging is needed. To comply with these requirements, an appropriate charging topology has been developed which integrates the aforementioned chargers in one single device.

By using the same power electronics and chokes the higher integrated converter is able to charge the EV battery not only from a single or 3-phase grid, but also from an inductive energy transmission system with variable voltage output. At the same time the converter allows for a cable-based and inductive energy flow back into the grid. This leads to a reduction of weight and required space in the vehicle. Additionally a reduction of components implies lower costs.
The core components comprise a DC/DC-converter as well as, depending on the operation mode, a DC/AC or DC/DC-converter and switching units (see Figure 5).

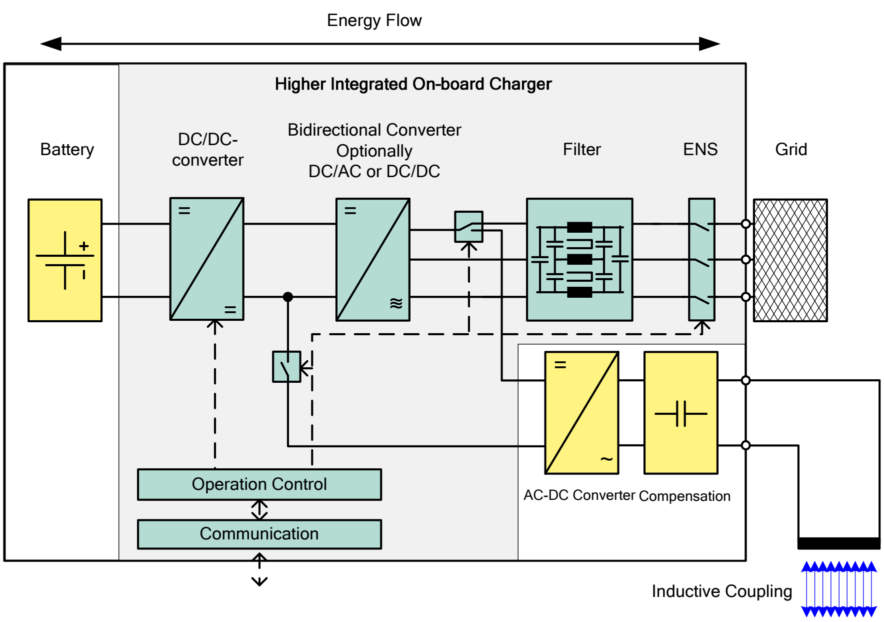

Figure 5 – Block diagram of the on-board electronics with the higher integrated charging converter

Thus the battery can be charged via cable from the low voltage network and on the other hand from an inductive energy transmission system. The operation control decides on the availability of sources and which one will be used. By means of the bidirectional DC/DC converter an energy feedback via cable or inductive charging system to the grid is possible. As a conclusion the availability und usability of electric vehicles as mobile storage devices will be increased.

4. Testing Facility

For analyzing the operational performance of the inductive charging system and its components a suitable testing facility was developed. This automated test bench, in which the components for inductive charging can be integrated, enables the Pick-up to be moved in all three dimensions. Thus, stopping at predefined points it is possible to conduct reproducible efficiency and field measurements at variable air gaps and offsets between the stationary and on-board transmission coils. In this way, important knowledge on the operational characteristics can be gained.

5. Vehicle integration

Besides the difficulties in hardware development also the integration of the inductive charging system into electric vehicles is subject to certain challenges.
On the one hand the available space at the vehicle’s underbody structure is limited and the location of an appropriate area to implement the Pick-up might not be placed optimally for parking concerns. Furthermore, an inductive charging system means additional weight.

The stationary transmitter unit of the inductive charging system has to be placed in the parking lot according to the mounting position of the pick-up at the vehicle. Though, with different vehicle types this mounting location may vary due to different installation space conditions. Further developments in the construction of electric vehicles relating to inductive charging systems have to consider these aspects in order to achieve a standardized and compatible solution.

According to [2] the operation range of the inductive charging system has to be between +/- 10 cm from the optimal centered position of the transmission coils. Thus, for inductive charging the car has to be parked more accurately than hitherto. As a parking study conducted within the W-Charge project reveals, this cannot be achieved by all drivers without auxiliary means. Electronic and simple non-electronic assistance systems are able to support the drivers in order to increase this accuracy. Through the choice of appropriate means, it was achieved, that all test persons were able to park within a maximum lateral tolerance of +/- 10 cm. Though, this more accurate parking takes more time than the conventional parking process. However, the expenditure of time is only around one quarter compared to the time needed for the plugging-processes associated with cable-based charging. Nevertheless, for reasons of improved usability an automatic parking assistant designed for the needs of inductive charging is recommended in future. [5]

6. Grid Integration

Current field trials with electric vehicles reveal that users usually plug-in the car only if necessary and public charging stations are rarely used [6]. This yields an average availability to the grid of only every third day. However, even during times of high traffic more than 88% of all cars are parked [7]. Hence, the actual potential of vehicles that could be connected to the grid is high.

The amount of connected vehicles is highly dependent on the time of day as well as on the weekday. As the vehicles are preferably charged at home, the amount of connected vehicles during the day is significantly lower than at night [6]. Figure 6 shows the share of connected vehicles to the grid under different charging scenarios, displaying the user behavior described above. Assuming that people with cable-based charging connect the vehicle solely at home after the last journey and only every three days in average the actual potential is exploited by only around 37%.

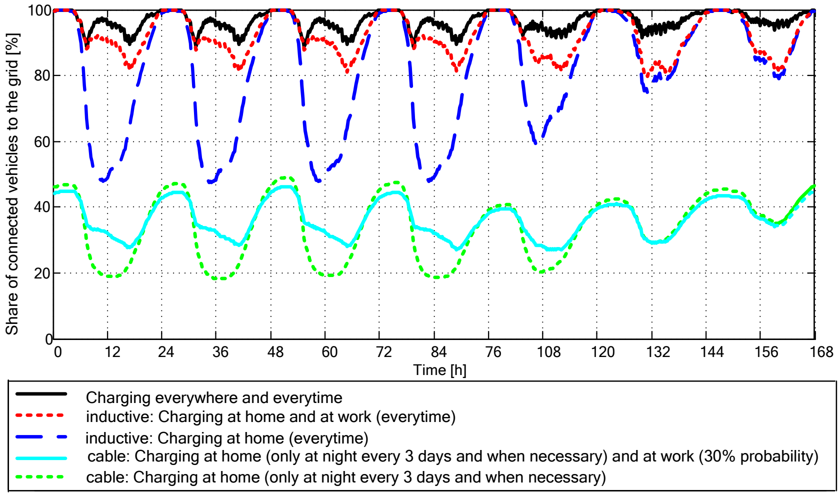

Figure 6 – Share of connected vehicles to the grid under different charging scenarios (based on mobility data [9])

This characteristic is unfavorable for a time-dependent coupling of electric vehicle charging to the energy production of renewable energy sources like. In contrast, with inductive charging it can be expected that a grid connection will always be established when the infrastructure is available. This leads to a significant higher share of connected vehicles to the grid and allows for an improved grid integration of electric vehicles as well as renewable energies.

7. Conclusion

The feasibility and the advantages of an inductive charging system for electric vehicles are introduced. Moreover, a system is presented, which is able to fulfill the requirements of the corresponding German application guideline. By employing this solution, a simple and reliable charging system can be established with an efficiency of $\eta > 90\%$. Although the potentials of inductive charging are obvious, there is still the need for certain improvements. As in the case of cable-based charging a standardization needs to be achieved in order to guarantee interoperability. Additionally, the vehicle design has to allow for an appropriate integration of the inductive charging system.

As renewable energies and electro mobility complement each other with regard to balancing generation and demand there is a need for a user-friendly charging infrastructure. An inductive charging system can contribute to an improved user acceptance and supports the exploitation of the actual potential of renewable energies.

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Project homepage: www.w-charge.de

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