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Wireless Power as a Charging Concept for Light Electric Vehicles: Technological Hype or a Real Solution

121 - LEP-Low Emission Powertrains

Abstract

Considering current technological trends, wireless power transfer (WPT) has the potential to address interoperability challenges in power supply. In several areas of industrial and robotics applications, wireless power is already broadly used providing advantages for moving platforms or for applications where electric shock or spark ignition prohibit the use of corded chargers. On the other hand, utilization of wireless power in electric mobility has not yet found broad deployment.
The main drawback of the wireless power transfer has been proven to be the inductive link between the charging and the pickup coils, which ultimately causes a significant drop in efficiency.
This paper investigates wireless power transfer efficiency, by providing comparison benchmarks to the manufacturer provided data and by refuting this data with the corded charger efficiency. The results evaluated are then applied to the particular case of the electrically powered wheelchair, and, finally, analyzed in an average 24-hours use case.

Keywords:

Wireless power transfer, power transfer efficiency, light electric vehicles charging, inductive power transfer

1. Technological Trends of Wireless Power Transfer

The idea of the current study originates in the Unterrichtslabor für Elektromobilität und Assistive Technologien (ULEA) project at the UAS Technikum Wien (ULEA 2014) founded by the city of Vienna MA 23. The aim is to set up a laboratory infrastructure for training with e-mobility systems and assistive technology. Furthermore, one of the project objectives is to implement an exemplary electrified wheelchair with assistive functions for people with restricted mobility.

Since conventional corded power supplies impose an additional obstacle on the way to full interoperability, the wireless power transfer (WPT) has been considered as an alternative to power the built-in battery pack of an electrified wheelchair. Despite the appealing simplicity of the proposed concept, the efficiency aspect has to be taken into account. Low efficiency imposes several challenges: i) the full recharge time ii) operational range iii) the safety aspect due to the power losses (Bululukova / Kramer 2014).

To confront these challenges, a critical analysis of the power transfer efficiency is required. The outcome should, in particular, define the main factors influencing efficiency, and provide validated benchmarks.

The few studies performed by manufacturers of the WPT components, as well as by standardization consortia are highly disputable, since no test setup specifications are available. Wireless Power Consortium (WPC), specifies **system efficiency** (power transfer to the load) of approx. 75%, with the **coupling factor efficiency** (inductive link only) between the primary and secondary side of approx. 80% (Siddabattula 2015).

A more realistic estimation assumes an average of 70-80% coupling factor efficiency, resulting in overall system efficiency in the range between 60-70% (Buchmann 2012) when combined with power conversion electronics.

Additionally, several exemplary test site project-based efficiency evaluations are available. One of the broadly known WPT projects is the implementation proposed by University of Auckland (Boys/ Covic 2012), achieving 85% efficiency with 2-5kW power rating. Korean Advanced Institute of Science and Technology has shown 71% efficiency with 17 kW power rating (Seungyoung et al. 2013). The highest efficiency has been achieved by Primove, in Germany, charging electric buses and electric trams in free flow with 90% at 40-200 kW power ratings (Bombardier Transportation 2010). These projects are highly proprietary solutions with no WPT standard support. This makes the available data unsuitable for benchmark comparison.

2. Modelling of the Wireless Power Transfer Efficiency

The analysis of the WPT eligibility for the electrical vehicles charging has been performed in several stages. The first stage included general mathematical analysis of the system efficiency, with consideration of the inductive coupling mechanism.

In the second stage, the proposed analytic model has been compared to the practical wireless power transfer efficiency data, to evaluate the main influential factors. Several test runs have been performed to observe the misalignment influence on the coupling factor.

2.1 Theoretical Modeling

The understanding of the mutual interaction is a major task in the pursuit of optimizing the efficiency of the power transfer. Based on the classical idealized inductive link models (e.g. infinitesimally thin solenoid), a mutual inductance model for multilayer flat coils with finite thickness wire was derived. According to the elaborated model, the mutual inductance between primary and secondary coils can be treated similarly as the mutual inductance between two individual round wires. Yet, in case of two multilayer coils, each unique pair combinations have to be considered. Knowing the mutual inductance, the coupling factor can be easily derived.

$$k=\frac{M}{\sqrt{L_1 L_2}} \qquad \frac{U_{tx}}{U_{rx}} = k\sqrt{\frac{L_{tx}}{L_{rx}}}$$

This approach shows reasonably precise results for z-distance misalignment between the coils, however it doesn't allow modeling of angular or lateral misalignments.

For the remaining two misalignment cases, von Neumann integral formula has been used (Soma et al. 1987). This model has shown more specific efficiency values dependent on angular and lateral distances. Despite the efficiency benchmarks delivered, the analytical coupling factor model developed has revealed several limitations. The main drawback of the model is that it estimates the theoretical inductive link efficiency isolated from the additional influences of the electronic circuits.

2.2 Empirical tests

The empirical efficiency evaluation method consists of 4 implementation stages. Firstly, as a scale-down model of an electric vehicle charging, an exemplary wireless transmitter (figure 2) was developed. For the purposes of the test, it was decided to scale the power level as well as the size of the transmitter down to a low power 5W system.

Secondly, a suitable test bench (figure 3) was configured, combined with the acquired low power receiver (figure 1) to allow reproducible efficiency measurements. Thirdly, the coupling efficiency definition was derived. Finally, the derived efficiency values are scaled up to the size of the electrical vehicle charging system.

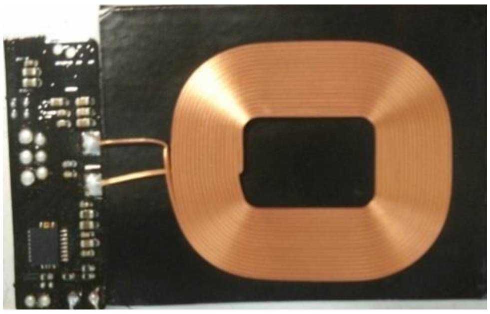

Fig. 1: WPT receiver

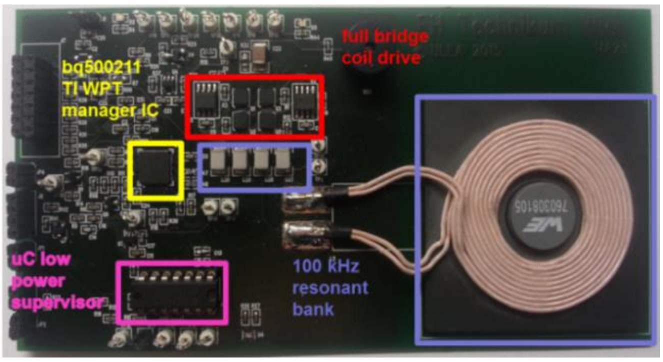

Fig. 2: WPT transmitter

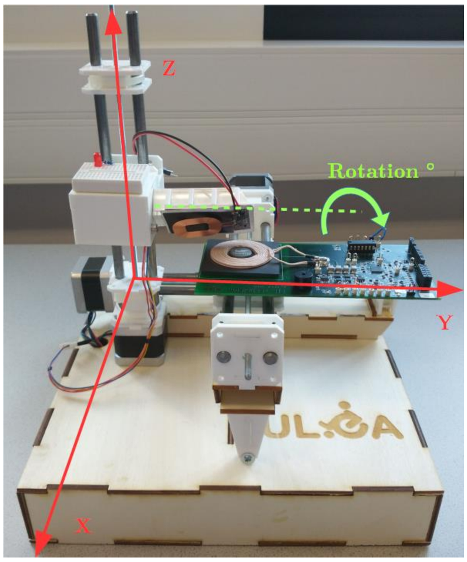

Fig. 3: WPT test bench

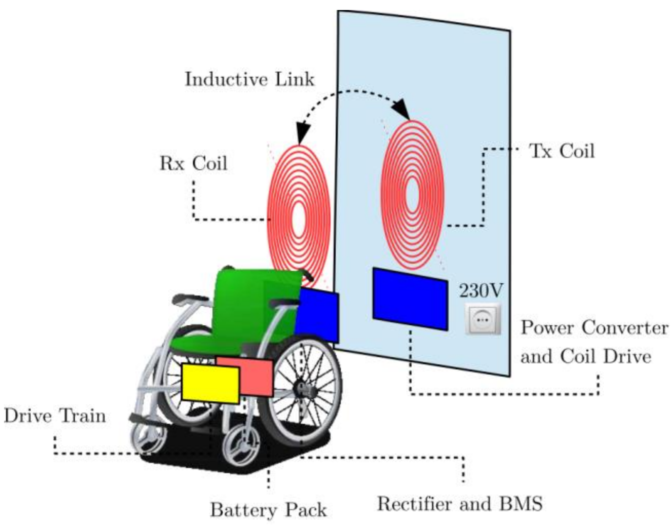

Fig. 4: Wireless charging of the wheelchair

To examine the influence of each individual misalignment case, those have been tested independantly for z-distance, lateral and angular misplacements. The coupling factor has then been derived according to the formula 2, given the individual inductances of the coils and the input / output voltages of the system.

3. Results of Practical Link Efficiency Evaluation

In order to compare a conventional wired charger to a wireless charger, it is important to define the system efficiency. In case of the wireless power system, the system boundaries often vary depending on the point of measurement, defined either as power reaching the load or as power reaching the receiver. After analysis and breakdown of both the wireless and wired chargers, the system efficiency of both could be reduced to the coupling factor efficiency between transmitter and receiver coils (in WPT case) and primary and secondary sides of power converter (wired charger).

One of the important limitations in the practical efficiency evaluation is the physical coupling factor, which cannot be measured directly, but has to be derived. Furthermore, the measurements of the coupling factor cannot be implemented on the isolated coils but has to be performed on the WPT system as a whole. For this reason, electronic losses have to be implicitly modeled and taken into consideration during the efficiency evaluation.

Results achieved during specified test runs have shown high deviation from the manufacturer-specified efficiency values. Significantly lower efficiency could be demonstrated compared to the available benchmarks.

Table 1 compares achieved practical values with the information provided by the WPC.

Estimated System Efficiency (Siddabattula 2015)	**>70%**
Practical System Efficiency	**<60%**

Tab. 1 Comparison of Wireless Power System Efficiency

In the next step, the study introduces a scale model to apply acquired efficiency evaluation to the electric vehicle use case. This allows examining power losses and their potential effects in the high power applications.

3.1 Mapping of the WPT Efficiency onto Commercial Electric Vehicle Use Case

Nissan Leaf was selected as an exemplary electrically powered vehicle for comparison of the charging efficiency values due to the available charging data and the broad adoption of the vehicle. According to the technical specifications, Nissan Leaf is equipped with a 24kWh battery and either a 3.3kWh (16A) charger for the common mains voltage, or optionally a 6.6kW for charging stations. However, to be able to charge from the domestic socket, a type 1 plug with 2.3kW power level is used. Complete recharge of the fully deprived battery takes approx. 10.5 hours with the average current drain of 10A (The mobility house 2015). The efficiency measured (socket to load) during the wired charging of the Nissan Leaf showed approx. 80-90% (Idaho National Laboratory 2015).

To compare wireless charging with a conventional wired charger, the primary question arising is what increase of the current is required to be able to charge the battery pack within the same time frame as the wired charger. Rough theoretical scaling up of the implemented low power 5W (5V/1A) WPT charging with 75% system efficiency (socket to load), would require 14 A average output current to

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charge the same battery within the same amount of time, considering the system losses. This value doesn´t differentiate between electronic losses and the losses in the inductive link between the primary and secondary side. Furthermore, it is important to mention that this scaling up is a first rough estimation, valid only assuming that losses behave linearly. Realistically, this is not the case, since most of the losses such as magnetic core, switching electronics and rectifier losses show more complex behavior.

The 75 % efficiency of the WPT system considers ideal case alignment of the coils with static electronic losses. Larger distances between the charging and receiving pad will result in increasing charging time. To compensate for the distance effect, the source must be able to provide higher currents.

3.2 WPT Electric Vehicle Charging 24-Hours Case Study

More meaningful comparison of the wired and wireless charger can be deduced by totaling up power consumption over the 24 hours, since power consumption in an idle state is a significant value for both wired and wireless chargers. During the day the system is either in standby mode or having its battery charged. For this evaluation, the benchmark efficiency provided by the WPC was used to estimate the optimistic scenario, even though the practically measured efficiency value is significantly lower.

Using the following input parameters for the calculations, several scenarios could be elaborated (see table 2), depending on the different number of operational and standby hours:

- Wired charger standby power consumption (scaled up): 0,06 kWh (Energy Star 2015)
- Wireless charger standby power consumption (scaled up): 0,138kWh (Texas Instruments 2015)
- Wired charger power transfer efficiency: 90%
- Wireless charger power transfer efficiency: 75% (Wireless Power Consortium, 2014)
- Charge power in: 2,3kWh (The mobility house 2015)

	WPT Charger [kWh]	Wired Charger [kWh]
Power Consumption 23-H Standby / 1-H Under Load	6,24	4,04
Power Consumption 19-H Standby / 5-H Under Load	17,96	14,00
Power Consumption 9-H Standby / 15-H Under Load	47,24	38,91
Power Consumption 1-H Standby / 23-H Under Load	70,67	58,84

Tab. 2: Wireless vs. Wired Charger Comparison based on 24 Hours Use Case

Even assuming the maximum WPT efficiency claimed by the WPC standard, the power consumption gap between wireless and wired charger is significant. Wireless charger shows efficiency values of up to one third lower than in a standard corded charger.

4. Prospective use of WPT in an electric wheelchair

As described above, the main motivation for the efficiency evaluation of the wireless power transfer within the research project was to improve interoperability of an assistive wheelchair. The advantages in this case differ from the other industrial applications. Rather than overcoming demanding environments, the main benefit to implementation of the WPT is the additional comfort factor afforded in the process. The use of a wireless charging simplifies the recharging process of the built-in battery to a large extent. The system architecture for the utilization of the wireless power transfer in the electrified wheelchair may look as shown in figure 4. A primary charging pad is mounted directly into/on the wall, powered by the mains voltage. The wheelchair is equipped with the battery pack, Battery Management System (BMS) for battery monitoring, voltage rectifier and converter, and the secondary coil. After the complete or partial discharge in the daily application, the user or a caregiver could simply move the wheelchair into the specified proximity of the charging pad. The charging process is initiated, monitored and terminated automatically by the WPT system.

The further research work intends to implement a wireless charging platform for the electric wheelchair based on the knowledge base established within the previous research work. The wheelchair is designed to consist of Commercial of the Shelf (COTS) electric pedelec components (motor, motor controller, BMS, WPT charging components, user interface) interconnected with a safety critical communication bus, e.g. TTCAN, Powerlink, EtherCAT. A battery with capacity of approx. 10kWh would be required and assuming 6 hours full recharge time, a wireless charger with the average current of 12A and mains voltage supply must be provided.

The high frequency power stage design is the deciding factor for achieving higher power levels, which might compensate the poor coupling factor. GaN FETs as well as Zero Voltage Switching (ZVS) concepts should be considered as potential technologies for their use in WPT systems.

Several important mechanisms have to be implemented to ensure safe usage of the technology, such as Parasitic Metal Object Detection (PMOD), Foreign Object Detection (FOD) and automated coil positioning. Those functions rely on a functional communication channel between primary and secondary coil, providing current and voltage conditioning according to the required power level. WPC Qi Standard (Wireless Power Consortium, 2014) compliant components will be used, since those mechanisms are compulsory.

5. Discussion and Outlook

Wireless power technology is expected to solve several problems in power supply by increasing charging convenience, eliminating charging cords and improving the interoperability for different charging standards and thus, increasing acceptance of electric vehicles.

Nevertheless, power transfer efficiency is a crucial issue for the broad acceptance of the technology. In case of the electrical vehicle charging, where charging power requirements are in the kW range, efficiency is crucial on the one hand, from the safety point of view, since losses in the kW range may cause heating and ignition. On the other hand, efficiency is likewise crucial when the charging time significantly exceeds the charging time of a conventional corded charger so that the technology becomes obsolete.

The analytical and practical models developed allow for estimating the coupling factor and for predicting efficiency of the target system. The advantage of the implemented approach is its simplicity, which allows gaining a quick overview over the link efficiency as a result of the parameter variation. In the design process of the new WPT system, both analytical and practical models can be reused to predict the system efficiency.

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