Impact of the Working Frequency on Wireless Power Transfer Systems

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Abstract

Inductive wireless power transfers systems work typically on frequencies above 10kHz. This is due to the relation between the size of the components and the nominal frequency. In most of the cases the higher the frequency the smaller the passive components are. On the other hand the working frequency is limited by the power semiconductors, which have to switch at this speed. Typically the switching losses are proportional to the frequency, which makes a trade-off mandatory.

An actual discussion about the choice of the ideal work frequency can be observed these times in the development of inductive charging systems for the e-mobility. Therefore the two frequencies 87kHz and 153kHz are examined here. A comparison between two conservative designs at the chosen frequencies shows a clear difference in the size of the secondary coils. Furthermore, it can be found that the same ferrite core is heated up stronger when used 87kHz. This has to be seen under the circumstance that the same power is delivered by the same ferrite core. Therefore it can be deduced that the higher frequency is the better choice when losses have to be reduced, size have to be minimized and the local heating has to be prevented.

Introduction

Inductive wireless power transfer systems usually consist of two coils. Each of them includes windings around a ferrite core. The most important characteristic is the air gap between the primary and the secondary coil (fig. 1).

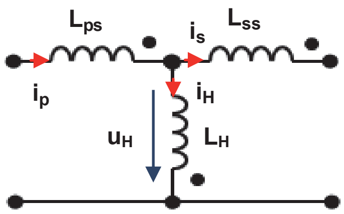
Fig. 1: Left: Inductive wireless power transfer system in an e-car. Right: The primary and the secondary coil in a labor setup (grey: ferrite, brown: cooper).

In fig. 1 it is to see clearly that an air gap is given by the space between the car (mobile part) and the primary system (fixed part) [1, 2]. Therefore experimental setups are designed similar to the alignment seen on the right.

In order to reduce the proportions of components, especially important for the secondary coil which has to be integrated in a car, a higher work frequency should be used. A theoretical derivation is presented in the next part of this paper. But as well interesting is the fact that a higher frequency causes less heating. This will be examined theoretically and experimentally in the following sections of this publication.

1. Theoretical derivation

The setup seen on the right in the fig. 1 above can be expressed in the following electrical circuit [3]:



$P = i_S' \cdot U_H$ $\quad$ $L_H = N_P^2 \cdot \Lambda_H$

$i_S' = i_S \cdot N_S / N_P$ $\quad$ $\Theta_S = N_S \cdot I_S$

$U_H = I_P \cdot 2\pi f \cdot L_H$ $\quad$ $\Theta_P = N_P \cdot I_P$

Fig. 2: Left: Equivalent electrical circuit. Right: Equation for the circuit seen here.

Here is L_{PS} the primary stray inductance, L_{SS} the secondary stray inductance and L_H represents the main flux. The transported Power can be written as:

$$P = \Theta_S \cdot \Theta_P \cdot \Lambda_H \cdot 2\pi f \quad (1)$$

Following the equation 1, it becomes clear that a lower work frequency f leads to less transported Power P [4]. The only alternative to transport the same power while applying lower working frequencies is to increase the ampere turns or the magnetic conductivity Λ_H. Each of these options results in an upscale of the setup and also more material are spend. In the following photo a design for 153kHz and one for 87kHz work frequency is presented.

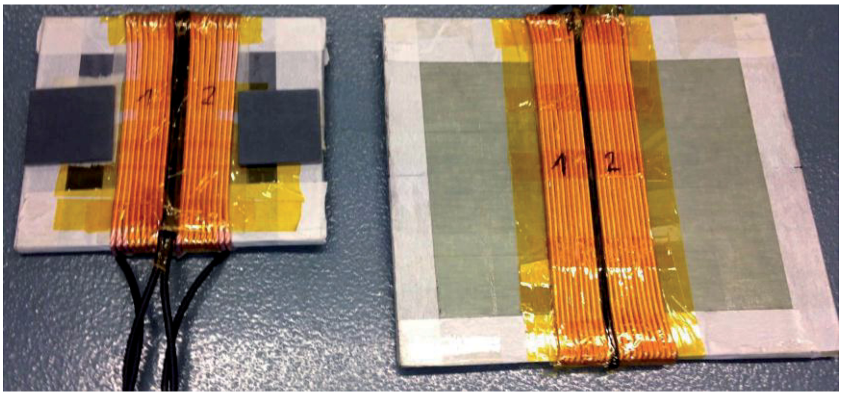


Fig. 3: A pickup which is designed for 153kHz work frequency (left) requires less volume than a pickup designed for 87kHz (right).

The two pickups in the fig. 3 are designed to transfer 3200Watt. It can be seen that the setup designed for 85kHz work frequency needs more volume and so more mass. In numbers: The coil for 85kHz is measured to 270mm x 310mm and the coil for 153kHz matches 185mm x 210mm.

Using more ampere turns leads to a higher magnetic flux density B in the ferrite core. The loosed power in the ferrite increases by the applied magnetics flux B in a nonlinear way. Especially at edges and at the boundaries of the ferrite plates the magnetic flux density is much higher than in the bulk. Therefore the magnetic losses will increase rapidly when the ampere turns are increased even if the mean magnetic flux seems to be in a noncritical range.

2. Practical examination

The aim of the experimental work presented here is to demonstrate the heating up of the ferrite core of the secondary coil when a lower work frequency is applied. It is supposed that the ampere turns are increased to transport the same power, when the frequency is decreased. The ferrite core for higher and lower frequency here is the same one. As lower frequency 87kHz and as the higher frequency 153kHz are elected for the experimental work.

2.1. Electrical circuit

The electrical circuit [5] is for both work frequencies the same. It is shown in the following picture (fig. 4).

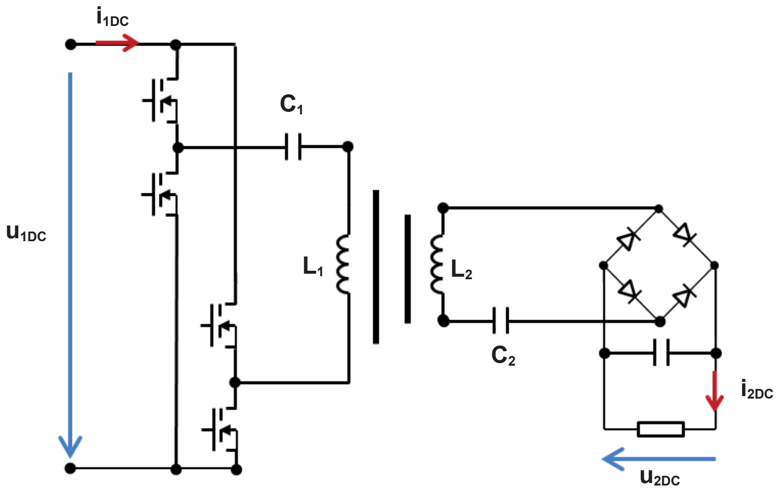


Fig. 4: The general electrical setup.

The complete primary inductance of the transformer is given by L_1. To obtain a higher magnetic flux the inductivity L_1 is compensated by the capacitor C_1 [6]. On the secondary circuit the capacity C_2 compensates the inductance L_2. The delivered Power P is defined as product of i_{2DC} and u_{2DC}. In order to compare the losses by equal conditions the delivered power P, the secondary voltage u_{2DC} and the secondary current i_{2DC} should be similar for the measurements with higher and lower frequency.

2.2. Magnetic properties of the coils for the two frequencies

In order to obtain higher ampere turn for 87kHz the number of the windings for the primary and the secondary coils are increased. In the following fig. 5 the winding numbers n_1 (primary) and n_2 (secondary) of the inductances L_1 and L_2 are shown for each frequency.

	87 kHz	153 kHz
n_1	13; L_1 = 378µH	10; L_1 = 224µH
ampere turns / A	130	100
n_2	30; L_2 = 265µH	20; L_2 = 118µH

Fig. 5: Magnetic properties of the coils

2.3. Experimental results

The voltage reached after the rectifier is between 335V and 340V while driving by 87kHz and 153kHz. So therefore the two different setups are comparable.

In such a setup two typical sources of heat are detectable. The first is the ohmic copper loss produced by the secondary windings and the second is the magnetization loss of the ferrite plates. The focus of this paper is the loss in the ferrite. So one temperature is measured in the winding packet and another temperature measurement is done at an edge of the ferrite (fig. 6).

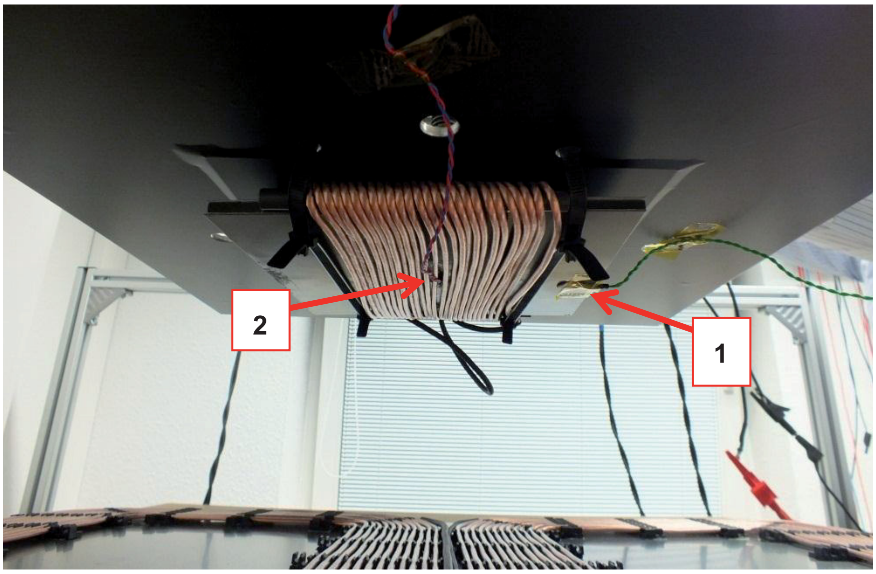


Fig. 6: In the secondary coil the temperature of the cooper windings (2) and the temperature of the ferrite (1) are measured.

The obtained temperature near the edge of the ferrite is visible in the fig. 7:

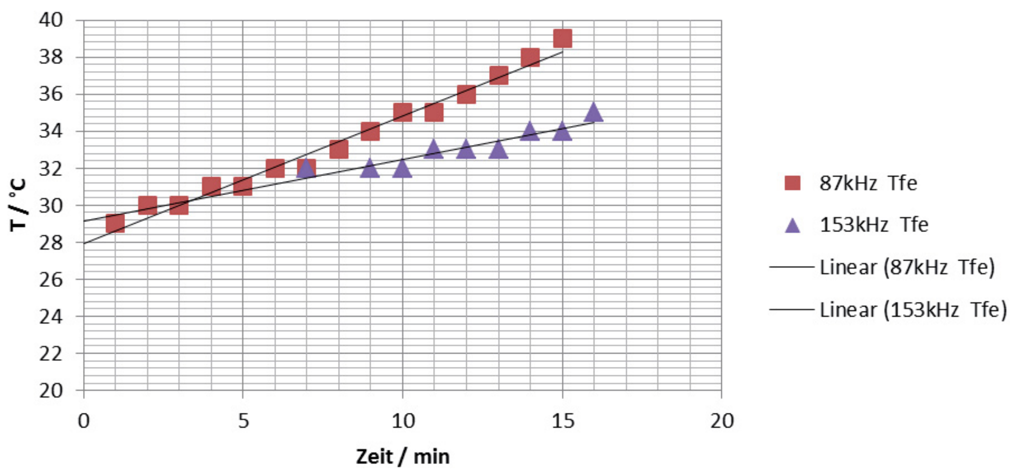


Fig. 7: The temperature of the ferrite rises faster when the work frequency is 87 kHz.

While the measurement is done the electrical power transferred is monitored as well. The transferred electrical energy is given in fig. 8:

	u_{1DC} / V	i_{1DC} / A	P_1 / W	u_{2DC} / V	i_{2DC} / A	P_2 / W
f = 87 kHz	396	8,92	3532	338	9,7	3276
f = 153 kHz	399	8,83	3523	339	9,6	3254

Fig. 8: Transported electrical energy.

It is clear that the electrical values of the setups for two different frequencies are nearly equal.

3. Conclusion and Outlook

In this work the additional losses caused by lower frequency are shown. Therefore a setup has been used which has the same ferrite body for both frequencies. For the lower frequency more magnetic flux had been necessary to transfer the power of 3200W.

Further experiments could be done to find a more common expression between the frequency and the losses respected to practical setups. But the essential conclusion, that lower frequency cause higher losses and more magnetic flux, should not change. Additional it has to be concerned that an increased magnetic flux will violate the critical value of magnetic field strength [7], which are recommended for human beings.

4. Reference

1. VDE-AR-E 2122-4-2, Elektrische Ausruestung von Elektro-Strassenfahrzeugen Induktive Ladung von Elektrofahrzeugen Teil 4-2: Niedriger Leistungsbereich, March, 2011
2. F. Turki, A. Körner, A. Guetif, C. Sourkounis: Stützung des Niederspannungs-Versorgungsnetzes durch Batterien in Elektrofahrzeugen oder kombiniert mit Photvoltaik Wechselrichtern.
3. F. Turki, T. Vosshagen, D. Kürschner, A. Kratser: Unified Supply Concept for Standardized Contactless Inductive Battery Charging of Electric Vehicles; Tagung Elektrik/Elektronik in Hybrid- und Elektrofahrzeugen und elektrisches Energiemanagement ; Haus der Technik RWTH Aachen. Bamberg (2013)
4. Meins, J.; Buehler, G.; Czainski, R.; Turki, F.: Contactless Inductive Power Supply. Maglev Conference 2006, p 527-535. Dresden (2006)
5. F. Turki, T. Vosshagen, B. Schmuelling: eCPS Ein induktives Ladesystem für Elektrokraftfahrzeuge: Tagung Elektrik/Elektronik in Hybrid und Elektrofahrzeugen und elektrisches Energiemanagement ; Haus der Technik RWTH Aachen. Miesbach (2012)
6. Faical Turki, Ulrich Reker: Further Design Approaches of the Standardization: Inductive Charging of Electric Vehicles; 2nd International Electric Drives Production Conference and Exhibition, Nürnberg 2012
7. ICNIRP 2010, http://www.icnirp.de/documents/LFgdl.pdf

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