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Design of a high frequency Inductively Coupled Power Transfer system for electric vehicle battery charge

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ABSTRACT

The development of a high autonomy purely electrical public mean of transportation is not currently viable because the required energy implies a very high battery weight. However, this weight would be significantly reduced if these batteries could be charged at the bus stops along the route, for instance using a contact-less power transfer system. An ICPT (Inductive Coupling Power Transfer) system with a large air gap has been developed and built for an electric vehicle battery charger. The practical sizing, the best compensation topology and the operational frequency have been studied in order to obtain maximum efficiency. The study has been focused on defining the prototype implementation process, validating the theoretical results and analyzing the influence of frequency deviation with respect to the resonant frequency and the effect of gap variation and misalignment in the behaviour of the system.

1. Introduction

In many applications, ICPT systems have several advantages over conventional energy transmission techniques using wires and connectors. For example, ICPT systems have been the preferred solution in hazardous applications due to the elimination of sparking and electrical shock risk [1]. The development of such systems is improving and the number of applications where they are suitable grows steadily: contact-less power supplies for professional tools [2], contact-less battery charging across large air gaps for electric vehicles [3], compact electronic devices [4], mobile phones [5] and public transport systems [6].

Generally, an ICPT is implemented using magnetic induction in specially constructed transformers. In such transformers, the energy is inductively transferred from the primary to the secondary through the air. It is quite common that ICPT systems have a relatively large separation between the primary and secondary winding (Fig. 1). Therefore, the characteristics of these transformers are very different from those of conventional transformers having good coupling between windings.

Due to a large winding separation, ICPT systems have relatively large leakage inductance and reduced magnetizing flux, which implies the need for greater magnetizing current.

All these features make the power factor to be low in both the primary and secondary sides reducing significantly the efficiency of the system. To improve the behaviour of ICPT systems several studies have been carried out in order to determine the best way of power factor compensation. In [7,8] different compensation schemes are proposed and their benefits are presented. In spite of these studies the design procedure is not clear. In [9] a design procedure is presented but there still remain many design decisions that depend on the actual case, which implies that the design procedure requires the development of four steps:

- Determining the minimum electrical requirements (voltage on both sides and power to be transferred to the load).
- Performing a first theoretical study.
- Simulating the approach.
- Testing experimentally the final approach.

The different studies consider a high distance between primary and secondary side something like 5 cm. We consider that for public transport this may be too short and, in addition, in such applications it is difficult to achieve constant gap and perfect winding alignment. So, to cover these questions, this paper studies the design of a 200 kW, 35 cm gap ICPT system and the design and test of a 5 kW laboratory-scale prototype with a 20 cm air gap. Simulating and testing this prototype, the influence of air gap variation and misalignment on the system behaviour is studied, focusing especially on the efficiency of the system.

There are other issues, not covered in this paper, that should be investigated, like the effect of the electromagnetic emissions associated with the ICPT system. These high frequency fields may affect the electronic equipment of the electric vehicle and some shielding could be required.

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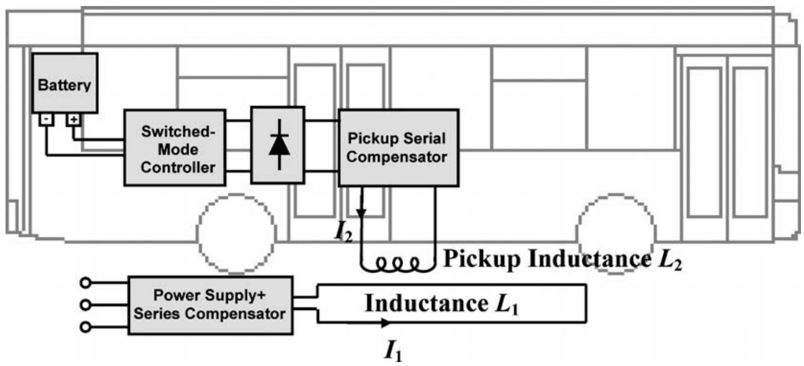

Fig. 1. Scheme of the ICPT battery charger.

2. ICPT theoretical model

The power transfer capability of an ICPT system depends directly on the coupling coefficient, k [1] which is given by

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{1}$$

where L_1 and L_2 are the self-inductance coefficients of the primary and secondary coils and M is the mutual inductance.

To improve the power transfer capability to the load, it is necessary to include capacitors in both sides. By working at the resonance frequency in the secondary selecting the appropriate capacitor C_2, the power transferred to the load is maximum. Selecting the capacitor in the primary side C_1 at this frequency, the total impedance of the system is purely resistive, so the current is in phase with the voltage and the source needs to deliver the minimum apparent power.

If Series–Series (SS) compensation is selected (i.e. both primary and secondary capacitors are connected in series with the respective coils), the primary capacitance is independent of both the magnetic coupling and the load [9]. The power transferred from the primary to the secondary is given by

$$P_2 = \frac{\omega_0^2 M^2}{R_L} I_1^2 \tag{2}$$

where ω_0 is the resonant frequency of the primary and secondary and is normally chosen [9]

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{3}$$

Thus, the capacitance values for C_1 and C_2 are:

$$C_1 = \frac{1}{\omega_0^2 L_1} \tag{4}$$

$$C_2 = \frac{1}{\omega_0^2 L_2} \tag{5}$$

To obtain the theoretical values for L_1, L_2 and M for the geometry shown in Fig. 2, the following expressions must be used:

L_1 is given by

$$L_1 = \frac{\mu_0}{\pi} N_1^2 \left[d \cdot \ln \frac{2Ld}{R_1\left(d + \sqrt{L^2 + d^2}\right)} \right] + \frac{\mu_0}{\pi} N_1^2 \left[L \cdot \ln \frac{2Ld}{R_1\left(L + \sqrt{L^2 + d^2}\right)} - 2\left(d + L - \sqrt{d^2 + L^2}\right) \right] + \frac{\mu_0}{4\pi} N_1^2 (L + d) \tag{6}$$

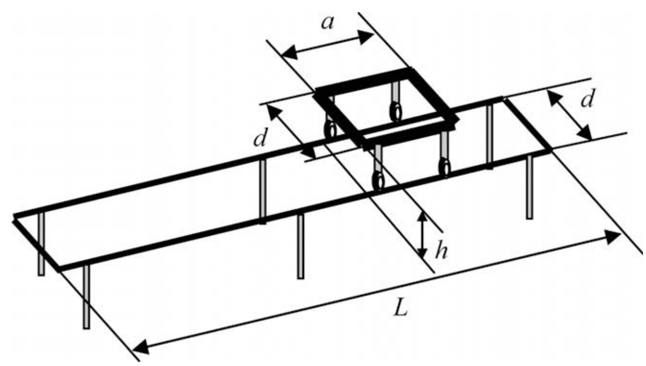

Fig. 2. Schematic of the implemented model showing design parameters.

and L_2 is given by

$$L_2 = \frac{\mu_0}{\pi} N_2^2 \left[d \cdot \ln \frac{2ad}{R_2\left(d + \sqrt{a^2 + d^2}\right)} \right] + \frac{\mu_0}{\pi} N_2^2 \left[a \cdot \ln \frac{2ad}{R_2\left(a + \sqrt{a^2 + d^2}\right)} - 2\left(d + a - \sqrt{d^2 + a^2}\right) \right] + \frac{\mu_0}{4\pi} N_2^2 (a + d) \tag{7}$$

where R_1 and R_2 are the equivalent radius of the windings.

$$R_1 = \sqrt{\frac{N_1 S_1}{\pi}} \tag{8}$$

$$R_2 = \sqrt{\frac{N_2 S_2}{\pi}} \tag{9}$$

If both coils have the same dimensions, the mutual inductance coefficient is given by

$$M = \frac{\mu_0}{\pi} N_1 N_2 \left[d \ln \frac{d + \left(\sqrt{h^2 + d^2}\right)\left(\sqrt{h^2 + a^2}\right)}{d + h\sqrt{h^2 + d^2 + a^2}} \right] + \frac{\mu_0}{\pi} N_1 N_2 \left[a \ln \frac{a + \left(\sqrt{h^2 + d^2}\right)\left(\sqrt{h^2 + a^2}\right)}{a + h\sqrt{h^2 + d^2 + a^2}} \right] + \frac{\mu_0}{\pi} N_1 N_2 \left[2\left(h - \sqrt{h^2 + d^2} - \sqrt{h^2 + a^2} + \sqrt{h^2 + d^2 + a^2}\right) \right] \tag{10}$$

Considering a case where the primary track is significantly longer than the secondary pick-up ($L \gg a$) the mutual inductance can be approximated by