A 3D Electromagnetic Analysis and Circuit Modeling for Wireless Charging of Electrical Vehicles

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***Abstract*—This paper focuses on the design of a contactless charging system for Electric Vehicle (EV) using inductive loops. A 3D Finite Element (FE) electromagnetic modeling approach is carried out to calculate the electromagnetic coupling and inductances of the system according to the change of some geometry parameters; also the effects of these changes on the electrical values of the whole system are studied.**

Index Terms— 3D Finite Element Method (FEM), inductive charging, resonance converter, radiated EMC.

I. INTRODUCTION

The automotive industry is currently undergoing a profound technological transformation in a context where environmental concerns are at the forefront. Restrictions in terms of CO2 emissions lead manufacturers to work on "cleaner" concept cars as the EV. Such a vehicle currently uses a regular cable connection for its recharge which may include elements tedious and / or inconvenient for the user. In this context, contactless charging by Inductive Power Transfer (IPT) is an attractive alternative. This solution provides ease of use, quick and a good robustness to vandalism [1]. The goal is to transfer energy from the ground to the vehicle (on board battery) by an inductive loop system (on the principle of a transformer) as shown in Fig. 1[2]. This principle requires obtaining a good yield and tolerance to positioning (transmitter / receiver coupling).

In fact, many works were dedicated before to IPT system design and its applications. In [4] theoretical and analytical calculations for the self and mutual inductances of a planar inductive transformer are performed for general application of wireless energy transfer. An optimized arrangement of ferrites sectors is proposed in [5]. The simulations in [4]-[6] also included the influences of variation of the distance and position of secondary coil on the electrical parameters. Moreover the whole system control and efficiency were studied in [6]. As the power transferred is relatively large it is necessary to control the level of Electromagnetic (EM) fields exposure inside and around the vehicle to insure that the values are consistent with acceptable standards [5], [6].

In this paper, a 3D FEM modeling for the contactless transformer is shown. The effect of magnetic shielding using closed circular ferrites to limit the penetration of the excitation field within the vehicle is quantified. Also an EV chassis is modeled in the structure of IPT system. The results then are used to calculate the mutual coupling and inductances of the transformer. An electrical circuit model of the whole system is shown including the resonance topology. Moreover it is demonstrated that the presence of the chassis has a significant influence on the mutual inductances values and radiated EM field exposure especially when the shift between the coils axes is important. Finally, open circuit and short circuit faults at the battery side are tested. Here some simulations are shown; the others will be illustrated at the conference.

II. SYSTEM DESIGN

A) *Equivalent System Model*

The simplified electrical circuit of the charging system is illustrated in Fig. 1. The model consists of two coils (inductive coupler), two resonant capacitors (C_1,C_2) to compensate and tune out (L_1,L_2) and thus maximum power transfer to the battery load at resonance frequency (1). The series-series (SS) resonant converter is chosen since it was shown that SS compensation is the best one among the others topologies for many reasons. The major one is that a series primary compensation is independent of the load, so it is not necessary to retune the system every time that the load changes. Moreover series compensated secondary has zero reflected reactance, whereas a parallel-compensated system reflects a capacitive load [3]. L_1 and L_2 are chosen identical, so $C_1 = C_2$ at air gap (*d=0.15m*) and coils axes shift (*sh=0m*) (see Fig. 2). And this case is taken as a reference at a frequency $f_0 = 30kHz$.

$$f_0 = 1/2\pi\sqrt{L_1C_1}=1/2\pi\sqrt{L_2C_2} \qquad (1)$$

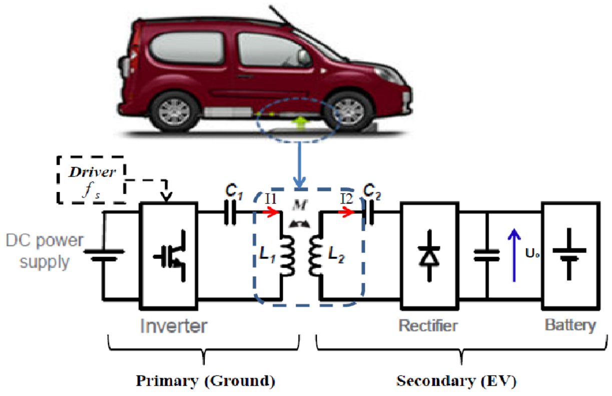

Fig. 1: IPT charging system for EV

B) *Inductive Coupler Transformer (ICT)Modeling*

The most efficient and effective magnetic flux is the one produced by planar parallel axes coils because the energy transfer takes place on receiver whole area, and shielding is used to improve the mutual inductance M by increasing the magnetic flux between the two coils. It is done by adding a magnetic non conducting material, and ferrite is usually used [4]. The 3D structure of the coupler can be constructed as in Fig. 2. It consists of a transmitter coil, a receiver coil and two ferrites plates that completely cover the coils. A steel plate which describes a simplified model of EV chassis is added in the design. The two coils in this model are identical with an air gap distance (*d*), and axes shift (*sh*) which corresponds to the EV position.

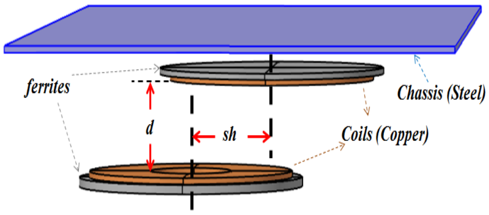

Fig. 2: 3D structure of an ICT with shielding and a simple EV chassis

III. SIMULATION RESULTS AND DISCUSSION

Based on the 3D FEM modeling, the values of L_1, L_2 and M are calculated. The calculation also includes the influences of variation of the parameters (*d and sh*). The plot in Fig. 3 shows one of these influences (variation of *d (m)* at axes shift *sh=0.1m*).

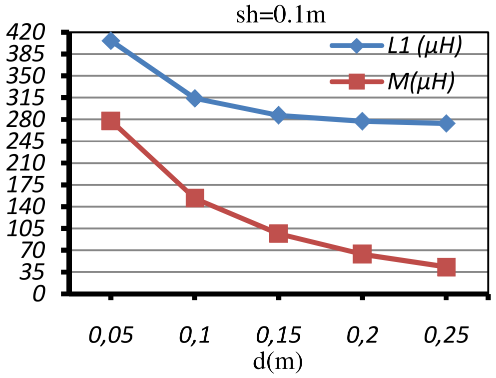

Fig. 3: Variation of *L1, M* values due to air gap *d(m) when sh=0.1m*

A circuit analysis for the whole system (Fig. 1) is then achieved taking into account the variations of *d* and *sh.* Many methods of system control can be used to command the inverter switches at a resonance frequency. In this paper, the current I_1 and the inverter driver frequency f_s are kept constants for all cases ($f_s = f_0 = 30kHz$). Other methods of control by varying f_s to achieve the resonance for each case and for fixed input power values will be discussed in future work. The change of the secondary current due to the sweep of the distance *d* is shown in Fig. 4; I_2 decreased by increasing the distance *d* between the two coils at same resonance frequency because the mutual M decreased. Also the phases are changed slightly from the reference case (*d=0.15m, sh=0*) because the system is not working at resonance. The goal is to transmit *3kW* at an output voltage $U_0 = 400Vdc$ for the reference case at $f_s = f_0 = 30kHz$. The voltage across the battery U_0 in Fig. 5 is obtained with the test of an open circuit fault when disconnecting the load. Other kinds of faults with series and parallel secondary compensation topologies were also studied.

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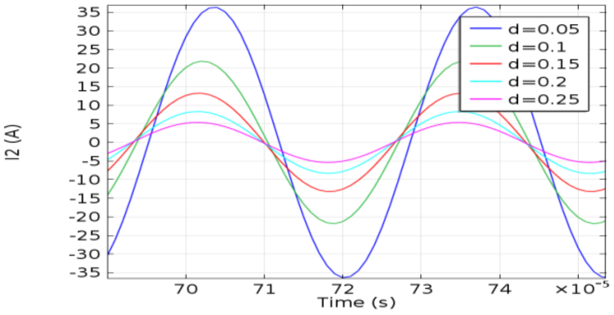

Fig. 4: Influence of air gap d in I_2 when *sh=0*

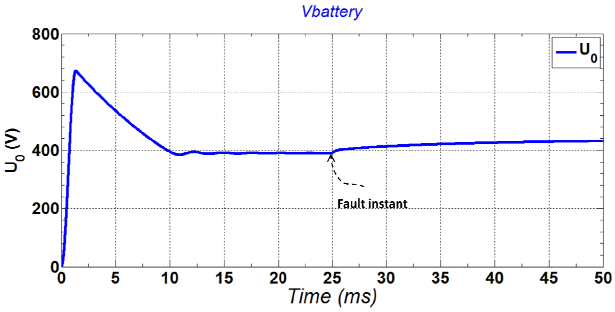

Fig. 5: Output voltage U_0time response with an open circuit fault at battery side after *25ms*

REFERENCES

[1] Y. Matsuda, H. Sakamoto, H. Shibuya, and S. Murata Sojo "A non-contact energy transferring system for an electric vehicle-charging system based on recycled products,'' Journal of Applied Physics 99, 08R902 2006.

[2] A. Neves, D. M. Sousa, A. Roque, J. M. Terras "Analysis of an inductive charging system for a commercial electric vehicle,'' Power Electronics and Applications Conference (EPE 2011), pp. 1-10, Aug. 30 2011-Sept. 1 2011.

[3] C. S. Wang, O. H. Stielau, and G. A. Covic, "Design consideration for a contactless electric vehicle battery charger," IEEE Trans. Ind. Electron., Vol. 52, No. 5, pp. 1308–1313, Oct. 2005.

[4] J. Acero, C. Carretero, I. Lope, R. Alonso, O. Lucía, and J.M. Burdio, "Analysis of the Mutual Inductance of Planar-Lumped Inductive Power Transfer Systems,'' IEEE Trans. On Industrial Electronics, Vol. 60 , No. 1 pp. 410-420, Jan. 2013.

[5] M. Budhia, G.A. Covic, J.T. Boys, "Design and optimization of circular magnetic structures for lumped inductive power transfer systems," IEEE Trans.on Power Electronics, Vol. 26, No. 11, pp 1115-1123, Nov. 2011.

[6] H. Wu, A. Gilchrist, Ky Sealy, D. Bronson, "A High Efficiency 5kW Inductive Charger for EVs using Dual Side Control," IEEE Trans. on Industrial Informatics,Vol. 8, No. 3, pp. 585 - 595, Aug. 2012..