Design of wireless power transmission for a charge while driving system

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***Abstract*—The key component in wireless power transmission for the recharging of electric vehicles is the couple made by the underground power line and the on-board pick-up module. This paper analyzes a charge while driving system by using a coupled formulation between the finite integration technique and the boundary element method.**

***Index Terms*—Finite integration technique, boundary element, electric vehicle, charge while driving**

I. Introduction

During the past few years, the wireless charging of electric vehicles was supposed to be only an academic technology without any commercial possibility. Due to the growth of the market of electric vehicles and wireless technology, many electric vehicle manufacturers have shown their interest into the wireless charging of electric vehicles. The static wireless charging is now a common technique proposed by many manufacturers: the charger consists basically in two parts: a charging plate attached to the bottom of the vehicle, and a charging mat placed on or below the ground. The efficiencies can go up to 90 %. The new frontiers of research in wireless power transfer is the so called *charge while driving* (CWD) system: the goal is to extend the battery range by a fast partial recharging during the movement of the vehicle [1], [2], [3]. The attention of manufacturers in wireless charging systems is also witnessed by an increasing number of recent papers dealing with this technology [4], [5].

The EU project eCo-FEV (efficient Cooperative infrastructure for Fully Electric Vehicles)[1] proposes an IT electric mobility platform for the integration of FEV into infrastructures, enabling connections and information exchanges between multiple infrastructure systems that are relevant to FEVs. Under this framework, one of the interests of the project is the design and performance analysis of a high efficiency CWD system.

This paper focuses the attention on the design of the inductive power transfer system by using a coupled formulation between the finite integration technique and the boundary element method.

II. Computational model and numerical formulation

The system under study is the couple made by the underground power line and the on-board pick-up module shown in

[1] `http://www.eco-fev.eu`

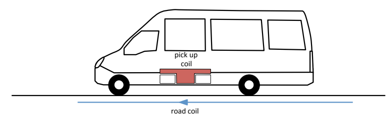

Fig. 1: Schematic representation of the CWD system: electric vehicle and the wireless power transmission.

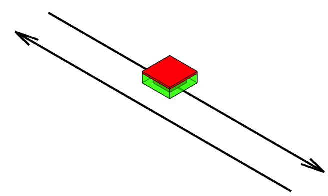

Fig. 2: Power line embedded in the road (arrows) and pick up coil (core in red, coil in green).

Fig. 1 and Fig. 2. The system is characterized by a resonance frequency of $20\ \mathrm{kHz}$. The couple road coil/pick-up coil can be analyzed by means of the coupled inductors model represented in Fig. 3. The secondary winding can be used to feed an external circuit:

$$v = M\frac{\mathrm{d}i_1}{\mathrm{d}t} + L_2\frac{\mathrm{d}i_2}{\mathrm{d}t} \tag{1}$$

The winding supplies a resonance capacitor, C_1 a rectifier, a filter and the battery charger (load). An additional resistor R_0 takes into account eddy currents and hystereses losses into the magnetic core. A simulink model is built in order to take into account the system dynamic Fig. 4. In this way it is possible to easily include the nonlinear behavior of the rectifying bridge and add the battery charging system. The circuit model is coupled with the field model by the maps of self and mutual inductance as described in the next section. The magnetic core is composed by nonlinear material, therefore the mutual

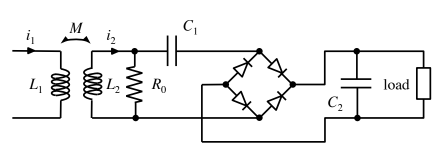

Fig. 3: Circuit model of the inductive power system.

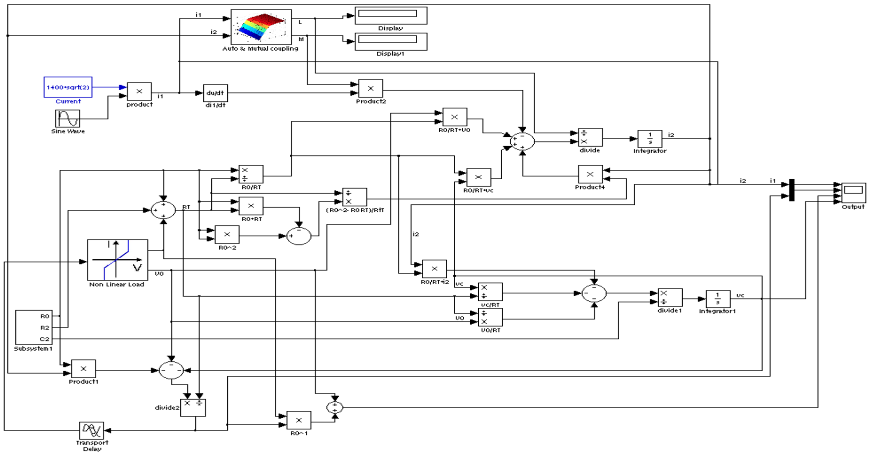

Fig. 4: Simulink model of the complete system.

inductance M and the self inductance L_2 are not constant for every working condition.The magnetic core of the pick-up coil is interested by a magnetic flux which depends both on i_1 and i_2. Hence, for a given configuration, the relation $\Psi = \Psi(i_1, i_2)$ has to be defined. M and L_2 are calculated as:

$$M = N_2 \frac{\mathrm{d}\Psi(i_1, i_2)}{\mathrm{d}i_1} \quad L_2 = N_2 \frac{\mathrm{d}\Psi(i_1, i_2)}{\mathrm{d}i_2} \tag{2}$$

It is worth noting that in some geometric configurations, the magnetic core can saturate due to the secondary current because it is strongly coupled with the magnetic core. Furthermore, although M and L_2 are independent in liner zone, the saturation creates a dependence between them. In fact, for large values of i_2 the magnetic core saturates (i.e. L_2 tends to zero); consequently, a further increase of the primary current cannot be seen by the system (i.e. M tends to zero).

The problem under study is characterized by large structures and distances between the power line and the pick-up coil. In order to have accurate results with standard computational resources, a hybrid FIT-BEM code is used for the calculation. The finite integration technique is used to discretize the ferrite core of the pick-up module, while the boundary element account rigorously for the regularity of the magnetic field at infinity. The formulation follows the same rationale of [6].

If eddy currents in the magnetic core are neglected, the magnetostatic FIT equations are used to describe the field in the core:

$$\tilde{\mathbf{S}}\mathbf{M}_\nu\mathbf{S}\mathbf{a} = \mathbf{i}_\mathrm{s} \tag{3}$$

where $\tilde{\mathbf{S}}$ and $\mathbf{S}$ are the curl matrices on the dual and primal meshes, respectively, $\mathbf{M}_\nu$ is the constitutive matrix and $\mathbf{a}$ is the line integral of the magnetic vector potential. This equation is coupled with the BEM equations formulated in reduced magnetic scalar potential:

$$\mathbf{G}\frac{\partial \phi}{\partial n} = \mathbf{H}\phi \tag{4}$$

The coupling between the two formulation requires:

- to complete the Faraday's law for elements on the boundary;
- the imposition of continuity of the magnetic field on the boundary.

The final system is:

$$\begin{bmatrix} \tilde{\mathbf{S}}\mathbf{M}_\nu\mathbf{S} & \mathbf{S}_\mathrm{b}^\mathrm{T} \\ \nu_0\mathbf{G}\mathbf{A}_\mathrm{b}^{-1}\mathbf{S}_\mathrm{b} & -\mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \phi \end{bmatrix} = \begin{bmatrix} \mathbf{i}_\mathrm{s} - \mathbf{h}_\mathrm{s} \\ \mathbf{G}\mathbf{H}_\mathrm{sn} \end{bmatrix} \tag{5}$$

where $\mathbf{S}_\mathrm{b}$ is the discrete surface curl $\mathbf{A}_\mathrm{b}^{-1}$ is a diagonal matrix having the surface areas of the boundary elements. A technique based on the Schur's complement is adopted to efficiently solve the final system.

In the full paper details about the implementation and the solution of the final system and the analysis of different configurations will be analyzed and commented.

III. Acknowledgement

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