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Field – Circuit Model of Wireless Transmission Power System using Ω–*T*–T_0 Formulation

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Abstract. The paper discusses the field-circuit model of the wireless power transmission system (WPTS) with the air-core high-frequency transformer. While working on the field model, a formulation which uses scalar magnetic potential Ω and electric vector potentials $\boldsymbol{T}$ and $\boldsymbol{T}_0$ was implemented. Model equations were provided. The system which consists of magnetically coupled coils connected with the elements of external circuits was taken into consideration. The selected results of simulation calculations were presented. The obtained results of simulation calculations were compared with the results of measurements obtained at a laboratory post.

1 Introduction

Wireless power transmission systems (WTPS), in which energy is transferred by means of the high-frequency electromagnetic field (HF) are more and more frequently used in contactless charging systems for mobile devices [1], portable computers [2]; or electronic devices. The WPTS are also more and more willingly used in the systems of contactless power supply of electric vehicle batteries [3], or systems which constitute the power supply for industrial manipulators [4]. The WPTS are also used in systems of wireless power transmission through a human tissue, thus enabling the battery charge of devices which support the functioning of human organs [5], as well as in medical examinations and diagnostics [6]. Various aspects of the wireless power transmission were and still are undertaken in numerous publications. These papers refer to analysis, modelling and design of WPTS components as well as the possibility of using the same systems in different fields of science and technology.

In this article, the authors wish to present the results of their research on the development and implementation of the field-circuit model of phenomena for the wireless power transmission system by means of the high-frequency electromagnetic field. While developing the model, the popular finite element method and the formulation that uses the scalar magnetic potential and electric vector potentials $\boldsymbol{T}$ and $\boldsymbol{T}_0$ were implemented. The model was designed for analysis of the system which consisted of magnetically coupled coils, which were connected with external passive elements, thus developing the external circuits. Selected results of calculations were presented and the said results were subjected to comparative analysis with the measurement results.

2 Field – circuit model

For the purposes of the paper, a field-circuit model of phenomena was developed for modelling and analysis of the operating conditions of the wireless power transmission system consisting of the wireless high-frequency transformer and external circuits (Fig.1). The model implements a three-dimensional (3D) approach which involves the finite element method (FEM) and the formulation which uses $\boldsymbol{\Omega}$-$\boldsymbol{T}$-$\boldsymbol{T}_0$ potentials. In the used approach, the distribution of the magnetic field is described by means of nodal values of scalar potential Ω, whereas the distribution of eddy currents in massive wires of air transformer windings and the external circuit currents is described by means of edge values of electric potentials $\boldsymbol{T}$ and $\boldsymbol{T}_0$ respectively. The application of the $\boldsymbol{\Omega}$-$\boldsymbol{T}$-$\boldsymbol{T}_0$ formulation under consideration leads to the system of equations (1), which, as has been demonstrated in [7], are equivalent to the equations of the coupled permeance - resistance network method, i.e.:

$$\begin{bmatrix} \boldsymbol{\Lambda}_w & \boldsymbol{k}_w^T\boldsymbol{\Lambda}_g & \boldsymbol{k}_w^T\boldsymbol{\Lambda}_g\boldsymbol{z}_0 \\ \frac{\partial}{\partial t}\boldsymbol{\Lambda}_g\boldsymbol{k}_w & \boldsymbol{Z}_0+\frac{\partial}{\partial t}\boldsymbol{\Lambda}_g & \boldsymbol{R}_{co}^T \\ \frac{\partial}{\partial t}\boldsymbol{z}_0^T\boldsymbol{\Lambda}_g\boldsymbol{k}_w & \boldsymbol{R}_{co} & \boldsymbol{Z}_c+\boldsymbol{R}_c+\frac{\partial}{\partial t}\boldsymbol{z}_0^T\boldsymbol{\Lambda}_g\boldsymbol{z}_0 \end{bmatrix} \begin{bmatrix} \boldsymbol{\Omega} \\ \boldsymbol{i}_0 \\ \boldsymbol{i}_c \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{u}_c \end{bmatrix} \tag{1}$$

where: $\boldsymbol{\Lambda}_w$ is the nodal permeance matrix of the edge network (SK), $\boldsymbol{\Lambda}_g$ is the branch permeance matrix of the edge network (SK), $\boldsymbol{Z}_0$ is loop impedance matrix of the facet network (SS) and $\boldsymbol{k}_w$ is the nodal incidence matrix. Symbols $\boldsymbol{\Omega}$, $\boldsymbol{i}_0$ and $\boldsymbol{i}_c$ represent the relevant vector of nodal values of potential Ω of the edge network and the vectors of edge values of potential $\boldsymbol{T}$ and $\boldsymbol{T}_0$, i.e. loop

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currents of the facet network and external circuits. Furthermore, matrix z_0 describes the winding in the edge element space [8], $\boldsymbol{R}_c$ is the loop resistance matrix for the external circuit, $\boldsymbol{R}_{c0}$ describes the mutual resistances between the facet network loops and external circuit loops [9], while $\boldsymbol{Z}_c$ is the external impedance matrix, i.e. resistance and reactance contained in external circuits of the system under consideration (see, Fig. 1). The developed model equations allowed for the development of the software which can analyse the working conditions and the distributions of the electromagnetic field in the studied WPTS.

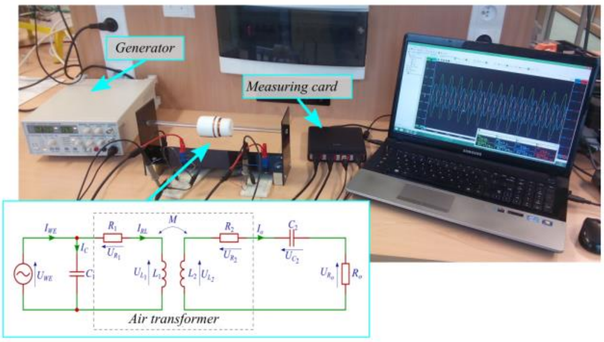

Fig. 1. View of the considered system of WTPS and its scheme diagram.

3 Results and Conclusions

The field-circuit model proposed in the paper has been tested based on the example of the existing WPTS from Figure 1, based on the parallel-series resonance circuit. A number of numerical calculations were performed for the system under consideration. Among other things, dependencies of self-inductances and mutual inductances between the air-core transformer coils were determined. On top of this, a number of static and dynamic calculations of operating conditions were performed, plotting numerous current and voltage waveforms. For instance, Figure 2 shows the voltage waveforms obtained from the calculations and measurements at the system input U_{in} and output (load) U_o for different distance values between coils. The calculations were performed for frequency of the power supply source equal to 840 kHz and the RMS value of supply voltage equal to 5 V.

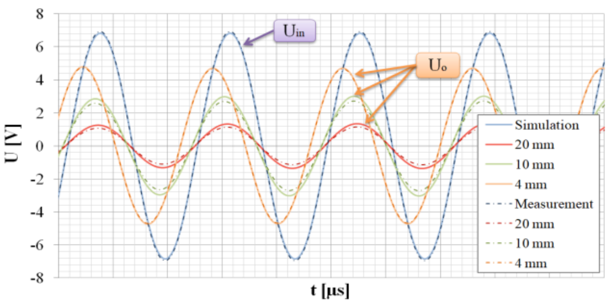

Fig. 2. Comparison of waveforms of input and output voltages obtained from the simulations and the measurements.

Figure 3, on the other hand, shows the comparisons of values of effective voltages $\boldsymbol{U}_o$ and currents $\boldsymbol{I}_o$ on the system load resistance $\boldsymbol{R}_o$ as a function of distance between the coils. In the studies, the value of resistance $\boldsymbol{R}_o$ was equal 50 Ω.

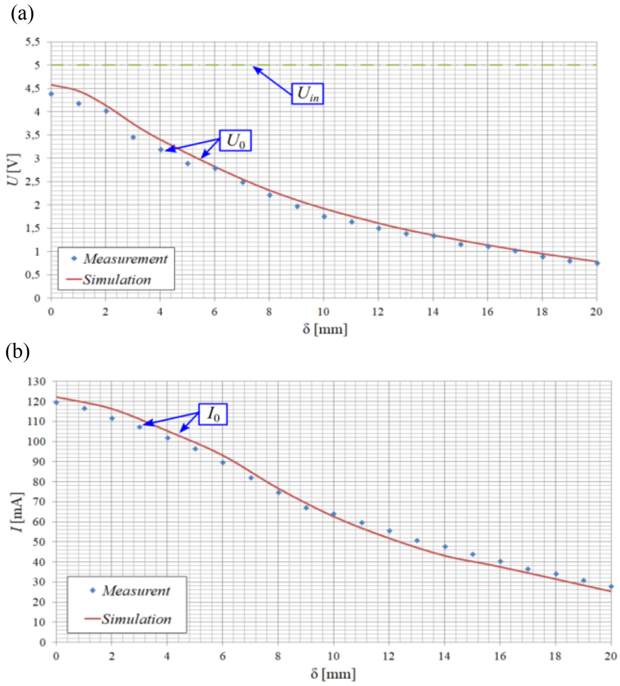

Fig. 3. Comparison of the values of output voltages (a) and currents (b) as a function of distance δ between coils of WTPS.

The presented comparisons show that the maximum values of differences between the results obtained from the measurements, and the results of calculations did not exceed 5.5% for the values of obtained voltages and 3.8% for the values of output currents in the system respectively. In the opinion of the authors, the developed model allows the results of calculations to be obtained with broad convergence in reference to the results.

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