Electromagnetic Compatibility of Contactless Power Transfer Modeled in FEM Analysis Software

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Abstract— This paper deals with basic parameters of contactless power transfer (CPT) and modelling of CPT in FEM analysis software. There are described basic equations for computing parameters of CPT components. The main part of this paper refers about creating CPT transformer model in multiphysics software Maxwell Ansys to determine basic CPT parameters such as induction and impedance of CPT transformer, its electromagnetic field and its effect on surroundings. CPT operates at high frequencies so its electromagnetic compatibility with other electric devices is very important because it may cause serious risks of fail of devices such as pacemakers or communication devices.

1. INTRODUCTION OF CONTACLESS POWER TRANSFER (CPT)

Contacless power transfer is action when electric energy is transferred between two physically unconnected electric devices. Electromagnetic induction is used to transfer energy between galvanically isolated electric devices. This solution of energy transfer is very useful in environment of applications where conventional electricity wire transfer would be impractical or even dangerous. CPT is used in many applications such as toothbrushes, mobile phones and public transportation for charging electric devices.

Figure 1 shows basic CPT component blocks which are used for contactless power transfer.

2. CPT ANALYSIS

As shown in Figure 1. CPT consists of many functional blocks. The main part is CPT transformer which is formed by two large gap air coils. To achieve high efficiency of energy transfer CPT transformer has to operate at high frequencies. But high operational frequencies cause high impedance of CPT transformer and increase reactive power transferred by CPT. There the primary and secondary capacity compensations are used on both sides of CPT transformer to reduce reactive power values.

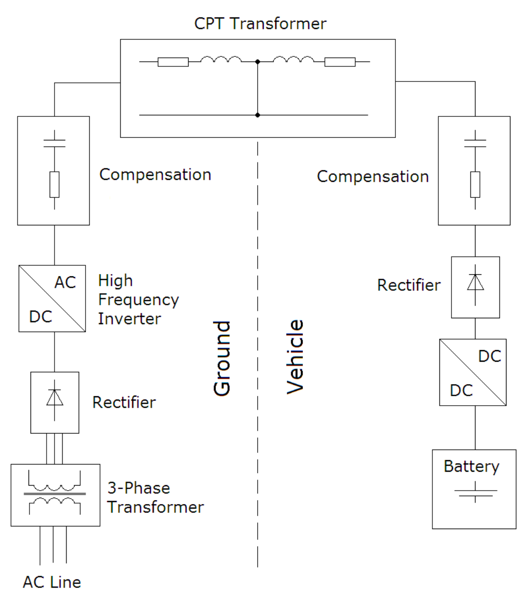

Figure 1: Scheme of basic CPT components.

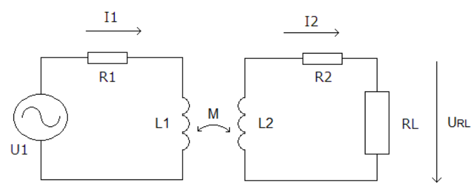

Figure 2: CPT transformer equivalent scheme.

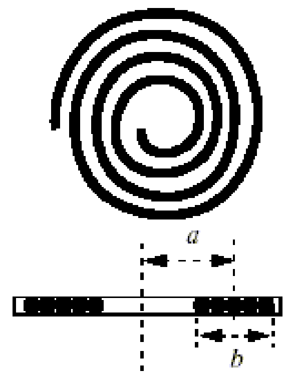

Figure 3: Spiral plate coil parameters.

2.1. CPT Transformer Parameters

CPT transformer consists of two air coils with large gap. Magnetic flux in CPT is transferred in air and doesn't need magnetic core thus CPT transformer is lighter and has nearly no-load losses (magnetization losses are just in wires). Figure 2 shows the CPT transformer equivalent scheme.

Basic CPT transformer parameters are primary R_1 [Ω] and secondary R_2 [Ω] resistances, primary L_1 [H] and secondary L_2 [H] self inductances and mutual inductance M [H].

This article deals with CPT transformer created by two spiral plate coils which are used for induction heating. The spiral plate coil parameters are shown in Figure 3.

The spiral coil self inductance L is given by Equation (1):

$$L = \frac{(aN)^2}{8a + 11b} * 10^{-6} \text{ [H]} \tag{1}$$

where N is turns of coil, a [cm] is coil mean diameter and b [cm] is layer thickness.

The spiral coil mutual inductance M is given by Equation (2):

$$M = k_V \sqrt{L_1 L_2} \text{ [H]} \tag{2}$$

where k_V [-] is mutual bond factor.

CPT transformer resistance is given by Equation (3):

$$R = \frac{\rho N a}{\pi b^2} \text{ [}\Omega\text{]} \tag{3}$$

where ρ [Ω/m] is resistivity of coil wire.

Active power transferred by CPT is given by Equation (4):

$$P_2 = \frac{\omega_0 M^2 Q_S}{L_2} I_2 \text{ [W]} \tag{4}$$

where ω_0 is resonant operational frequency (angle velocity).

Impedance Z of CPT transformer is given by Equation (5):

$$Z = \frac{(\omega M)^2 + (R_1 + j\omega L_1)(R_L + R_2 + j\omega L_2)}{R_L + R_2 + j\omega L_2} \text{ [}\Omega\text{]} \tag{5}$$

CPT efficiency η is given by Equation (6):

$$\eta = \frac{R_L}{(R_L + R_2)\left(1 + \frac{R_1(R_L+R_2)}{(\omega M)^2}\right) + R_1\left(\frac{L_2}{M}\right)^2} \text{ [-]} \tag{6}$$

If condition given by Equation (7) is fulfilled the maximal efficiency $\eta_{\max}$ is given by Equation (8).

$$\frac{R_1(R_L + R_2)}{(\omega M)^2} \Rightarrow 0 \tag{7}$$

$$\eta_{\max} = \frac{R_L}{R_L + R_2 + R_1\left(\frac{L_2}{M}\right)^2} \text{ [-]} \tag{8}$$

2.2. CPT Capacity Compensation Parameters

From Equation (4) is evident that transferred active power depends not only on CPT transformer parameters but also on operational frequency and transformer quality Q_S. Reactive power has to be compensated to increase transferred active power value. There are four basic connection scheme of compensation used in CPT. They differ in capacitors connections. Most used capacity compensation is series-series (SS) shown in Figure 4. It can operate as a current source (first stage of battery charging) and a voltage source (second stage of battery charging).

The secondary capacity compensation value for compensated reactive power is given by Equation (9):

$$C_2 = \frac{1}{\omega_0^2 L_2} \text{ [F]} \tag{9}$$

The primary capacity compensation is given by Equation (10):

$$C_1 = \frac{C_2}{L_1 L_2} \text{ [F]} \tag{10}$$

3. CPT MODEL IN MAXWELL ANSYS

Equations mentioned in previous text are very simplistic and they don't conclude many factors that affect CPT operational parameters. These factors are for example electric vehicle construction parts, transformer coils misalignment and others.

CPT components arrangement in an electric vehicle is shown in Figure 5, which are 1 — Power supply, 2 and 5 — capacity compensation, 3 and 4 — CPT transformer air coils, 6 — DC Buck, 7 — Batteries, 8 — Driver, 9 — Electric motor.

All vehicle components have to be included in computing to achieve correct CPT operational parameters.

Maxwell Ansys is FEM analysis software that is able to compute electromagnetic field distribution in electric devices and display it. It is also able to compute basic electromagnetic and

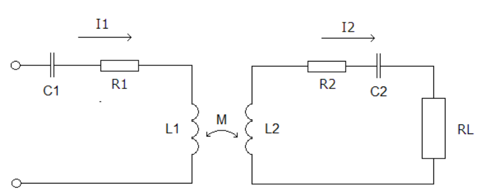

Figure 4: Scheme of SS capacity compensation.

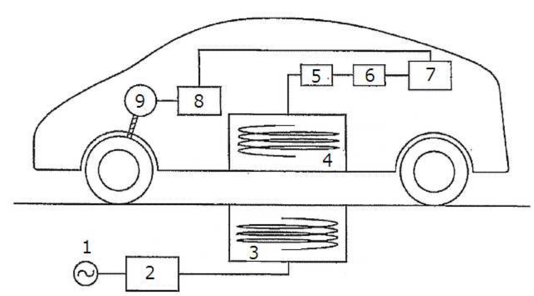

Figure 5: CPT components arrangement in an electromobile.

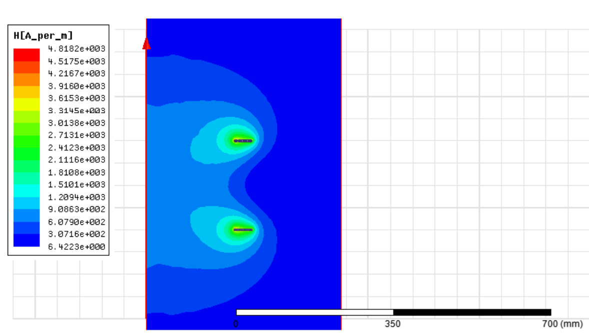

Figure 6: Two air coils CPT transformer magnetic field.

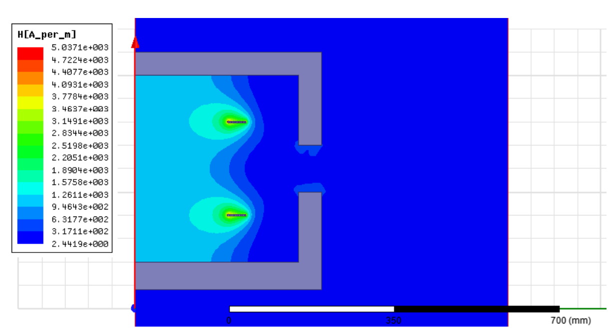

Figure 7: Shielded CPT transformer magnetic field.

mechanical parameters of electric devices. Some simulations of contactless power transfer was made in this software and obtained basic CPT parameters.

Figure 6 displays magnetic field in CPT transformer formed by two large gap air coils. This model is cylindrical around Z axis and current density value in wires is $2\,\mathrm{A/mm^2}$.

Magnetic field of shielded CPT transformer is shown in Figure 7.

These simulations and their results can be used for computing real CPT transformer parameters and its operational behavior.

4. COMPARISON OF CPT PARAMETERS OBTAIN FROM ANALYTIC EQUATIONS AND MODEL SIMULATIONS

Table 1 shows differences between CPT parameters computed by analytic equations described in first part of this paper and CPT parameters obtained by FEM analysis software Maxwell Ansys. It's calculated for two spiral coils with same physical parameters with air gap 20 cm. The CPT transformer operates at frequency 100 kHz.

Table 1: Calculated CPT parameters.

Parameter	Analytical computed	Maxwell Ansys
L_1 [μH]	246.6	147.1
L_2 [μH]	246.6	147.1
R_1 [Ω]	0.017	0.023
R_2 [Ω]	0.017	0.023
M [μH]	49.32	29.42

Spiral coils parameters are — number of turns 10, mean coil radius 20 cm, layer thickness 0.2 cm, air gap 20 cm and material copper and mutual bond factor $k_V = 0.2$.

5. CONCLUSIONS

In the previous paragraphs are described basic CPT operational parameters and how they can be computed by FEM analysis software. Data of CPT model simulations in this software are very useful for creating real CPT device for electric vehicle battery charging. It's possible to obtain basic CPT parameters such as inductances, impedances, operational frequency, capacitance of capacity compensation, magnetic field layout and others. Parameters obtained from basic analytic circuit equations don't include other construction parts in CPT environment. But CPT model simulations in FEM analysis software are able to obtain precious data. Maxwell Ansys is multiphysics software and is able to compute CPT electromagnetic compatibility and how it can affect its surroundings.

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