Calculating Power Loss of Contactless Power Transmission Systems with Ferrite Components

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Abstract: In this paper a methodology for calculating loss within contactless inductive power transmission systems, resulting from hysteresis and eddy current effects, is presented. The usage of the mathematical models of *Stoll* and *Steinmetz* for the determination of core loss with COMSOL (AC/DC module, application mode quasi-statics magnetic, time-harmonic analysis) is explained. Apart from the metrological verification of selected aspects of power loss, the results of a parametrical investigation, with reference to the optimization of contactless power transmission systems, are presented.

Keywords: Wireless power transmission, magnetic hysteresis, ferrite core loss, eddy current loss

1. Introduction

Contactless inductive power transmission for mobile and stationary devices is based on the transformer principle. This technology offers a number of advantages over contact-based power transmission systems due to the lack of mechanical wearing [1, 2]. Ferrite components are used for improving the magnetic coupling of coils separated by an air gap. Furthermore the transferable electrical power as well as the efficiency can be increased by using frequencies up to several hundred kHz [1, 2, 3]. Dimensioning of contactless power transmission systems is closely related to the optimisation in terms of transferable power, efficiency and heat development within the devices. Hysteresis and eddy-current-effects in ferrites and housings (consisting of electric conductive material) enlarge the energy dissipation of the overall system. These effects are enhanced by high frequencies. Therefore it is necessary to analyse the loss effects separately. The analysis will be presented by a typical inductive transmission system for rotary consumers for both transmitting power and information.

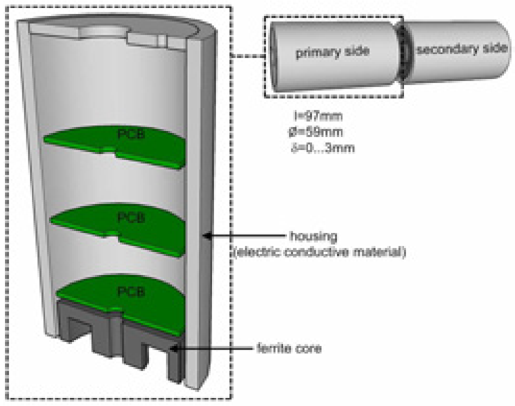

Figure 1: Schematic illustration of the considered transmission system [13]

Within this system, ferrite P-core halves are used for the coil arrangement. In terms of electromagnetic shielding, improvement of the degree of protection and as a mechanical interface, the system is surrounded by a metallic housing. The use of this elements result in losses due to magnetic hysteresis and eddy currents. Furthermore due to its construction, the allocation of the magnetic flux within the ferrites as well as the allocation of the current density within the electrically conductive material is inhomogeneous. For this reason and because of the use of materials with high permeability and due to large air gaps, analytic calculation methods are only valid at special constraints and operating conditions. For the determination of the magnetic field distribution as well as for the calculation of the power loss, the Finite-Element-Method by using COMSOL Multiphysics is suitable.

2. Loss sources of a contactless inductive power transmission system

To describe the transmission characteristic of a contactless power transmission system, the T-equivalent circuit (Figure 2) with the primary and secondary resistors of the winding R_1 and R_2, the leakage inductances $L_{1\sigma}$ and $L_{2\sigma}$ as well as the main inductance L_H can be used.

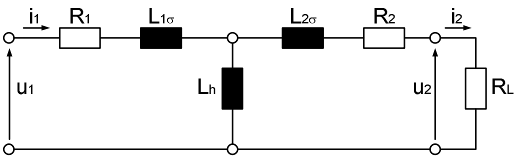

Figure 2: T-equivalent circuit of a contactless inductive power transmission system

The Joule´s loss (i^2R) includes the power loss caused by the ohmic D.C. resistance of the copper wire and the resistance caused by the skin and proximity effect. However the usage of ferrites and electrically conductive housings additionally requires a detailed analysis of the loss portions resulting from hysteresis and eddy current effects.

The core loss can be separated into the components hysteresis loss, eddy current loss and residual loss. Hysteresis loss can be regarded as the dominating part of energy dissipation. The portion of eddy current loss can be neglected due to the small electrical conductivity of ferrite material [3]. The residual loss, which mainly result from inertia of the ferrite material referring to the magnetization, is also negligible.

Eddy current loss arise in the electrical conductive housing or other electrically conductive structural elements of a contactless inductive power transmission system. By using technical relevant materials like aluminium or steel, the housing materials have significant electrical conductivity compared with ferrite materials. Due to the high frequencies of a contactless power transmission arrangement the eddy current loss within the housing represent a considerable portion of the total loss.

3. Loss models

The Joule´s copper loss is in proportion to the square of the winding currents i_1 and i_2 and can be calculated with the absolute value of the coil resistance. The determination of the hysteresis loss as well as the eddy current loss requires the knowledge of the magnetic flux density B and the current density J within the regarded material.

The area of the hysteresis loop of a magnetic material corresponds to the magnetization energy per unit volume, which is converted into heat.

$$W_{hys} = \oint H \cdot dB \qquad (1)$$

Multiplied by the frequency, the power loss density P_l/V (kW/m^3) result, which is a common information (e.g. typical data sheet information of ferrite manufacturers) for comparing ferrite materials. Thus mathematical models are of interest, which consider the hysteretic connection between the magnetic flux density B and the magnetic field strength H. There are physical models, which usually are based on the common models of *Preisach* and *Jiles-Atherton* [6, 7, 10]. Beyond that, there are the behavioural models of *Stoll* and *Steinmetz*, which are based on the properties of the core material. The calculation of core loss within the particular finite elements is made via the magnetic flux density B, which is directly calculated by the magnetic vector potential A (result of the COMSOL solver).

$$B = \mathrm{rot}(A) = \nabla \times A \qquad (2)$$

In order to be able to use time-harmonic solver, the computational effort can be reduced compared with transient solver. At time-harmonic solver, the dependence between the magnetic flux density B and the magnetic field H is assumed as linear.

The power loss per unit volume is determined by (3).

$$\frac{P_{l,c,n}}{V_n} = k \cdot f^{\alpha} \cdot B_n^{\beta} \qquad (3)$$

For using the *Steinmetz*-model the parameters k, α and β are necessary.

With the hysteresis loss angle φ_h and the effective permeability $\mu_{eff,}$ the parameters of the *Stoll*-model are [3, 9]:

$$\alpha = 1, \beta = 2 \text{ and } k = \pi \cdot \frac{\varphi_h}{\mu_0 \cdot \mu_{eff}} \qquad (4)$$

The required parameters for both procedures can be determined either directly or by systematic parameter variation on the basis of data sheet information. For the material Siferrit N27 (Epcos AG) an effective permeability $\mu_{eff} = 6631$ and a hysteresis loss angle $\varphi_h = 34.6°$ as well as the parameters $k = 0.065$, $\alpha = 1.18$ and $\beta = 2.11$ were determined. It has been proven, that the results of the *Steinmetz*-model with variation of flux density and frequency are more exact than the results given by the *Stoll*-model.

A methodology for calculating eddy current loss by means of FEM is presented in [11]. According to that, the determination of loss per unit volume can be done by (5).

$$\frac{P_{l,eddy,n}}{V_n} = \frac{1}{\sigma} \cdot \left(\frac{|J_{\varphi,n}|}{\sqrt{2}} \right)^2 \qquad (5)$$

The absolute value of power loss is determined by integration over the volume of the particular element V_n. In the next step the total power loss (core loss, eddy current loss) is calculated by summation of the power loss of all m finite elements.

$$P_{l,tot} = \sum_{n=1}^{m} \left(P_{l,c,n} + P_{l,eddy,n} \right) \qquad (6)$$

4. Simulation and experimental results

With the material-specific parameters of the loss models it is possible to calculate the power loss within arrangements of nearly arbitrary shape. Exemplary this will be demonstrated at the inductive power transmission system, which was mentioned before. Figure 3 shows the design of the transmission system in terms of an axis-symmetric sectional drawing.

Within the scope of the investigation, the geometrical parameters (Figure 3b) and the electrical conductivity of the housing material were subject of the investigation.

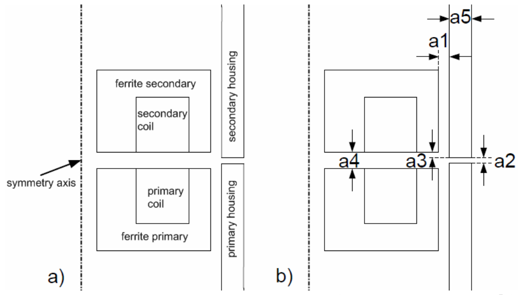

Figure 3: Transmission system; a) Arrangement, b) Definition of the geometrical parameters

4.1 Simulation of core loss and housing losses

In the following the results of a power loss analysis (f = 100 kHz) are presented. The value of the primary current was $N \cdot i_{pri} \approx 21 \cdot 2$ A. This corresponds to a transferred power of about $P_2 = 50$ W. Figure 4 shows the allocation of the power loss density determined by simulation, which is significant within the corner areas of the ferrites and near the housing surface. The power loss due to eddy current effects within the electrical conductive housing (aluminium, $\sigma_{housing} = 37.7 \cdot 10^6$ S/m) mainly arises in the internal area of the arrangement near the air gap.

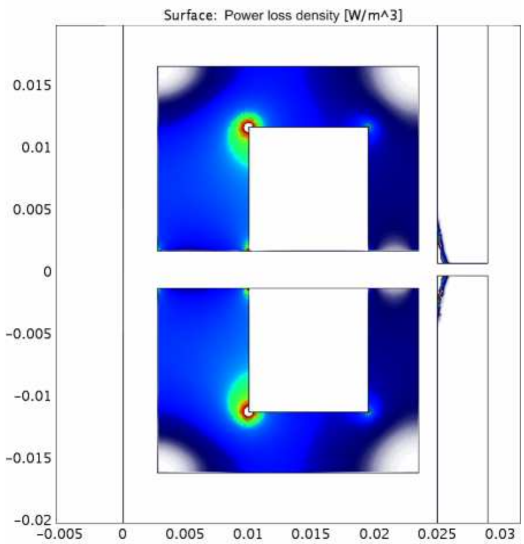

Figure 4: Regions with high power loss density

Figure 5 shows the ratio between the overall power loss and the input power. A good match of calculation results and measurement can be found. Deviations result from saturation effects and measurement inaccuracies. The amount of loss approximately complies with the ohmic losses of the windings.

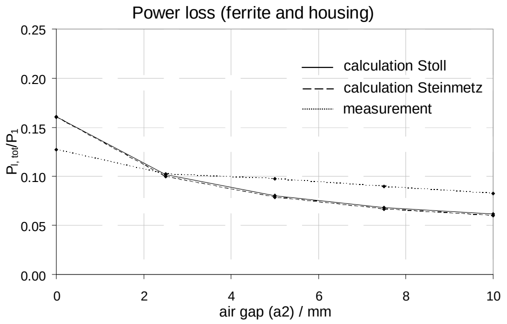

Figure 5: Total loss of the presented transmission system at air gap variation (P_2 = 50 W)

Because the total loss can amount over 10 % of the input power shows the necessity of power loss analysis during dimensioning of contactless transmission systems.

4.2 Parametrical investigation of the housing losses

On the basis of the metrological verified models, following the eddy current loss by variation of the total air gap is investigated. This represents a typical and important case at using contactless inductive power transmission systems. The valid parameters for investigating the influence of the variation of the air gap are listed in Table 1 (also see Figure 3). The parameters a2 and a4 w a typical inductive transmission system ere varied in the range of 0 … 10 mm.

Table 1: Geometrical parameters for investigation of the housing loss

parameter	value / mm
a1	2
a2	variable
a3	1
a4	variable
a5	4

Electric input:

$$f = 100\,\text{kHz}$$
$$N_{pri} \cdot i_{pri} = 50\,\text{A}$$
$$\sigma_{housing} = 37{,}7 \cdot 10^6 \frac{S}{m} \text{ (Aluminium)}$$

Figure 6 shows the eddy current loss $P_{l,\,eddy}$ as well as the values of the main inductance L_{H0} and the leakage inductance $L_{1\sigma0}$ (values at one winding). These values also can be determined by the field distribution [2] and can then be used to calculate the magnetic coupling coefficient k. At identical coil geometries the coupling coefficient is:

$$k = \frac{L_{H0}}{L_{H0} + L_{1\sigma0}} = \frac{L_{H0}}{L_{H0} + L_{2\sigma0}} \tag{7}$$

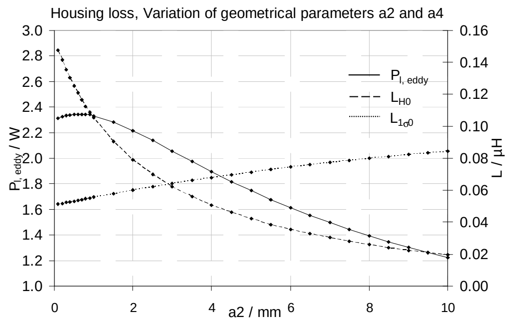

Figure 6: Housing loss and coupling parameters with variation of the geometrical parameters a2 and a4 (variation of the air gap)

Figure 7 shows the allocation of the magnetic flux within the arrangement as well as the power loss density within the housing material at different air gaps. The variation of the air gap results in a point of maximum power loss inside the housing. The allocation of the power loss density is closely related to the magnetic field distribution within the arrangement.

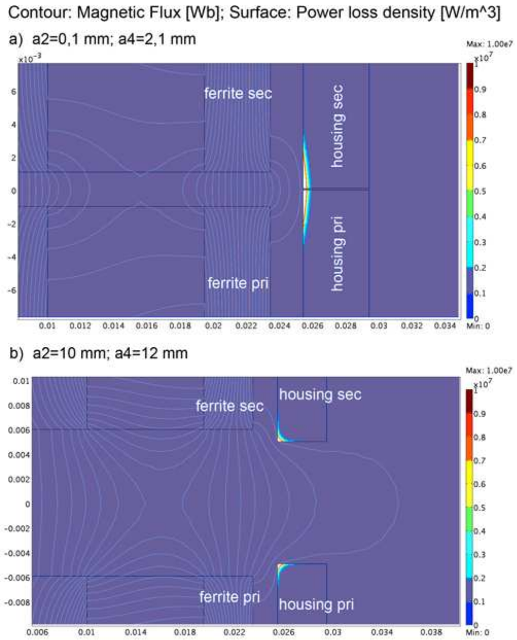

Figure 7: Eddy current power loss density within the housing at different air gaps

Hence the power loss mainly arises at the inner edges of the housing, in an area near the air gap the flux steps out of the ferrite material concentrated. Due to the constant distance between the edges of ferrite and housing material (parameter a3), the allocation of the power loss, even at large air gap, does not surpass the inner areas of the arrangement near the housing edges. The enlargement of the total air gap leads to a distinct decrease of the main inductance and an increasing leakage inductance. Hence in terms of good transmission characteristics and low power loss within the housings a small air gap is recommendable.

Further investigations regarding the housing loss were done by changing geometrical parameters (see Figure 3) and by variation of the electrical conductivity of the housing material. On the basis of simulation results of the considered transmission system it turned out, that with suitable selection of the geometrical parameters the power loss can be minimized. A small distance between ferrites and housings (parameter a1) results in a high eddy current loss, which decrease significantly already at a slight increase of the parameter a1. High power loss also arises at small air gaps. In that case the variation of the overlap of ferrite and housing (parameter a3) does not have a significant influence on the absolute values of the loss. When changing the total air gap the power loss reach a maximum level and then decrease at increasing air gap. At very large air gaps the difference between the amount of power loss of an arrangement with or without overlapping ferrites and housings is negligible. The thickness of the housing material (a5) does not influence the power loss as long as it is bigger or equal to the skin depth. Housing materials with a high electrical conductivity are advisable. Regarding to costs and processing effort aluminium represents the most interesting material.

5. Conclusion

Contactless inductive power transmission systems are afflicted with special power loss effects because of high transmission frequencies and permeable core materials. For calculating core and eddy current power loss the software COMSOL Multiphysics was used. To determine the core hysteresis loss of soft ferrite materials the models of *Stoll* and *Steinmetz* were implemented. The determination of loss within the housing material due to eddy current effects was directly made via Joule's law by using the current density and the electrical conductivity. With the FEM-solver the distribution of the flux density B and the current density J could be determined for special coil geometries. For the consideration of unequal elements, which are typical for the FEM, the power loss was first calculated as a loss per unit volume. After that the power loss of the particular elements was numerically summed up. For the calculation of power loss due to hysteresis effects within ferrites of arbitrary shape via the models of *Stoll* and/or *Steinmetz* it was first necessary to determine specific model parameters.

On the basis of the compiled methodology the power loss characteristic was investigated by means of a specific inductive transmission arrangement with ferrite core halves inside a metallic environment. The results of the numerical simulation were compared with measurement result. A good match could be found. Deviations result from saturation effects and measurement inaccuracies.

The investigation of the eddy current loss within the housing material was made via parametric simulation procedure. The selection of the specific parameters took place with reference to a special contactless power transmission system. On the basis of the theoretical view it was worked out, that by choosing suitable geometrical parameters the power loss inside the housing could be minimised. However the magnetic coupling of the transmission system is also affected. According to that the selection of the parameters must be done in many respects.

The developed methodology and the knowledge regarding to the influence of hysteresis and eddy current effects of ferrite and housing components of a contactless power transmission system, allows the systematically calculation of power loss during a computer-aided dimensioning procedure.

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7. Nomenclature

f	… Frequency
i	… Current
$N \cdot I$	… Magnetomotive force
J_φ	… Current density φ-component
σ	… Electrical conductivity
A	… Magnetic vector potential
W_{hys}	… Energy per hysteresis loop
B	… Magnetic flux density
H	… Magnetic field strength
R_1	… Ohmic resistance, primary coil
R_2	… Ohmic resistance, secondary coil
L_H	… Main inductance
$L_{2\sigma}$	… Leakage inductance primary side
$L_{2\sigma}$	… Leakage inductance secondary side
$P_{1,c}$	… Ferrite core loss
$P_{l,eddy}$	… Eddy current loss
$P_{l,tot}$	… Total loss
n	… Single finite element
m	… Number of finite elements
μ_0	… Magnetic constant
μ_{eff}	… Effective permeability
φ_h	… Hysteresis loss angle
k, α, β	… *Steinmetz* – coefficients
V	… Volume
FEM	… Finite element method