

Homogenization Methods in Simulations of Transcutaneous Energy Transmitters

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Abstract—Transcutaneous Energy Transmitters (TET) are usually devices composed of two pancake coils to transfer wireless energy through an inductive link from outside to inside the body of a patient. The simulation of the misalignment between the coils must be performed in 3-dimensions, e.g. with Finite Elements (FE). This paper introduces a homogenization method to minimize the expensive 3D FE computation in the frequency domain. Moreover, the meshing process of the non-homogeneous TET geometry is lightened. The results of this technique are compared with those obtained by considering regular stranded TET coils, showing improvements, mainly at kilohertz frequencies, the typical TET operating frequency range.

Index Terms— Approximation methods, Finite Element Methods, Inductive Power Transmission.

I. INTRODUCTION

Transcutaneous Energy Transmitters (TETs) are devices to transfer energy from outside the body to inside the body without the need of wires trespassing the skin. They use an inductive link between a primary coil, external to the body, and a secondary coil underneath the skin, similar to a coreless transformer [1]. In order to consider different distances and misalignments between the coils during the early design stages, Finite Element (FE) simulations could be performed. However, when solid massive conductors have to be detailed, a computationally expensive 3D FE model is required, mainly at high frequencies to precisely consider eddy current effects.

Considering that the TET design involves a wide frequency range with different wire gauge, the skin and proximity effects cannot be ignored and the commonly used stranded model is not accurate anymore. Such a stranded approach ignores these effects and estimates the losses a posteriori by computing them individually through, e.g. analytical approaches [2], [3]. However, the eddy current effects may significantly alter the performance of the TET. Thus, their direct inclusion in the FE simulations is mandatory, proving the need of dedicated homogenization methods. In the frequency domain, they usually amount to the use of complex frequency-dependent reluctivity and resistance values, the expression of which is obtained either analytically [4], or using an elementary FEM [5]. Several authors have presented homogenization methods in the frequency [5], [6] and time domain [7], [8], to study a multi-turn typical winding inductor with homogenized geometry. Others have used the method on 3D FE model with a magnetic core around the coil geometry [9].

In this paper, a homogenization method is applied to study the single layer coils from a coreless TET with a 3D FE model in the frequency domain. Results are compared with both the stranded approach and experimental measurements, showing that the homogenization method is very reliable even for single layer pancake coils, where the geometry is not homogeneous.

II. METHODOLOGY

In the frequency domain, skin and proximity effects can be characterized by adopting a complex permeability (or reluctivity). These two effects are decoupled in the following complementary cases: net current $I \neq 0$ when induction field $B = 0$ (skin effect); and $B \neq 0$ with $I = 0$ (proximity effect). Then, the associated losses are simply added. Hence, the important quantities for the method are the net current in the conductors, I , and the two components of the average induction, $\{B_x, B_y\}$.

This method characterizes the general skin and proximity effect of the winding by a representative FE model consisting of a wire and air around it. Hence, two steps are necessary to simulate the system. First, this representative FE model is simulated in three situations (with $\{I, B_x, B_y\}$ equal to $\{1, 0, 0\}$, $\{0, 1, 0\}$ and $\{0, 0, 1\}$) at a wide frequency range. At each frequency, three elementary solutions are obtained and the complex power absorbed by the representative wire computed. The first case allows determining a complex impedance Z_{skin} due to skin effect, while the two last allow to compute a complex and frequency dependent reluctivity tensor ν_{prox} that accounts for proximity effects [6].

In order to detail the way to obtain Z_{skin} and ν_{prox} , a unitless parameter X , referred as reduced frequency is defined by

$$X = r/\delta = \sqrt{f \cdot r \cdot \pi \cdot \sigma \cdot \mu_0}. \quad (1)$$

with r , the radius of the conductor, $\delta = \sqrt{2/(\sigma \cdot 2 \cdot \pi \cdot f \cdot \mu_0)}$, the skin depth, f , the frequency, σ , the conductivity of the conductors and μ_0 , the free space permeability.

The complex impedance $Z_{skin}(X)$ can then be calculated as:

$$Z_{skin} = \frac{S_{skin}}{\frac{1}{2} \cdot I^2} = p_I(X) R_{DC} + i \cdot q_I(X) \omega \cdot \frac{\mu_0 I}{8 \cdot \pi \cdot \lambda}. \quad (2)$$

In (2), $R_{DC} = l/(\sigma \cdot S)$ is the direct current (DC) resistance of the conductor. The factor $(\mu_0 I)/(8 \cdot \pi \cdot \lambda)$ in the imaginary part of (2), usually negligible, is in fact the DC inductance of a round

conductor (internal field only). The dimensionless factors p_I and q_I depend on the winding type and the reduced frequency X . As evidenced in [6], the skin-effect losses and the coefficient are practically independent of the fill factor.

By imposing a zero net current and a unit average horizontal induction, a pure proximity-effect flux pattern is produced in the central cell. The same happens by imposing a unit average vertical induction. The tensor v_{prox} is given by the corresponding complex reluctivity calculated at both situations (horizontal and vertical induction). In the case of round conductors and a symmetric representative cell, the tensor becomes a scalar and it reads:

$$v_{\text{prox}} = q_B(X)v_0 + i.p_B(X)\omega \frac{\lambda \cdot \sigma \cdot r^2}{4}. \quad (4)$$

In (4), $\omega \cdot \lambda \cdot \sigma \cdot r^2 / 4$ follows from the analytical expression for low-frequency proximity losses [4]. The dimensionless factors q_B and p_B for induction are calculated from the energy absorbed by the cell. In this way, a group of curves is attained for the six dimensionless but frequency-dependent factors p_I and q_I , and q_B and p_B (note that in the general case both x and y directions need to be considered). Thus, Z_{skin} and v_{prox} can be estimated by the interpolation of these curves at the frequency considered in the complete TET device. The complete TET geometry is then simulated without the fine discretization of the solid wires to include the skin depth. That means the windings are simulated as stranded conductors in which a uniform current density, with the number of conductors and the overall surface area, is adopted. Afterwards, at the terminal voltage of the winding in the electrical circuit equation, the DC resistance has to be replaced by a component with impedance Z_{skin} and v_{prox} , defined in the mentioned simulated curves.

III. RESULTS

In order to prove that this method works well for 3D FE simulations in a frequency domain and to check the advantage of this method, a TET configuration containing wire gauge of 0.8 mm was tested with laboratory measurements and simulated with five different methods in an Intel Core i7 processor with 12 GB of internal memory running Windows 7.

Each method performed a new mesh and 4 simulations for 90 different frequencies, considering the coils aligned in:

- 1) 2D axisymmetric with massive conductors (1 hour);
- 2) 2D with stranded windings (25 minutes);
- 3) 2D with the homogenization method (11 minutes);
- 4) 3D with the homogenization method (7.2 hours); and
- 5) 3D with stranded windings (14.35 hours).

Fig. 1 shows the impedance (real and imaginary) of the primary coil aligned at 5 mm from the secondary coil at no-load, comparing the these situations. Note that the results obtained from the simulations stranded (2 and 5) start diverging from the reference at few dozen of kilohertz. When using homogenization (3 and 4), the results follow the measured reference tightly even better than the simulation that considers massive solid conductors (simulation 1). Thus, the proposed method for 3D in frequency domain proves to work well even in situations where the coil has a planar geometry.

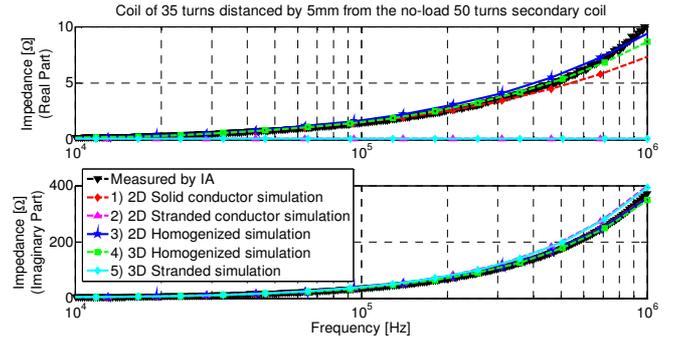


Fig. 1. Impedance (real and imaginary part) of the primary coil containing wire gauge of 0.8 mm aligned at 5 mm from the secondary coil at no-load.

There are situations where the 2D simulations cannot be used, such as when the coils are misaligned. In this condition, this paper compares 3D simulations considering stranded windings and the homogenization method with physical measurements, showing that this method is still reliable.

IV. CONCLUSIONS

The use of homogenization methods in FE is shown as an excellent approximation to minimize the computational cost of a dense mesh in 3D FE simulations without losing important effects such as skin and proximity effects. In this way, a TET that must be simulated in 3D can be simulated with simple stranded windings associated with the homogenization technique to decrease the simulation time.

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