Homogenization Methods in Simulations of Transcutaneous Energy Transmitters

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Transcutaneous Energy Transmitters (TETs) transfer wireless energy through an inductive link established between two pancake coils placed, respectively, outside and inside the body of a patient. The simulation of the misalignment between the coils must be performed in three dimensions (3D), e.g., with a Finite Element (FE) method. This paper introduces a homogenization method to minimize the cost of the expensive 3D FE computation in the frequency domain. Its originality lies in the non-homogeneous TET geometry during the meshing process. The results of this technique are compared with those obtained by considering regular stranded TET coils. They showed improvements mainly at kilohertz frequencies, the typical TET operating frequency range.

***Index Terms*— Approximation Methods, Finite Element Methods, Inductive Power Transmission, Proximity effect.**

I. Introduction

Transcutaneous Energy Transmitters (TETs) are devices that 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 would be required, mainly at high frequencies, to precisely account for the eddy current effects.

Considering that the TET design involves a wide frequency range with different wire gauges, the skin and proximity effects cannot be ignored and the commonly used stranded model (region with uniform current density averaged by the number of wires and the overall surface area) is not accurate enough anymore. Such a stranded approach disregards these effects and estimates the losses a posteriori by computing them individually, e.g., through analytical approaches [2], [3]. However, the eddy current effects may significantly alter the performance of the TET. For this reason, the direct inclusion of these effects 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 impedance, the values of which are obtained either analytically [4] or numerically, e.g., via an elementary FE [5].

Several authors have presented two-dimensional (2D) homogenization methods in both frequency [5], [6] and time [7] domains. Three-dimensional (3D) simulations with homogenization methods have also been studied in frequency [8] and time [9] domains. This method has also been used in a 3D FE model of a coil with magnetic core [10], [11]. However, the mentioned researchers deal with the study of multi-turn windings in the abscissa (x direction) and ordinate (y directions), i.e. with a homogeneous distribution of cables.

In this paper, a homogenization method is used with a 3D FE model in the frequency domain to study the single-layer coils of a coreless TET similar to Fig. 1. For validation, the results of this study are compared with the results of the stranded approach and physical measurements.

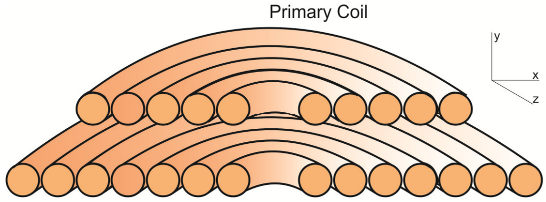

Fig. 1. Cross-sectional view of the coils of a single-layer coreless TET.

II. The Application Problem

As mentioned, other authors have applied homogenization methods on the FE models of coils with multi-turns typical winding inductors with several layers of wires in the abscissa and ordinate, i.e. both directions have homogeneity. On the other hand, as shown in Fig. 1, each TET coil has only one layer of turns, i.e. the turns are concentric and the centers of the wires are positioned in the same ordinate. Thus, this type of coils presents geometries with homogeneity only in the abscissa.

Fig. 2 shows the real (a) and imaginary (b) parts of the iso-values of the current density in the three innermost (left) and outermost (right) turns of the coils of a 2-D FE axisymmetric model of a TET. In this example, since the secondary coil has more turns than the primary coil, the three right turns of the secondary coil shown in Fig. 2 are not the outermost turns but

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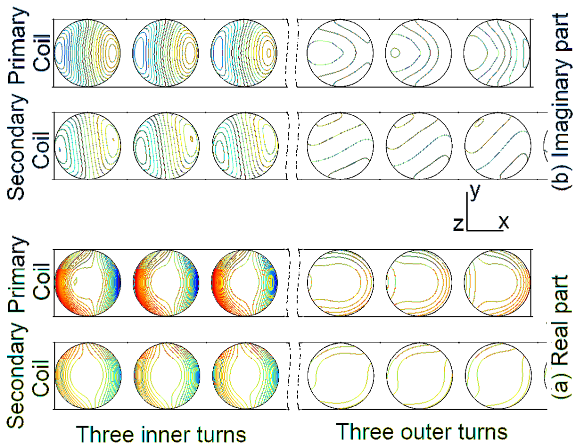

Fig. 2. 2-D FE model of axisymmetric TET obtained by FE software. The coils have wire gauge of 0.8 mm and are aligned at 5 mm distance. The primary coil is supplied with 12 V at 50 kHz. The secondary coil is at no-load.

the turns that have nearly the same abscissa of the three outermost turns of the primary coil. The iso-values resulted from a simulation of a 35-turn primary coil supplied by 12 V at 50 kHz and aligned with a 50-turn secondary coil without load, both with a wire gauge of 0.8 mm.

Observe that the iso-values of the current density in the primary coil are strongly concentrated in the inner turns. Moreover, even though the net current of the secondary coil is zero – since it has no load – this coil presents a small value of current density. This behavior pattern is not common on the geometries studied in previous researches [5]-[9]. Thus, this paper analyses the validity of the homogenization method for "pancake" coils.

III. Methodology

The homogenization method characterizes the general skin and proximity effect of the winding by a representative FE model consisting of only one wire surrounded by air.

In the frequency domain, the eddy current effects can be characterized by adopting complex skin-effect impedance in the electric circuit and complex proximity-effect permeability (or reluctivity) in the homogenized winding volume [6], [7]. The values of these parameters are determined by simulations of a representative FE model. Taking advantage of the spatial orthogonality between the net current in the inductors (complex representation *I*) and the transverse magnetic induction (complex representation *B*), two decoupled effects are identified and the associated losses are simply added: the skin effect ($I\neq0$ and $B=0$) and the proximity effect ($I=0$ and $B\neq0$). Hence, the key quantities of the method are *I* and the two components of $B=\{B_x, B_y, 0\}$.

Thus, the full characterization of the winding requires solving the representative FE model in three situations: $\{I, B_x, B_y\}$ equal to {1,0,0}, {0,1,0} and {0,0,1} for a wide range of frequency [6]. In order to simplify the equations, a non-dimensional parameter *X*, denoted as reduced frequency, is defined as:

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

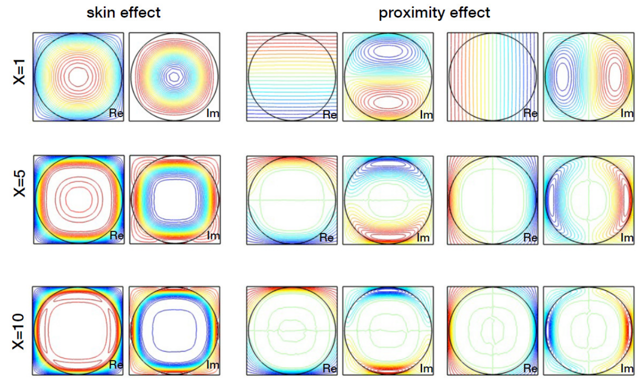

Fig. 3. Elementary flux patterns obtained by FE software for skin (left) and proximity (right) effects at different reduced frequencies (*X*).

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

Fig. 3 shows some solutions obtained with this representative FE model in all three situations for three different reduced frequencies (*X*). Note that, as the frequency increases, the flux pattern is less homogeneous with flux lines concentrating near the boundaries.

The three elementary solutions and the complex power absorbed by the representative wire are computed at each frequency. The first solution ($\{I, B_x, B_y\}=\{1,0,0\}$) allows the determination of a complex impedance $Z_{skin}(X)$ due to skin effect:

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

in which the non-dimensional factors p_I and q_I depend on the winding type and on the reduced frequency *X*, as explained in [6], and $R_{DC}=l/(\sigma.S)$ is the direct current (DC) resistance of the conductor. The factor $(\mu_0.l)/(8.\pi.\lambda)$ in the imaginary part of (2), usually negligible, is in fact the DC inductance of a round conductor (only internal field). As evidenced in [6], the skin-effect coefficient is practically independent of the fill factor, as well as the losses.

By imposing a zero net current and a unit average horizontal or vertical induction ($\{I, B_x, B_y\} = \{0,1,0\}$ or $\{0,0,1\}$), a pure proximity-effect flux pattern is produced in the central cell. The frequency-dependent complex tensor υ_{prox} is then fully determined. In the case of round conductors, the representative cell is symmetric and the tensor reduces to a scalar.

$$\upsilon_{prox} = q_B(X).\upsilon_0 + i.p_B(X).\ \omega.\lambda.\sigma.r^2/4 \quad (3)$$

In (3), $\omega.\lambda.\sigma.r^2/4$ follows from the analytical expression for low-frequency proximity losses [4]. The non-dimensional factors q_B and p_B for induction are calculated from the energy absorbed by the cell, as detailed in [6].

In this way, a set of data is attained for the six non-dimensional (but frequency-dependent) factors p_I and q_I, and

q_B and p_B (note that in the most general case both x and y directions need to be considered). Thus, Z_{skin} and υ_{prox} can be estimated by the interpolation of these data at the considered frequency during the simulation of the TET device.

Next, the complete TET geometry is simulated with the windings considered as stranded inductors, i.e. without the fine discretization of the solid wires to include the skin depth. Then, the homogenization approach is adopted by: 1) replacing the DC resistance with the skin-effect impedance Z_{skin} at the terminal voltage of the winding in the electrical circuit; and 2) using the proximity-effect reluctivity υ_{prox} in the homogenized volume.

IV. Results

In order to validate and illustrate the advantages of using the above described homogenization method in 3D frequency domain FE simulations, three TET configurations were tested with physical measurements and simulated in an Intel Core i7 processor with 12 GB of internal memory running Windows 7. The following TET configurations were considered:

1) Primary coil with 35 turns, secondary coil with 50 turns, both coils with wire gauge of 1.45 mm;

2) Primary coil with 62 turns and wire gauge of 0.9 mm, secondary coil with 24 turns and wire gauge of 0.4 mm.

3) Primary coil with 24 turns and wire gauge of 0.4 mm, secondary coil with 62 turns and wire gauge of 0.9 mm.

With the coils aligned, this research performed 5 different simulations at 90 different frequencies in the range [10^4, 10^6] Hz. A new mesh was generated for each new simulation and frequency. The list of the acronyms of the considered FE models and their computational time is following:

1) 2DM: 2D axisymmetric with massive conductors (1 h);
2) 2DS: 2D with stranded windings (25 min);
3) 2DH: with the homogenization method (11 min);
4) 3DH: with the homogenization method (7.2 h); and
5) 3DS: with stranded windings (14.35 h).

Fig. 4 analyzes the first TET configuration with coil gap of 5 mm, showing the real and imaginary impedance (Z) of the primary coil aligned with the no-load secondary coil.

Note that the results obtained from the stranded simulations (curves 2 and 5) start diverging from the reference at few dozen kilohertz. In fact, the skin depth of round copper conductors at 10 kHz is 0.66 mm, which is nearly the size of the radius of the conductor. When using the proposed homogenization method (curves 3 and 4), the results follow the measured reference tightly even for higher frequencies.

An analogous behavior is observed for the second and third TET configurations, shown in Fig. 5 and Fig. 6. For these configurations, the stranded simulation starts diverging from the reference at around 80 kHz and 40 kHz, respectively. At these frequencies, the skin depths of the round copper conductors are respectively 0.23 mm and 0.33 mm, which are comparable to the radii of the respective conductors.

The resonant frequency due to capacitive effects is around 2.8 GHz, 2.4 GHz and 12 GHz for the first, second and third TET configurations, respectively. The FE magnetodynamic models used disregard these capacitive effects. That is the

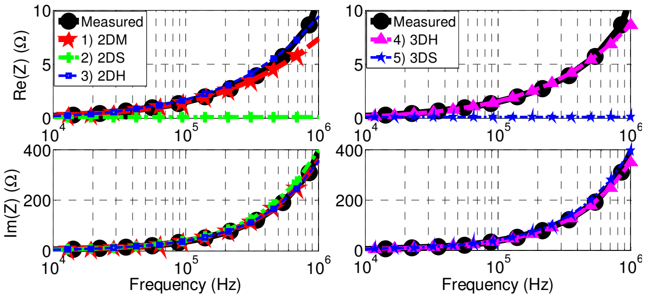

Fig. 4. Impedance (Z) of the primary coil aligned with the no-load secondary coil with 5 mm of coil gap (first TET configuration).

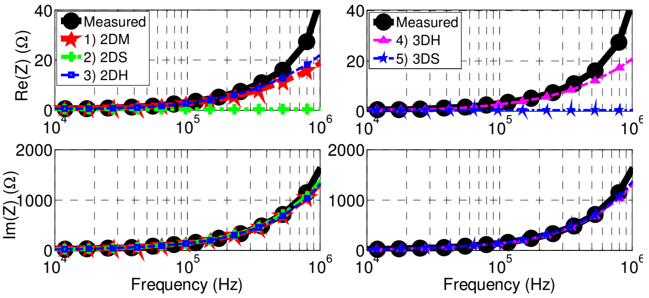

Fig. 5. Impedance (Z) of the primary coil aligned with the no-load secondary coil with 5 mm of coil gap (second TET configuration).

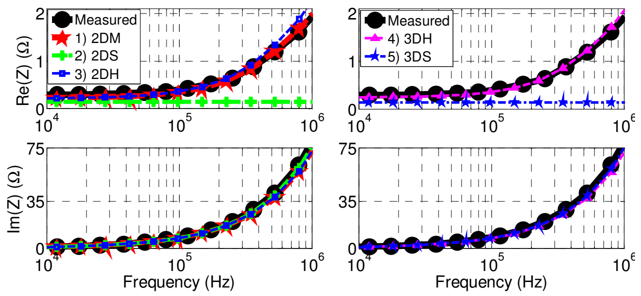

Fig. 6. Impedance (Z) of the primary coil aligned with the no-load secondary coil with 5 mm of coil gap (third TET configuration).

reason why, in Fig. 5, the solid conductor and homogenized simulations (curves 1, 3 and 4) start diverging from the measurement data for frequencies above 350 kHz.

From the aforementioned data, one could say that the 2D model is faster than the 3D model for the same accuracy. However, there are situations where the 2D model cannot be used, such as when the coils are misaligned.

This paper analyzes the 3D method of the coils misaligned at different distances in two coupling situations. In both situations, the coils were electrically connected in series. For the first situation, the coils were positioned such that the flux of the first coil was in the same direction as the flux of the second coil. For the second situation, the flux of the first coil opposed the flux of the second coil.

Fig. 7 and Fig. 8 compare the 3D simulations of stranded windings and the homogenization method with physical measurements of the first TET configuration at 105 kHz, showing that the homogenization method is still reliable.

It is noteworthy that the coils of the first TET configuration were difficult to assemble and the turns were not precisely positioned in the same ordinate. However, the simulations were performed as if the turns were all precisely allocated. This may be the reason why there is a very small difference between the impedance measured and simulated with the homogenization technique in the first set of coils in Fig. 7. Since the windings in the second and third TET configurations were better assembled and all their turns were in the same ordinate, the mentioned error of Fig. 7 is minimized, as shown in Fig. 9 and Fig. 10.

Since the second and third TET configurations have the same coils with different order, the mutual impedance, when connected in series, presents the same behavior. Thus, the comparison between the 3D simulations at 213 kHz is shown

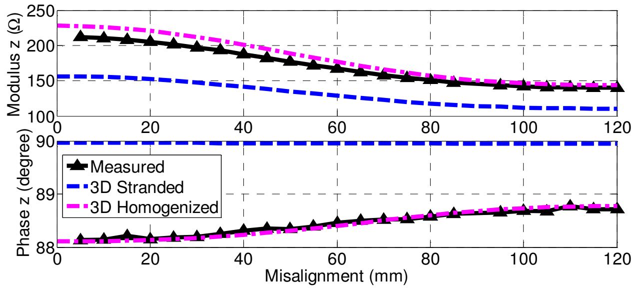

Fig. 7. Impedance of the first TET configuration with the coils in series, separated by 10 mm at different conditions of misalignment. Coils positioned such that the flux of one coil complements the flux of the other coil.

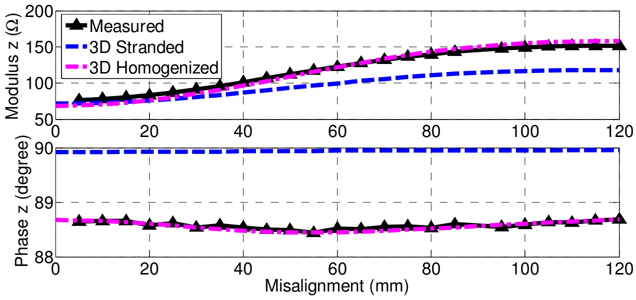

Fig. 8. Impedance of the first TET configuration with the coils in series, separated by 10 mm at different conditions of misalignment. Coils positioned such that the flux of one coil opposes the flux of the other coil.

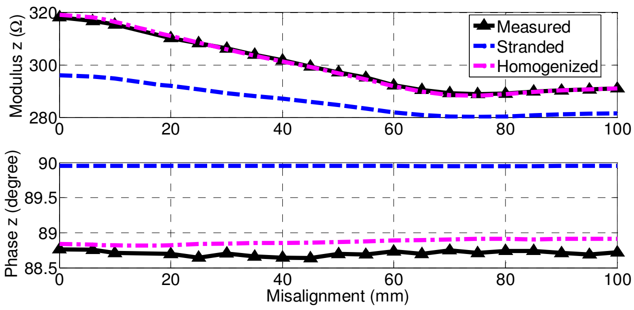

Fig. 9. Impedance of the second TET configuration with the coils in series, separated by 5 mm at different conditions of misalignment. Coils positioned in a way that the flux of one coil complements the flux of the other coil.

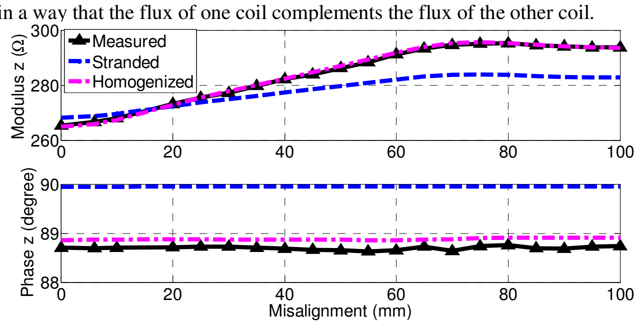

Fig. 10. Impedance of the second TET configuration with the coils in series, separated by 5 mm at different conditions of misalignment. Coils positioned in a way that the flux of one coil opposes the flux of the other coil.

only once in Fig. 9 and Fig. 10. Note that, for the stranded case, the impedance phase remains very close to 90^o for every TET. However, for the homogenization case, the phase follows the measured values with a very small error for all misalignments. This error is probably due to the mesh of the stranded conductors in the complete geometry. Since we have one thinner coil with wire gauge of 0.4 mm, the mesh of the geometry should be finer, what is difficult to achieve.

Thus, the proposed frequency domain 3D method provides very accurate results even for coils with a planar geometry.

V. Conclusion

The use of FE homogenization methods provides an excellent approximation for accurately accounting for eddy current effects, while minimizing the computational cost linked to a dense 3D FE mesh. In this way, a TET that must be simulated in 3D can be simulated with simple stranded windings together with the homogenization technique to decrease the simulation time. The compared results showed that the homogenization method is very reliable even for single-layer "pancake" coils, where the geometry is only periodic and homogeneous in one direction.

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