Modeling coreless transformers with relative large wire gauge using an optimization method

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***Abstract*—Coreless transformers are used in several applications, operating in a large range of frequencies. In cases that the coils have relative large wire gauge compared with the skin depth, eddy currents can generate losses that must be included when modeling these devices. This work proposes a method that allows modeling this kind of phenomenon with lumped parameters using an optimization method that uses the Genetic Algorithm as solver. The whole method was designed in a generic way in order to allow the modeling of different types of electric equipment.**

***Index Terms*—Optimization, Equivalent circuits, Eddy currents, Electromagnetic devices.**

I. Introduction

Wireless energy transfer [1] is a subject widely researched nowadays. It is usually composed of two or more coils working together as a coreless transformer, operating in the frequency range of kilohertz. Hence, the modeling of such devices should represent physical phenomena such as the skin, proximity and capacitive effects, typical in high frequency systems. Moreover, when the coils of the device have relatively large wire gauge compared with the skin depth, the coupling between the two coils induces additional losses by eddy currents. In [2], the authors study an improved model calculated analytically for such transformer considering higher frequency, when the capacitive effects are important, but it does not consider the losses due to the eddy currents. This work proposes an alternative technique to identify parameters of a model for the coreless transformer considering all effects, including the additional losses by eddy currents. It uses an optimization method to promote the model of the studied device by using data supplied by simulations through a Finite Element Method (FEM) software. It was developed in a generic way in order to allow any kind of circuit to be identified. Finally, a particular case of coreless transformer with spiral pancake coils geometry, such as a transcutaneous energy transmitter device [3] was simulated to validate the method. In this case the capacitive effect could be neglected.

II. Experimental Method

A. *The optimization method*

The proposed modeling method consists in minimize an error function that compares the calculated input current of the simulated device and the input current of an adopted circuit (model). For that, measured and/or simulated results from different tests for the same transformer should be supplied. The optimization process searches for parameters to this specific model. The results of this circuit are then calculated to compare with the supplied data. It is expected that, by giving physical information about the problem with appropriate constraints, the optimization method will guide the problem to a reliable solution. The amplitude and phase of steady-state current will be computed and compared with an experimental value that contains information of different load conditions, such as no-load, short circuit and nominal load. The error due to amplitude is defined in (1) and the error due to phase defined in (2). The objective function is the error equation presented in (3) and it is a sum of phase and amplitude error in the three aforementioned load situations.

$$error_{amplitude} = \left(\frac{\left|\hat{I}_{model}\right| - \left|\hat{I}_{fem}\right|}{\left|\hat{I}_{fem}\right|} \right)^2 \quad (1)$$

$$error_{phase} = \left(\frac{\underline{\hat{I}_{model}} - \underline{\hat{I}_{fem}}}{\underline{\hat{I}_{fem}}} \right)^2 \quad (2)$$

$$error = \sum_{load\_type} \left(error_{amplitude} + error_{phase} \right)\Big|_{load\_type} \quad (3)$$

The current (Î) parts labeled "model" is determined only by the chosen circuit and the parts labeled "fem" is the reference given by the FEM simulation. Therefore, the error function depends on the circuit parameters which will be adjusted to fit data simulation. As will be shown in the next sessions, the ranges of values of the circuit parameters, which are the variables of the optimization problem, are unknown. For this reason, the optimization is performed in two stages. First, the domain is searched by a stochastic algorithm in order to identify good initial values of the parameters. Although these types of algorithms never produce the same results, its advantage is that it has more chance to not get stuck in local minimums. Then, a deterministic algorithm is used in a refinement stage. In this work the Genetic Algorithm [4] was used to find a global solution and then a deterministic method [5] is performed to refine the solution. In [6], the authors propose a method of modeling transformers using several optimization methods, analogously the method used in this work.

B. *Choosing a circuit model*

The equivalent circuit model must be chosen in a way that every important physical phenomenon is represented. It is known that, in the kilohertz range, the particular device has negligible capacitance effects [2], but proximity and skin effect may be important depending on the wire gauge. When the coils consist of relative large wire gauge, another important effect appears: complementary losses due to eddy currents have strong effect in the equipment performance and should also be modeled. A standard complete equivalent circuit of a coreless transformer models the usual physical phenomena of joule effect on copper and mutual and dispersion flux on the coils. This circuit should be improved to also contemplate another kind of effects, which depends on the frequency value. It is expected that the series resistances (r_1 and r_2') change due to combination of skin and proximity effect, making these parameters frequency dependent. The series inductances (L_1 and L_2') and magnetization inductance (L_M) should change as well. Concerning the eddy current on large wire gauge coils, it is proposed that a resistance (r_p) in parallel with the magnetization reactance should model this effect, just like a core losses resistance of a standard transformer; both effects have similar physical significance. The value of the resistance r_p is usually very large at coreless transformers, but in some cases, when the wire gauge is large, this parameter plays an important role. Therefore, the circuit model should consist of six parameters, analogous to the complete circuit of a standard transformer but with more complex circuit elements, as shown in Fig. 1.

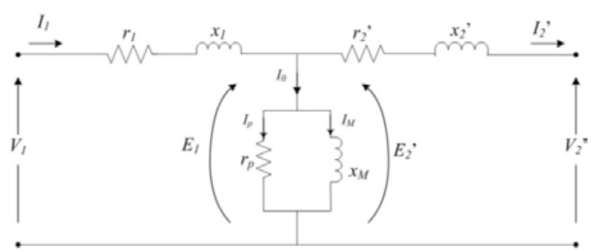

Fig. 1. The Adopted Circuit Model

C. Device simulation and estimative of initial parameters

The simulation of the device was performed by using a FEM software with magnetodynamic formulation and thus, it does not consider the capacitive effects. The mesh was highly discretized to well describe the proximity and skin effects.

The first estimation of the parameters has great importance because it allows defining a good domain of search for the optimization. Thus, three tests were simulated to define the first evaluation of r_1, r'_2, x_1, x'_2 and x_M. The first and second tests were performed with each individual coil electrically and magnetically uncoupled from the other coil to determine their resistance and self-inductance by connecting each to a voltage source. For the third test, the first coil was magnetically coupled to the second coil (aligned with a small distance between them) and electrically connected to a voltage source to determine the mutual-inductance.

This first estimative is useful to determine the lower and upper bound of only these five parameters. However, the great challenge is that the value of r_p was still unknown at that time. In order to estimate a good value for this parameter and find the best fit for the initial circuit, a sensitivity analysis was made by varying this resistance value in a large domain. After finding the best r_p, these six initial value parameters were the input data of the search algorithm through optimization method and they were optimized in conjunction to model the device.

III. RESULTS

In order to validate the method, a simulated transcutaneous energy transmitter, was tested in different configurations of wire gauges (AWG 5 to 32), number of turns (20 to 65) and frequencies (50 and 100 KHz). In the cases that the wire gauge was relatively small, the inclusion of r_p was not relevant, i.e., the initial values of the others parameters and the algorithm are sufficient to well model the equipment. However, in the cases of medium and large wire gauge, the sensitivity analysis of r_p shows that exist better parameter values that models the equipment. Fig. 2 shows the behavior of the relative error in nominal load when changing r_p in a range of 0.01 to 50 ohm (the abscissa axis is in logarithm scale), in the case of large wire gauge (AWG 5). Note that, for this specific configuration, if the parallel resistance is not used, i.e. has high value, the error increases. However, if r_p equals to 9 ohms is considered in the model, then the error of the nominal load presented by the model is around zero.

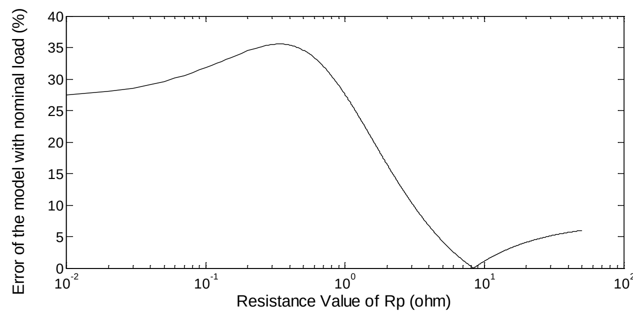

Fig. 2. Error of the model when changing the value of r_p

IV. CONCLUSION

The tests on the particular equipment show that the proposed method can model the losses by eddy current in relatively large gauges. The proposed method, in the way that it was created, can be a tool to model any kind of electric equipment, given that an equivalent circuit synthetize the physical phenomena and good chosen input currents or voltages could be previously measured or simulated.

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