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► **To cite this version:**

Kaoutar Hazim, Guillaume Parent, Stéphane Duchesne, Christophe Geuzaine. A Circuit Model Accounting for the Frequency-Dependent Behavior of Electrical Machine Windings. 24th International Conference on the Computation of Electromagnetic Fields (COMPUMAG), May 2023, Kyoto, Japan. hal-04114183

HAL Id: hal-04114183

<https://hal.science/hal-04114183>

Submitted on 5 Jun 2023

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A Circuit Model Accounting for the Frequency-Dependent Behavior of Electrical Machine Windings

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This paper presents a method to take into account, in a circuit model, the frequency-dependent behavior of electrical machine windings. First, the frequency-dependent inductances (both self and mutual) and resistances are determined thanks to time harmonic finite element (FE) computations in the frequency range of interest. The frequency-dependent behavior of the capacitances is investigated and the choice of using an electrostatic model is justified. Then, the different frequency-dependent parameters are included in a circuit model using behavioral voltage sources placed in series, which allows to forego delicate fitting techniques. A test winding with 69 turns is used for validation of the proposed method. An excellent agreement between experimental and simulation results is observed in the frequency domain. Time-domain node voltages can be computed by an Inverse Fast Fourier Transform after reducing the circuit to the nodes of interest, which enables the usage of the proposed method as a diagnostic tool before or during the phase of electrical winding design.

Index Terms—Finite element method (FEM), frequency-dependent parameters, frequency-domain simulation, time-domain simulation.

I. INTRODUCTION

The new generation of semiconductor devices imposes high steep-fronted voltages, which ends up generating intense inter-turn electric fields in the winding of electrical machines. When these high electric fields exceed the partial discharge inception voltage, partial discharges occur. The latter may result in an inter-turn local fault, which increases the thermal stress that electrical machines have to withstand. Accordingly, an expansion of the local fault followed by an eventual premature breakdown of the machines can take place. Thus, the need of a well parameterized model of the winding of machines that will serve as a predictive diagnostic tool. Appropriately, the electrical field stress can be computed from the predicted voltage distribution and the probability of the occurrence of partial discharges can be determined using, for instance, Paschen's law [1]. In previous research works [2]–[4], a phenomenological lumped parameter circuit (LPC) of the winding of electrical machines was presented. Nonetheless, the values of the elements of the LPC were computed at a single frequency regardless of their frequency-dependent behavior. This paper presents a method to take into account the frequency-dependency of these elements—including the different couplings between turns—in both frequency-domain and time-domain. The originality of the proposed method lies in the fact that unlike other methods [5] it does not need fitting techniques, which are notoriously difficult to make robust.

II. CIRCUIT MODEL

In previous works [2,3], the phenomenological elementary cell presented in Fig. 1 was used to model the turns of the winding. It allows to represent each of the occurring physical phenomena (resistive, inductive and capacitive) within the winding of the machine using an electrically passive component. Iron losses, Joule losses and dielectric losses are

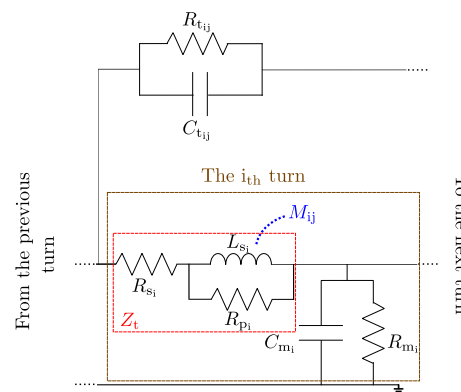


Fig. 1. The elementary cell of one turn of the winding of the machine [3].

modelled using resistances R_{p_i} , R_{s_i} , $R_{t_{ij}}$, and R_{m_i} , respectively. The appearing electromotive force across each turn 'i' is modeled using an inductance L_{s_i} , and the mutual inductive coupling with turn 'j' with M_{ij} . Finally, the capacitive coupling (turn-to-turn and turn-to-ground) is modeled using the capacitances $C_{t_{ij}}$ and C_{m_i} , respectively. Henceforth, the self impedance of the turns is referred to as Z_{t_i} .

However, using the elementary cell seen in Fig. 1, the frequency-dependent behavior of the parameters is neglected. In this work, we account for the frequency-dependency of these parameters without using any fitting techniques. The new elementary cell is depicted in Fig. 2, where the frequency behavior of the resistances, inductances as well as the different couplings between turns is taken into account using behavioral voltage sources placed in series. Those highlighted in red represent the frequency behavior of the self impedance Z_{t_i} , whereas those in blue model the couplings between turns. The intervention of the user to properly configure the fitting parameters is no longer needed, making the model automatic.

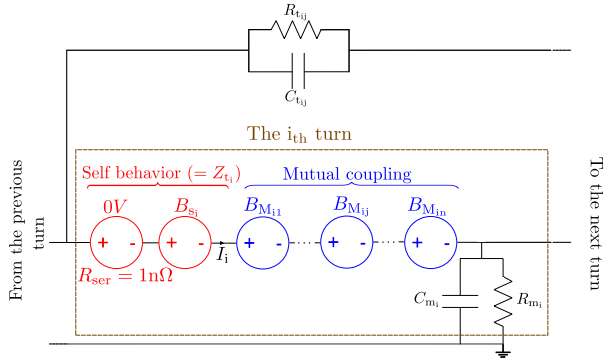


Fig. 2. The proposed frequency-dependent elementary cell .

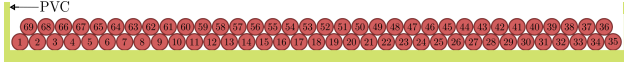


Fig. 3. Cross section of the 69 turns winding used for the experimental validation. (Only half of the cross section is shown, with the symmetry axis at the bottom.)

III. DETERMINATION OF THE CIRCUIT PARAMETERS

The values of the resistances and inductances (both self L_{s_i} and mutual M_{ij}) are computed over the frequency range of interest by means of magnetodynamic (magneto-quasistatic) finite element simulations. The frequency-dependent behavior of the capacitive coupling, i.e. $C_{t_{ij}}$, C_{m_i} , $R_{t_{ij}}$ and R_{m_i} , has been investigated experimentally. It was noticed that the frequency behavior could be considered constant, and is thus neglected. Hence, an electrostatic approximation is sufficient.

IV. FREQUENCY AND TIME-DOMAIN SIMULATION

After computing the different parameters in the frequency range of interest, they are stored in LTspice tables, that are later on called using behavioral voltage sources, where the circuit simulator takes care of the interpolation when needed. In Fig. 2, B_{s_1} contains the frequency-dependent values of $Z_{t_i}(f) = R_{s_1}(f) + jL_{s_1}(f)\omega$ modelling the self behavior of the turn, whereas $B_{M_{11}}$, $B_{M_{ij}}$ and $B_{M_{in}}$ contain the frequency-dependent values of the impedance coupling between turns: $R_{s_{11}}(f) + jM_{11}(f)\omega$, $R_{s_{ij}}(f) + jM_{ij}(f)\omega$ and $R_{s_{in}}(f) + jM_{in}(f)\omega$, respectively. Here, $R_{s_{11}}$, $R_{s_{ij}}$ and $R_{s_{in}}$ refer to the mutual resistances. The 0V voltage source, used as a current sensor, contains a $1n\Omega$ series resistance to avoid having parallel voltage sources. Hence, not only the frequency-dependency of the self behavior is accounted for, but that of the coupling between turns as well.

To experimentally validate the frequency simulations, a winding of 69 turns whose cross section is shown in Fig. 3 is used. The comparison of the model and the impedance measurements from 40 Hz to 110 MHz shows an excellent agreement over the entire frequency range.

To account for the frequency behavior of the parameters in time domain, we use the frequency-domain simulation to extract the reduced nodal admittance matrix on any node of interest. The circuit is thus reduced to the input node of the

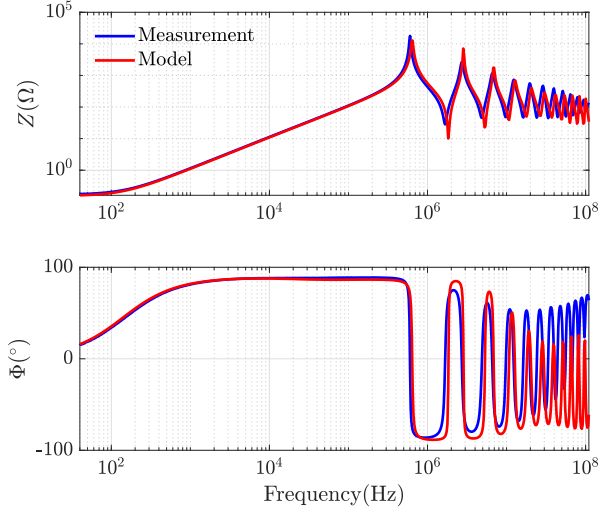


Fig. 4. Comparison of the proposed model and the measurement on the 69 turns test winding.

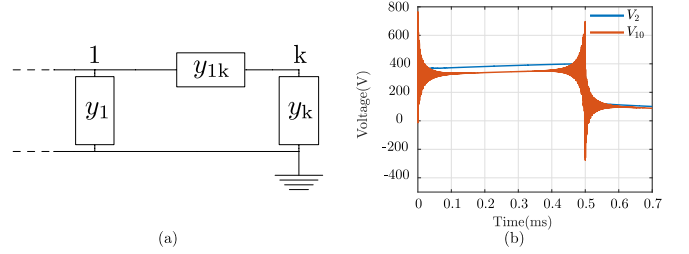


Fig. 5. (a) The equivalent circuit reduced to the node of interest k . (b) The time domain nodal voltages of nodes 2 and 10.

winding and the node of interest labelled k in Fig. 5(a). Deducing the spectrum of the node voltage $V_k(f)$ is straightforward as expressed in (1),

$$V_k(f) = V_1(f) \frac{y_k^{-1}}{y_k^{-1} + y_{1k}^{-1}}. \quad (1)$$

where $V_1(f)$ is the spectrum of the input voltage. Then an IFFT is applied to compute the time-domain voltage: $V_k(t) = \text{IFFT}(V_k(f))$. Time domain model results are presented in Fig. 5(b); their experimental validation will be discussed in the extended version of the paper.

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