Finite-Element Supported Transmission-Line Models for Calculating High-Frequency Effects in Machine Windings

Herbert De Gersem[1], Annette Muetze[2]
[1]Katholieke Universiteit Leuven, Wave Propagation and Signal Processing Research Group
Etienne Sabbelaan 53, 8500 Kortrijk, Belgium; herbert.degersem@kuleuven-kortrijk.be
[2]Graz University of Technology, Institute of Electric Drives and Machines
Inffeldgasse 18/I, 8010 Graz, Austria; muetze@tugraz.at

***Abstract*— Wave-propagation effects in machine windings are simulated on the basis of a transmission-line model where the parameters are calculated from finite-element models and analytical formulae. The laminated core, the end-winding parts and the wire cross-coupling are appropriately modelled. The simulation results indicate the necessity of these additions.**

I. Introduction

Insulated Gate Bipolar Transistors are switched at more and more high rates. Inverter and machine are sometimes positioned far from each other and connected by a long cable. The decreased wave length and increased system size cause wave-propagation effects to become increasingly important [1], [2]. At the considered frequencies, capacitive couplings between different machine parts are no longer negligible. Inverter-fed electric machines suffer from voltage surges which leads to an accelerated aging of insulation material, bearing currents and eventually break-down [3]. Further unwanted phenomena include but are not restricted to electromagnetic compatibility problems and triggering of protective circuits.

Commonly, transmission-line models (TLMs) are used to simulate wave-propagation effects in windings [4]. The parameters are determined on the basis of analytical formulae or computed from 2D finite-element (FE) models of the cross-section of a slot or the entire machine [5], [6]. Thereby, the parameters should be determined up to a sufficient accuracy according to the relevant frequency range [7]. This paper provides additional modelling techniques for dealing with particular geometric features of electric machines.

II. Extended Transmission-Line Model

The inductance matrix $\mathbf{L}$ follows from a 2D magnetostatic FE solution of the machine cross-section [8]. The capacitance matrix $\mathbf{C}$ is obtained from a 2D electrostatic FE solution or, together with the conductance matrix $\mathbf{G}$, from a 2D electroquasistatic FE solution in frequency domain. The resistance matrix $\mathbf{R}$ is diagonal and contains the resistances of the individual wires accounting for the eddy-current effect. The individual matrices are brought together in the impedance and admittance matrices $\mathbf{Z} = \mathbf{R} + j\omega\mathbf{L}$ and $\mathbf{Y} = \mathbf{G} + j\omega\mathbf{C}$, with ω the angular frequency (Fig. 1). The eigenvalue decomposition of $\mathbf{YZ}$ decouples the propagating modes. Each mode is characterised by a voltage and current pattern, propagating with a particular velocity and experiencing a certain characteristic impedance. The arrangement in a single winding, the winding scheme and the star or delta connection of the stator coils requires a further manipulation of the TLM model, finally leading to the impedance and admittance matrices $\mathbf{Z}_0$ and $\mathbf{Y}_0$.

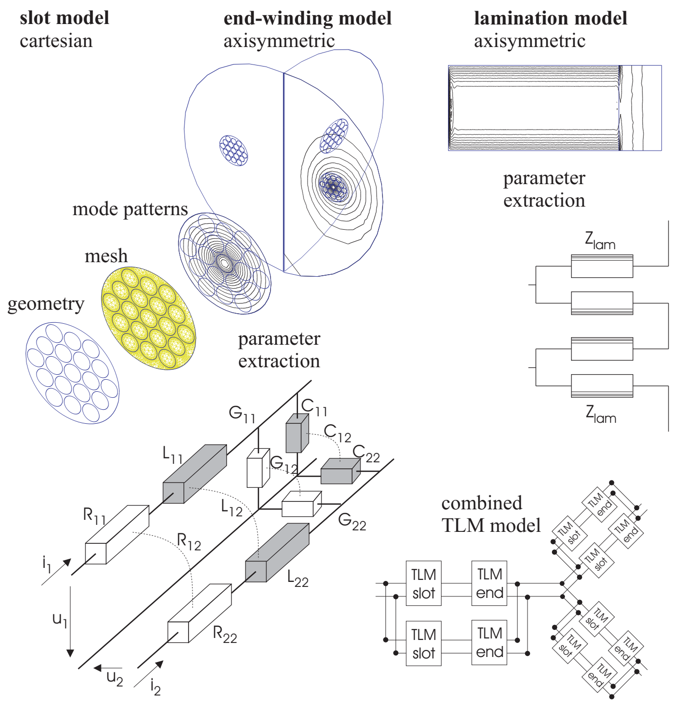

Fig. 1. FE-TLM calculation approach: FE model for the slotted winding part, FE model for the winding overhang and FE model for an individual lamination; multi-conductor transmission-line model for the exemplary case of 2 conductors and 1 return path; resistance $\mathbf{R}$, inductance $\mathbf{L}$, conductance $\mathbf{G}$ and capacitance $\mathbf{C}$ matrices (mutual effects indicated by dashed connection lines); circuit model for the stator core return path; winding scheme implemented with TLM model parts.

Several extensions of this model are needed in order to accommodate the fact that the windings are part of an electric machine.

- The assumption of an infinitely conductive return path has to be alleviated. In reality, the capacitive current closing through the yoke follows a path through the individual laminations zigzagging between the housing and the air-gap side [9]. The higher frequency and the relatively long distance causes this path to have a non-negligible impedance. The radial parts of this path are modelled as suggested in [10]. A series impedance Z_{lam} is calculated and added to the impedance matrix: $\mathbf{Z}_{\text{core}} = \mathbf{Z}_0 + Z_{\text{lam}}\text{ones}(n,n)$, where n is the dimension of $\mathbf{Z}_0$ and $\text{ones}(n,n)$ denotes an n-by-n matrix filled with 1s. The admittance matrix is unaltered, i.e., $\mathbf{Y}_{\text{core}} = \mathbf{Y}_0$.
- The windings are embedded in slots. Within the magnetically active part, the wires experience a substantial

capacitive coupling to the yoke, whereas at the winding overhang, only mutual capacitances are of importance. Each transition from the slotted part of the winding to the overhang comes together with a drastic change in propagation modes and characteristic impedances. At these places, one has to deal with transmission and reflection coefficients. For the end-winding part, an additional axisymmetric FE model is built [11] and used for determining the additional impedance and admittance matrices $\mathbf{Z}_{\text{end}}$ and $\mathbf{Y}_{\text{end}}$. Both TLM models are combined by multiplying the corresponding multi-conductor propagation matrices, each of them properly scaled by the length along the propagation direction.
- Simple analytical formulae for the inductance and capacitance matrices assume a perfect magnetic coupling of the wires related to the presence of the highly permeable stator yoke and a negligible mutual capacitance between the wires expressing the fact that the coil to yoke insulation is much better than the inter-wire insulation, i.e., $\mathbf{L} = L\,\text{ones}(n,n)$ and $\mathbf{C} = \text{diag}\{C,\ldots,C\}$. When a relative order of the wires is known, a FE model is able to provide full matrices representing realistic cross-coupling effects.

III. Results

The improved TLM model is applied to an example machine with a rated power of a few kilowatt. The common-mode impedance is calculated using different TLM models. As a reference solution, the model incorporating the return path through the laminated yoke, the end-winding parts and the cross coupling, is considered. In each of Figs. 2-4, one of the additional modelling features is discarded. The importance of the added feature is recognised from the difference of the common-mode impedance against the reference solution.

- The return path through the stator lamination causes a resistive component to the overall common-mode impedance in the kHz-range (Fig. 2). In the higher frequency range, the additional resistance smooths out some of the internal resonances. The first resonance frequency, however, is not affected.
- The winding overhang is responsible for an additional inductive effect (Fig. 3). The first resonance frequency decreases.
- The mutual capacitances between the individual wires of the winding are not negligible as is obvious in the low-frequency range (Fig. 4).

IV. Conclusions

The complicated return path through the stator laminations, the end-winding parts and the cross-coupling effects between the wires have a significant influence on the common-mode impedance of a stator winding. This motivates their inclusion in the extended transmission-line model developed here.

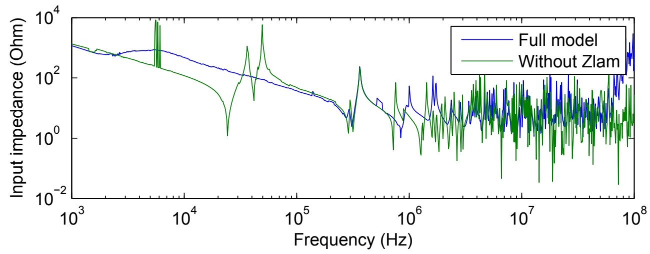

Fig. 2. Influence of the impedance of the return path through the laminated yoke on the common-mode impedance.

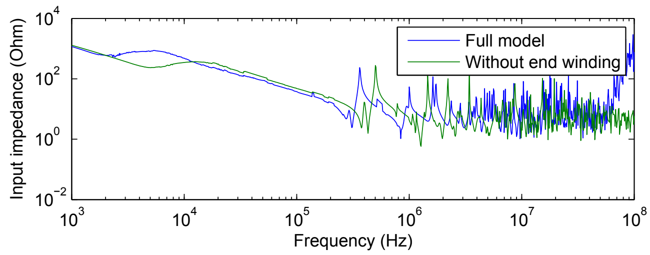

Fig. 3. Influence of the end-winding parts on the common-mode impedance.

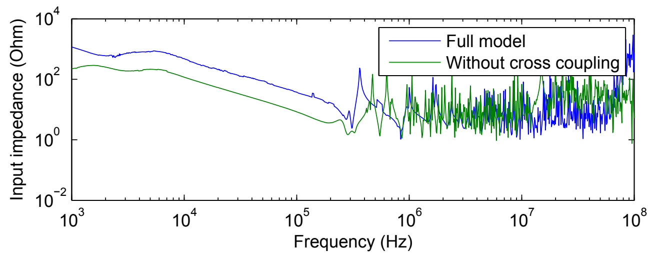

Fig. 4. Influence of the cross coupling on the common-mode impedance.

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