Frequency Domain Decomposition of 3-D Eddy Current Problems in Steel Laminations of Induction Machines

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***Abstract*—A novel method to reduce the computational burden of three-dimensional eddy current problems in steel laminations of induction machines is presented. The nonlinear transient analysis used originally is decomposed into a set of linear time harmonic simulations for known frequencies. The linear model considers the machines' saturation by means of an effective reluctivity obtained from a nonlinear two-dimensional field solution. Comparisons with the original transient approach confirm the validity of the proposed method.**

***Index Terms*—AC machines, eddy currents, electric machines, finite element methods, magnetic losses**

I. Introduction

Iron losses in steel laminations of electrical machines are originating from fundamental and high order frequency fields. High order harmonics are particularly prominent in induction machines, whereupon the eddy current effects induce a major iron loss component. Mostly, the eddy current losses are evaluated using simplified postprocessing methods fed by a transient two-dimensional (2-D) field analysis [1], [2]. Enhanced methods employ three-dimensional (3-D) homogenization techniques [3], as well as one-dimensional (1-D) lamination models [4].

In [5], a new method to compute the 3-D eddy current distribution in the steel sheets has been presented. The applied 3-D time-stepping finite element analysis exhibits the drawback of high computational costs, since the high frequency effects require a dense mesh and sufficient small time step sizes. In order to reduce the numerical burden, a novel approach is introduced in the present work by reducing the cumbersome nonlinear transient 3-D simulation to a set of linear time-harmonic ones. The reduced approach is validated against the transient reference solution by using the example of a megawatt rated slip ring induction machine.

II. Numerical Method

Applying the method of [5], a transient 2-D field analysis is first carried out for the whole machine in order to generate a set of boundary conditions for the 3-D model. In a second step, the transient 3-D eddy current problem is solved separately for a single stator and rotor sheet. In this work, the second step is substituted by time harmonic evaluations of dominant frequency components. Considering induction machines, all possible field frequencies can be determined a priori using analytical approaches, see e. g. [6].

The time harmonic 3-D eddy current analysis is performed for different angular frequencies ω_k using the $\boldsymbol{A}$-V formulation based on second order hexahedral edge elements. Under quasistatic approximation, the magnetic vector potential $\boldsymbol{A}$ and the electric scalar potential V have to fulfill:

$$\begin{aligned} \nabla \times \nu \nabla \times \boldsymbol{A} + \mathrm{j}\omega_k \sigma \boldsymbol{A} + \mathrm{j}\omega_k \sigma \nabla V &= \boldsymbol{0}, \\ \nabla \cdot (\mathrm{j}\omega_k \sigma \boldsymbol{A} + \mathrm{j}\omega_k \sigma \nabla V) &= 0 \end{aligned} \tag{1}$$

where σ is the conductivity of the sheet material. To account for the actual saturation level of the machine, ν in (1) is replaced by an effective reluctivity using the field values obtained from the nonlinear transient 2-D analysis [7]:

$$\nu_{\mathrm{eff}} = \frac{H_{\text{2-D,rms}}}{B_{\text{2-D,rms}}} = \frac{\sqrt{\frac{1}{T}\int\limits_0^T H_{\text{2-D}}^2(t)\ \mathrm{d}t}}{\sqrt{\frac{1}{T}\int\limits_0^T B_{\text{2-D}}^2(t)\ \mathrm{d}t}}. \tag{2}$$

Here, $H_{\text{2-D}}$ and $B_{\text{2-D}}$ are the mean values of the field strength and flux density in a 2-D element, respectively. The symbol T denotes the time period of the fundamental line frequency, t is time. The variation of the reluctivity in axial direction in the 3-D elements is neglected, and the same reluctivity values are used for all time harmonic simulations.

The 3-D model of a single sheet is excited by the tangential component of $\boldsymbol{A}$ impressed on the boundaries along the lamination thickness. The exciting vector potential is derived from a harmonic decomposition of the transient 2-D field solution. Since the emerging frequencies do in general not coincide with multiples of the simulation period, the reconstruction procedure of [8] is used to avoid leakage effects. The individual harmonics are prescribed separately to the 3-D model. A more detailed description on the specification of the boundary conditions is given in [5].

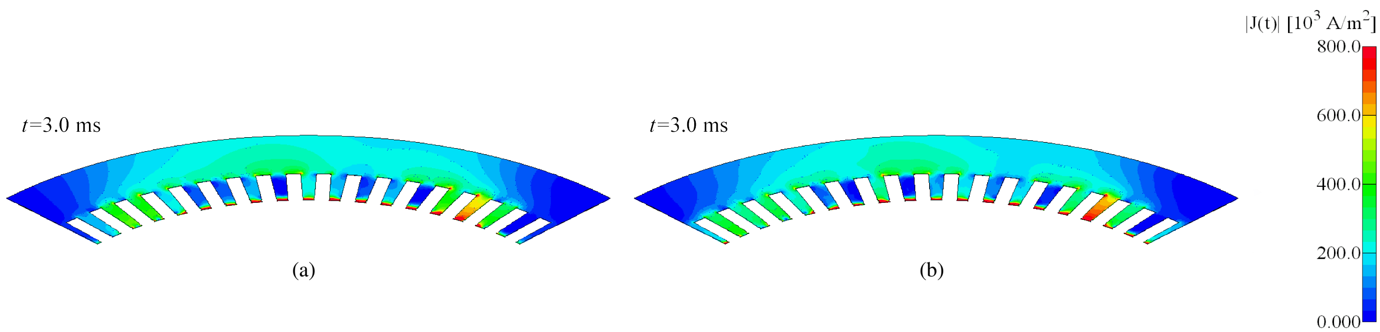

Fig. 1. Current density distribution in a stator sheet at a specific time instant and rated load computed by the harmonic superposition principle (a) and a transient analysis (b).

An arbitrary field value at a specific time instant $X(t)$ is finally received by superposition of the individual frequency components $X(\mathrm{j}\omega_k)$ in proper phase relation:

$$X(t) = \mathrm{Re}\left\{\sum_{\omega_k} X(\mathrm{j}\omega_k) \cdot \mathrm{e}^{\mathrm{j}\omega_k t}\right\}. \quad (3)$$

III. Preliminary Results

Simulations for different loading conditions have been carried out on a megawatt rated, 50 Hz, 690 V, three-phase, four pole slip ring induction motor fed by sinusoidal voltage. Figure 2 shows the frequency spectrum of the flux density evaluated in a stator and rotor tooth tip of the 2-D model. In the 2-D simulation, the rotor windings have been short circuited and the load has been defined by the rotational speed. In order to guarantee correct modeling of all relevant high frequency effects, a time step size of $\Delta t = {}^{T}\!/_{500}$ has been used. The dominant spectral lines near the 3th, 5th and 7th multiples of the fundamental frequency are induced by the discrete winding distribution and saturation effects. In addition, slotting effects cause considerable high harmonics appearing next to 2100 Hz in the stator, and 1800 Hz in the rotor tooth. By increasing the load, higher currents have to be provided resulting in enlarged winding and slotting fields as well as elevated losses.

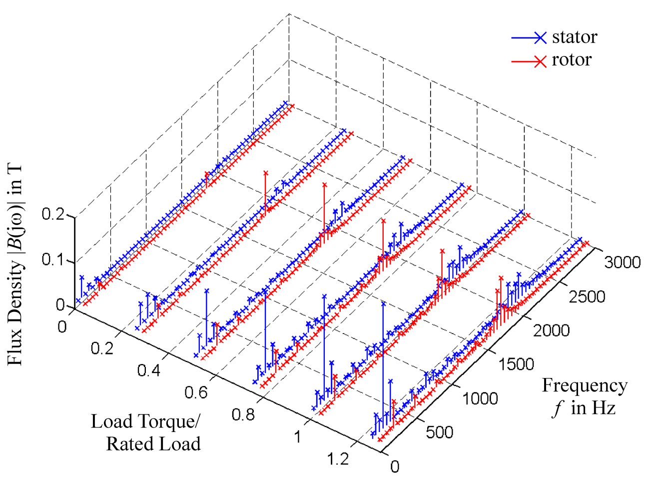

Fig. 2. Load dependent frequency spectrum of the tangential component of the flux density observed in a stator and rotor tooth tip. The fundamental frequency component is not shown, the rotor frequencies are given in a moving rotor coordinate system.

Figure 1 compares the 3-D current density in a stator sheet at a specific time instant obtained by the harmonic superposition method to the solution yielded by a transient analysis. The current density attributed to the fundamental frequency is quite uniformly distributed within the lamination, the high-order frequency eddy currents are concentrated in the teeth and their tips. Beside the fundamental frequency component at 50 Hz, four more high-order frequencies at 247, 347, 2029 and 2129 Hz have been considered in the time harmonic simulations. Using this limited set of frequencies, good agreement can already be achieved compared to the transient solution, indicating the applicability of the reduced approach.

In the final paper, further validations will be performed involving also simulations for the rotor sheet. Moreover, the loss behaviour for different loading conditions will be subjected to an in-depth analysis.

IV. Acknowledgment

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