Hybrid Simulation Methods for Induction Machine Calculation

Reduction of Simulation Effort by Coupling Static FEA with Transient FEA and Analytic Formulations

G. von Pfingsten, M. Nell and K. Hameyer
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
georg.vonpfingsten@iem.rwth-aachen.de

***Abstract*—Induction machines for traction applications are operated at working points of high ferromagnetic saturation. Depending on the working point, a broad spectrum of harmonic frequencies appears in the magnetic flux density of induction machines. Detailed loss analysis therefore requires local and temporal highly resolved nonlinear field computation. This loss analysis could be performed in the post processing of nonlinear transient finite element simulations of the magnetic circuit. However, it takes a large number of transient simulation time steps to build up the rotor flux of the machine. In this paper we will discuss, analyze and compare hybrid simulation approaches that allow to decrease significantly the computational effort.**

Keywords*—induction machine; finite element analysis; model coupling; analytic machine models; equivalent circuits.

I. Introduction

Two approaches of coupling transient FEA with static FE models and analytical formulations to a hybrid simulation model are described and assessed in this paper.

Both approaches (Fig. 1) rely on the extraction of the lumped parameter matrix **L** from static no-load FEA simulation I. The full inductance matrix **L** that contains inductance values L_{ij} between all conductors are extracted from the FEA solution as described in [1].

Simulating torque-speed operating maps of induction machines from transient FEA is very time consuming [2]. A large share of computational effort is caused by the transient build-up of the rotor flux. To accelerate this flux build-up in the simulation and save computational time, the steady state flux linkage is calculated from the lumped parameter matrix **L** and the rotor resistance matrix $\mathbf{R}_2$. In *approach a*, one static no-load simulation is conducted and one matrix **L** is extracted. The fundamental wave model is parameterized with this matrix **L** and the steady state rotor currents are calculated. However, since only one saturation state is stored in **L**, the saturation state of the final transient simulation should be known beforehand. This is easily fulfilled for a linear simulation. For drives operating in different levels of saturation, such as traction drives for electric vehicles, the saturation state is difficult to estimate beforehand. Hence, *approach b* is introduced, which interpolates the saturation state from multiple matrices **L** at different levels of saturation.

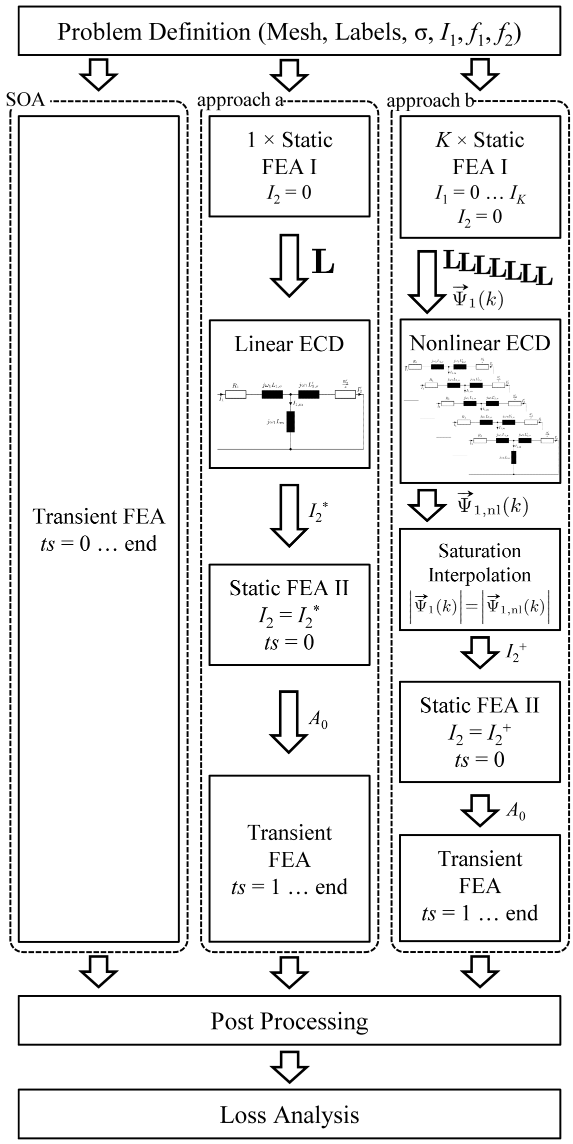

Fig. 1: State of Art (SOA) and two different hybrid simulation approaches for reduced simulation effort.

Both hybrid simulation models use the steady state rotor currents I_2^* or I_2^+, which are calculated from the analytical equivalent circuit diagram (ECD), as excitation for a second static FEA II. From the static FEA II, the magnetic vector potential solution A_0 in time step zero is calculated. This solution A_0 is used in the following time step $ts = 1$ as previous solution of the time stepping solution algorithm. From $ts = 2$ on, the transient simulation is conducted without any modifications.

The static nonlinear simulation is conducted $k = 1 \dots K$ times and the full inductance matrix $\mathbf{L}$ is extracted for every of the k simulations.

The K full inductance matrices $\mathbf{L}(k)$ is subdivided into four sub matrices: The self-inductance matrices $\mathbf{L}_{11}(k)$ and $\mathbf{L}_{22}(k)$ and the mutual inductance matrices $\mathbf{L}_{12}(k)$ and $\mathbf{L}_{21}(k)$. Eq. (1) is evaluated for the $k = 1 \dots K$ different values of $\mathbf{L}$. Each k represents a different saturation state. By solving (1), the rotor current I_2 is calculated. I_2 is then inserted to (2) to calculate the stator flux linkage vector Ψ_1. The magnetizing current value at which the stator flux linkage vector Ψ_1 from (2) and the no load stator flux linkage vector $\Psi_{1,\mathrm{nl}}$ from (3) are equal in length is then found by means of numerical interpolation.

$$\vec{I}_2(k) = \mathrm{inv}\left(-j \cdot \omega_2 \cdot \mathbf{L}_{22}(k) + \mathbf{R}_2\right) \cdot \left(j \cdot \omega_2 \mathbf{L}_{21}(k) \cdot \vec{I}_1\right) \quad (1)$$

$$\vec{\Psi}_1(k) = \mathbf{L}_{11}(k) \cdot \vec{I}_1 + \mathbf{L}_{12}(k) \cdot \vec{I}_2(k) \quad (2)$$

$$\vec{\Psi}_{1,\mathrm{nl}}(k) = \mathbf{L}_{11}(k) \cdot \vec{I}_{1,\mathrm{nl}}(k) \quad (3)$$

Fig. 2 shows the interpolation of the stator flux linkage vectors to find the saturation states for one operating point with a fundamental frequency of the rotor currents of $f_2 = 5$ Hz and different stator excitation peak current density values $\hat{J}_1$. The intersection of the stator flux linkage value $\Psi_{1,\mathrm{nl}}$ (solid black line) and Ψ_1 (colored lines) are marked by black crosses. For a frequency of $f_2 = 5$ Hz, the machine would be operated in the linear range at stator current density values below $\hat{J}_1 = 5\mathrm{A/mm}^2$. For higher values of stator current density, the machine would be operated in a nonlinear case. The saturation is not only determined by the stator current, but also by the value of the frequency f_2. This points out, why saturation is not simple to pre-determine and that the interpolation of the saturation state should be applied when simulating induction machine drives for torque density applications such as electric vehicle traction motors.

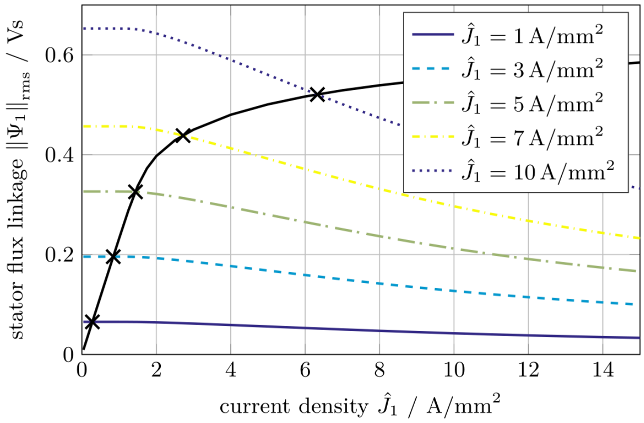

Fig. 2: Interpolation of the stator flux linkage vector ($f_2 = 5$ Hz).

II. Results

Fig. 3a and 3b show the loci of the rotor flux linkage vectors for the state of art method (SOA) and *approach b*. For the SOA simulation method, the rotor flux linkage shoots over the steady values before settling to the steady state circle (Fig. 3a). For *method b* it is clearly observed, that the rotor flux linkage vector builds-up almost instantaneously (Fig. 3b).

Fig. 3c and 3d show the instantaneous value of the rotor flux linkage vector for SOA and *approach b*. It is observed, that for the SOA approach it takes more than 300 simulation time steps for the rotor flux linkage to reach an error of less than 5 %, whereas simulation *approach b* instantaneously reaches an error of less than 5 % in time step $ts = 1$.

III. Conclusions

Two hybrid simulation approaches that couple static FEA with transient FEA and analytic formulations are presented. The hybrid simulation approaches drastically decrease the simulation time by reducing shortening the transient build-up of the rotor flux. The full paper will present a more detailed description and analysis of both hybrid simulation methods.

References

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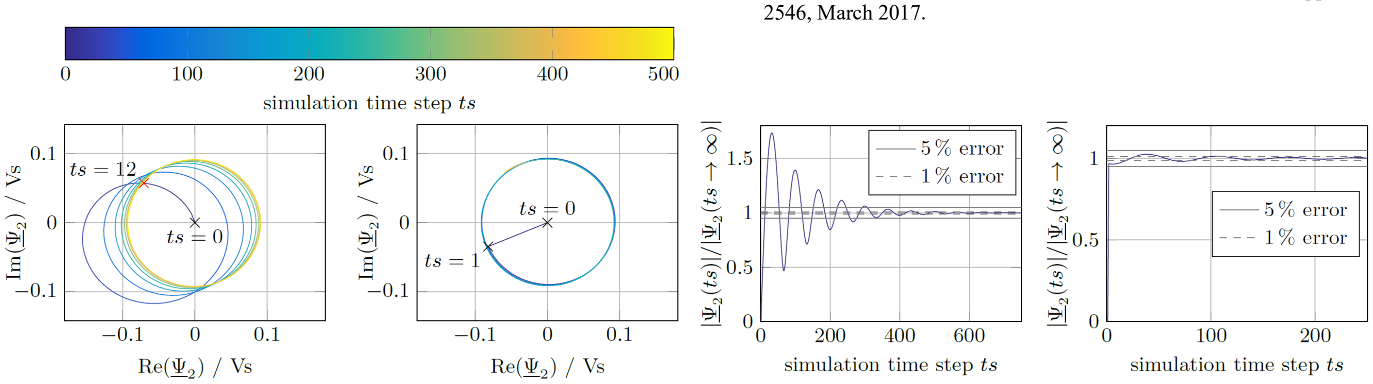

(a) zero flux starting condition (b) with analytical starting condition (c) zero flux starting condition (d) with analytical starting condition

Fig. 3: Rotor flux loci vector and error in amplitude of rotor flux linkage vector in dependency of simulation time step ts. With zero flux starting condition (SOA) and with analytical starting condition (*approach b*).