Inductances as Dynamic Exchange Parameters for Electrical Machine Computation based on the Method of Frozen Permeabilities

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***Abstract*— Simulation of the operational behavior of electrical machines is of high interest for design and optimization purposes. Various approaches have been presented relying either on system-simulation or on numerical models. In general, system simulations are utilized to consider the macrostructural environment, such as machine and accordant rectifier, power supply and load. System simulations also allow for regarding load changes and duty cycles. Due to their structure, system simulations are not capable to independently take magetic saturation into account. These circumstances require the provision of saturation-dependent inductances determined for a discretized machine model by numerical computation approaches. Basing on the applicable excitational state, flux-density contributions of all excited windings need to be separated for the determination of accordant self- and mutual inductances. Therefore, the method of frozen permeabilities is utilized, considering the discretized machine model as grid of magnetic resistances.**

I. Introduction

SYSTEM simulations are utilized to determine the operational behavior of electrical machines and accordant environment such as rectifier and control, power supply and load. This approach is based on a set of differential equations considering the electromagnetic behavior and motion of the machine at its terminals. Due to the structure of this method, circuit-based system simulations are not capable to independently regard saturation-dependent inductances. Finite Element simulations offer the opportunity to determine self- and mutual inductances of windings, even for complex arrangements but they require external provision of the excitational state. Therefore, an interactive coupling of system simulation and Finite Element (FE) simulation is first-time utilized for the determination and provision of required parameters, described in this paper. Required methods for the determination of inductances as exchange parameters are introduced such as accordant machine models used.

II. Structure of the Simulation Process

The entire iterative simulation process to appear as closed loop as of Fig. 1 consists of macrostructural and microstructural computation approaches. The excitational state due to a preselected and defined operational state is to be computed in a system simulation of electrical machine and accordant supply and load environment. Inductances therefore used are

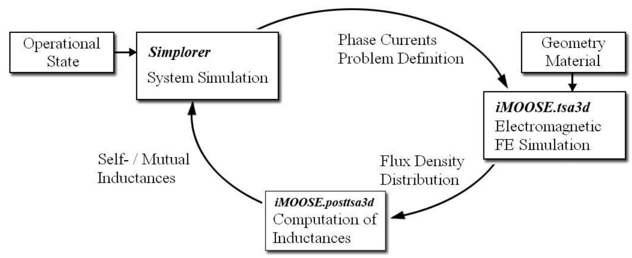

Fig. 1. Structure of the Simulation Process.

to be chosen arbitrarily but reasonably for the very first loop cycle. Resulting phase currents define the applicable excitational state used for injection into accordant windings of the dicretized Finite Element Model. The flux-density distribution thus determined is utilized to compute corresponding self- and mutual inductances of the arrangement in subsequent post-processing steps. These refined and updated inductances are then runtime-dynamically read by the system simulation, stating the origin for a second cycle of the process loop for further increase of the accuracy of simulation results. Other than for simulation approaches previously used, the presented method is applicable on arbitrary numbers of polyphase windings and synchronous machine designs.

III. Simulation Approaches

As the description of the system simulation approach is to be considered in the full paper, focus is exclusively put on the numerical computation approach herein.

A. Numerical Simulation

Due to a non-sinusoidal waveform of the phase currents and the distinctive three-dimensional design of the considered claw-pole machine design, a transient 3D Finite Element solver is used [1] for computation.
A discretized symmetry cut out of the considered electrically excited synchronous machine with regular three-phase winding is used for the computation of the flux-density distribution due to the pre-determined excitational state. The resulting flux-density distribution for any element covers collective contributions of all windings participating in the excitation.

B. Method of Frozen Permeabilities

The appliance of the Method of Frozen Permeabilities (MFP) allows for the required separation of each flux contributions excited by corresponding windings [2]. This method is based on considering the discretized machine model as grid of magnetic resistances. In fact, the permeabilities of each element, ensuing from the FE simulation with total excitation are stored (”frozen”) for further processing. Subsequent FE simulations with independent excitation of windings separately considered are processed for permeabilities as stored for the state of total excitation previously. Therefore the magnetic behavior is linear with applied currents due to frozen permeabilities. The appliance of MFP is validated and verified using the simple and well-known arrangement of a ring core with air gap as of Fig. 2. Both iron sections of different permeability feature a coil with different number of windings, fed with different exciting currents each.

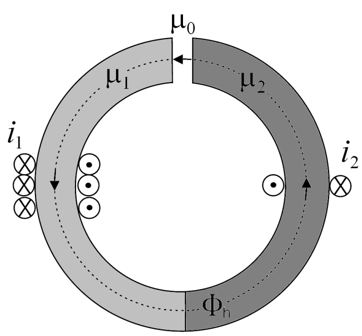

Fig. 2. Test arrangement for validation of the MFP.

C. Formulation

The mutual flux linkage [3] through a coil region 2, solely excited by a current I_1 through coil 1 is defined as of

$$\Psi_{21} = \frac{\int\limits_V \vec{A}_1 \cdot \vec{J}_2 dV}{I_2}. \quad (1)$$

Applying the method of Frozen Permeabilities requires I_2 and accordant J_2 to equal zero for exclusive regard of the mutual influence of the excited coil 1. This condition ends up in Ψ_{21} equal zero due to equation (1). The appliance of either of the two opportunities allows for a workaround of the zero current condition:

- extrapolation of sample points,
- injection of auxiliary current.

As the first option is based on assuming linear magnetic behavior due to frozen permeabilities, the flux linkage is computed for two different non-zero currents I_2 and extrapolated towards $\Psi_2(I_2)$. The second option utilizes a known auxiliary current $I_2 \neq 0$ to be injected into coil 2 with subsequent elimination of its influence. It recursively computes the nominator in expression

$$\Psi_{21} = \frac{\int \vec{J}_{(I_2\neq 0)} \vec{A}_{(I_1\neq 0)}\, \mathrm{d}V}{\int \vec{J}_{(I_2\neq 0)}\, \mathrm{d}F} \qquad \left(= \frac{\int \vec{J}_2 \vec{A}_1\, \mathrm{d}V}{\int \vec{J}_2\, \mathrm{d}F} \right) \quad (2)$$

as in equation (1) with $\vec{J}$ derived from $\vec{J} = \mathrm{rot}\, \vec{T}$. Both options are subject to detailed introduction in the full paper.

IV. Results

Computation results for the simple test arrangement as of Fig. 2, using both analytical and MFP approaches match with very satisfying accuracy. The extension of the method described onto the considered arrangement of an electrically excited synchronous machine leads to the inductance characteristics for the simulated range. As of Fig. 3 the mutual inductance L_{SH} of two stator-phase windings is exemplarily shown for a simulated range of two pole pitches, due to symmetry of the geometry.

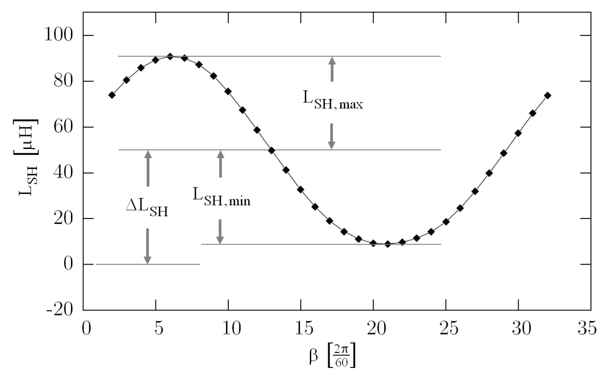

Fig. 3. Mutal Inductances between two selected Stator Phases.

The system simulation approach uses time- or position dependent descriptions of the inductances to appear as terms within the characteristical set of differential equations. Therefore, inductances are modeled as sinusoidal oscillations, solely requiring information of amplitude and offset ($L_{SH,min}$, $L_{SH,max}$, ΔL_{SH} as of Fig. 3) of computed characteristics to be exchanged between simulation approaches described. Computation results of inductances thus determined and furthermore processed for system simulations of phase currents match measured currents very well.

V. Conclusion

The Method of Frozen Permeabilities is introduced as a means to determine self- and mutual inductances of electrical machines for dynamic parameter exchange with system simulations and first-time integrated into a combined system simulation and FE simulation process. The method is validated and verified on a simple ring core test arrangement and furthermore successfully applied on winding arrangements of arbitrary complexity. Results determined for the machine application match measurements with satisfying accuracy.

References

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