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A Field–Circuit Coupling Accounting for Movement Based on a 2nd Order Accurate Approximation of the Energy

Enno Lange, François Henrotte, and Kay Hameyer
Institute of Electrical Machines, RWTH Aachen University, Schinkelstr. 4, D-52056 Aachen, Germany
enno.lange@iem.rwth-aachen.de

***Abstract*— The basic idea of this paper is to define by means of FE simulations a series of temporary representations of the electrical machines seen from stator terminals, which is valid as long as saturation has not changed too much. This concise representation is inserted in the circuit simulation of the electronic power supply, yielding a dynamic coupled model of the complete drive, which can then be solved with a time step adapted for considering electronic commutations etc. An estimator checks on the level of saturation in the machine and triggers the generation of a new set of linearized data when the accuracy of the present one exceeds a given threshold.**

I. Introduction

The numerical simulation of the interdependencies of the governing physical phenomenons of inverter fed electric machinery requires a model taking into account both the field and the circuit domain. Numerically strong coupled approaches, e.g. [1] and [2], applied to 3D field problems and non–linear circuit components suffer from high computational cost.

As an improvement to the accuracy of weakly coupled approaches, e.g. [3], this paper proposes a first order accurate lumped parameter approximation of the field domain.

II. Circuit Representation of the FE–Model

Say the fluxes φ_i embraced by the various coils of the FE–model, e.g. the coils of a rotating machine, are given at the time t_k. With the current I_r through the coil r being a function of the fluxes φ_i and the angular position Θ of the rotor, one has (with implicit summation on repeated indices assumed):

$$I_r = \mathcal{R}_{ri}\varphi_i, \tag{1}$$

$$\partial_{\varphi_k} I_r = \left(\partial_{\varphi_k}\mathcal{R}_{ri}\right)\varphi_i + \mathcal{R}_{rk} := \mathcal{R}^{\partial}_{rk}, \tag{2}$$

$$\partial_\Theta I_r = \partial_\Theta\partial_{\varphi_r}\Psi = \partial_{\varphi_r}\partial_\Theta\Psi = \partial_{\varphi_r} T. \tag{3}$$

Here, $\mathcal{R}_{ij}$ and $\mathcal{R}^{\partial}_{ij}$ represent respectively the secant and tangent reluctivity matrices, $\Psi(\varphi_i,\Theta)$ the magnetic energy of the system, and T the torque.

With the relations (1) – (3), a 1st order accurate representation of I_r can be obtained by Taylor expansion around the point $\varphi(t_k),\Theta(t_k)$:

$$I_r(t) = \mathcal{R}_{rk}\varphi_k(t_k) + \partial_{\varphi_r}T\delta\Theta + \mathcal{R}^{\partial}_{rk}\delta\varphi_k \tag{4}$$

with $\delta\Theta = \Theta(t) - \Theta(t_k)$ and $\delta\varphi_i = \varphi_i(t) - \varphi_i(t_k)$.

The relationship between the flux φ_r and the terminal voltage of the coil r — in terms of the circuit simulator the nodal potentials $\nu_{r,1}$ and $\nu_{r,2}$ — is given by

$$\partial_t\varphi_r = \nu_{r,1} - \nu_{r,2}. \tag{5}$$

Equations (4) and (5) and the corresponding state variables φ_i and Θ can be incorporated into the equation system of a circuit simulator based on the Modified Nodal Analysis. The circuit simulator solves the transient initial value problem up to the next FE step at $t_{k+1} = t_k + \Delta T$ with adaptive time step if required.

III. Lumped Parameter Extraction

Since the current density can always be written as $\mathbf{j} = I_i\mathbf{w}_i$ and with the magnetic vector potential $\mathbf{a} = a_i\boldsymbol{\alpha}_i$ obtained by the Galerkin scheme, the mapping between $\mathbf{a}$ and φ_r can be expressed by a matrix:

$$\varphi_r = W_{ri}a_i \quad \text{with} \quad W_{ri} = \int_\Omega \mathbf{w}_r\boldsymbol{\alpha}_i \mathrm{d}\Omega. \tag{6}$$

Here, $\mathbf{w}_r$ is the shape function of the phase current I_r.

The linearisation (4) requires the knowledge of $\mathcal{R}_{ri}$, $\mathcal{R}^{\partial}_{ri}$, $\partial_{\varphi_r}T$, as well as the initial values $\varphi_i(t_k)$ and $\Theta(t_k)$. Beginning from (6), it can be shown that

$$\mathcal{R}^{-1}_{ri} = W_{rj}{\mathbf{M}^*}^{-1}_{jk}W_{ki}, \quad {\mathcal{R}^{\partial}_{ri}}^{-1} = W_{rj}{\mathbf{J}^*}^{-1}_{jk}W_{ki}, \tag{7}$$

$\mathbf{M}^*$ and $\mathbf{J}^*$ are the stiffnes and the Jacobian matrices of the FE–system around a given working point $\mathbf{a}^*$ provided by a standard transient FE solution process.

IV. Conclusion

A weak coupling approach to simulate field-circuit coupled problems is presented. The 2nd order approximation of the energy stored in the FE–system accounts for the non–linear permeability as well as the EMF provoked by mesh deformation and is applicable to 2D and 3D field problems. Simulation results and a verification with measurements will be presented in the full paper.

References

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