Computing Eddy Currents in Permanent Magnet Synchronous Machines by a 3D Finite Element Model without Motion

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Abstract — In this paper, a new method is presented for simulating three-dimensional eddy currents in the permanent magnets of a synchronous machine with surface mounted magnets. The method uses the T,Φ-Φ formulation with a position and time dependent boundary condition on the stator surface. The tangential component of the magnetic field intensity there is determined by magneto-static simulations. The method is justified by comparing the boundary values obtained by two-dimensional analyses with and without eddy currents.

I. INTRODUCTION

Determining the eddy currents in the permanent magnets (PM) of synchronous machines (PSM) is very important for calculating the losses and the resulting heating of the PM [1], [2]. Furthermore, the reduction of the torque due to field weakening can be in the focus of interest. Both effects must be investigated by transient simulations.

For such quasi-static simulations the finite element method (FEM) with the rotor in motion is usually used. Hence, the air gap must be re-meshed in every simulation step or some kind of coupling between the stator and rotor must be established. For 3D FEM, this coupling is still not state of the art, although initial results have been already published [3], [4], [5]. Furthermore, the stator must be modeled too, increasing the number of elements and thus, the calculation time.

Both problems would not appear if the rotor could be separated from the problem and simulated alone. This could be done by applying position and time dependent boundary conditions. The **T**,Φ-Φ formulation [6] offers the possibility to do this in an easy way by using the tangential component of the magnetic field intensity $\mathbf{H}_T$ as boundary condition.

II. THE SIMULATION METHOD

Due to the solenoidality of the current density **J** in the conducting domain Ω_c in the quasi-static case, **J** can be written as the curl of a current vector potential. This current vector potential can be considered itself as a sum of an impressed current vector potential $\mathbf{T}_0$ and a reduced current vector potential **T** in Ω_c:

$$\nabla \cdot \mathbf{J} = 0 \quad \Rightarrow \quad \mathbf{J} = \nabla \times (\mathbf{T} + \mathbf{T}_0) \ \text{ in } \Omega_c. \qquad (1)$$

In the non-conducting domain Ω_n the vector potential $\mathbf{T}_0$ can be used for modeling current sources. With the reduced magnetic scalar potential Φ, the magnetic field intensity **H** can be written as

$$\mathbf{H} = \mathbf{T}_0 - \operatorname{grad}\Phi \ \text{ in } \Omega_n. \qquad (2)$$

The boundary conditions of the non conducting domain Ω_n can be either the specification of the normal component of the magnetic flux density **B** (3) or of the tangential component of **H** (4), with **n** being the outer normal unit vector and b, **K** are the given field values for the FEM simulation:

$$\mathbf{B} \cdot \mathbf{n} = -b \ \text{ on } \Gamma_B, \qquad (3)$$

$$\mathbf{H} \times \mathbf{n} = \mathbf{K} \ \text{ on } \Gamma_{Hn}. \qquad (4)$$

By setting the magnetic scalar potential Φ to zero on the boundary surface Γ_{Hn}, the tangential component of the gradient of Φ is zero too. With (2) and (4) the tangential components of the magnetic field intensity $\mathbf{H}_T$ and of the impressed current vector potential $\mathbf{T}_{0T}$ are equal:

$$\mathbf{H}_T = \mathbf{T}_{0T} \ \text{ on } \Gamma_{Hn}. \qquad (5)$$

In many cases, $\mathbf{H}_T$ on some surface Γ_{Hn} does not strongly depend on the eddy currents, and can hence be determined from a static simulation.

In case the eddy currents in Ω_c are generated due to motion, Γ_{Hn} must be stationary in the moving coordinate system. Then $\mathbf{H}_T$ can be determined from static analyses at various positions of Ω_c. After a transformation into the reference system of the conducting domain in motion, $\mathbf{H}_T$ becomes the boundary function in this new reference system. As we shall show in the following section, $\mathbf{H}_T$ on Γ_{Hn} chosen as the inner surface of the stator in a PSM (a stationary surface in the rotor reference frame), is practically independent of the eddy currents in the permanent magnets, and can hence be obtained from static simulations at different rotor positions.

In the case of a PSM, several properties of $\mathbf{H}_T$ must be taken into account:

- The spatial distribution in the air gap caused by the stator and rotor inhomogeneity.
- The rotor position dependence due to the rotor inhomogeneity as well as the PM located on it.
- The machine current dependence.

The first two properties transform to a time-dependence in the rotor reference system, thus modeling motion.

For obtaining the boundary function (BF) on the stator surface, a couple of static simulations will be needed. But this must be done only once during preprocessing. With this

BF, a model of the rotor with constant mesh will be sufficient for simulating the eddy current problems inside the PM at various speeds.

III. PRELIMINARY RESULTS AND CONCLUSION

The required independence between $\mathbf{H}_T$ and the eddy currents is a prerequisite not valid in general. However, for machines with large air gaps, this requirement is expected to be fulfilled approximately due to the fact that $\mathbf{H}_T$ on the stator side of the air gap is almost zero on the iron surface and basically caused by the stator currents in the slot openings.

For the PSM under investigation, this is be shown below by a comparison of magneto-static and quasi-static 2D FEM simulation results. All simulations were done with ANSYS 12.0.

Fig. 1 shows a detail view of the model with focus on the air gap, the mesh and the path **P** along which $\mathbf{H}_T$ is evaluated for the comparison. The path is defined as a circle crossing through the center of the first air gap element layer on the stator side. The coupling between the rotor and stator is realized by constraint equations.

The fact that the path **P** is defined as a circle (or circle segment) that does not cut through different materials simplifies the transformation of the BF into the rotor reference system as well as the implementation of this method.

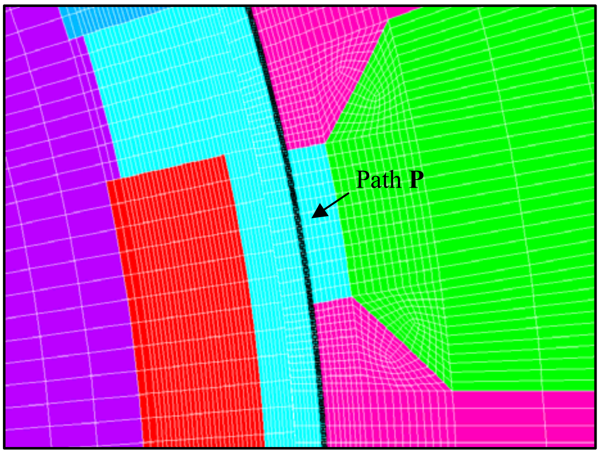

Fig. 1. Detail of 2D FEM model (air gap with path **P**)

Fig. 2 shows the comparison between static and transient simulations for different rotor positions at open circuit condition and Fig. 4 shows the same comparison at nominal load. The abscissa is the path in polar coordinates along one pole pair (=360 deg_E), the ordinate shows $\mathbf{H}_T$. The various curves show the dependence on the rotor position. Obviously all curves for the stationary and transient simulations are in good agreement. Based on these results, the conclusion can be drawn that the method will work properly.

In the full paper, the implementation of the method for 3D problems will be shown. A comparison between a conventional transient simulation and one using this method will be also presented.

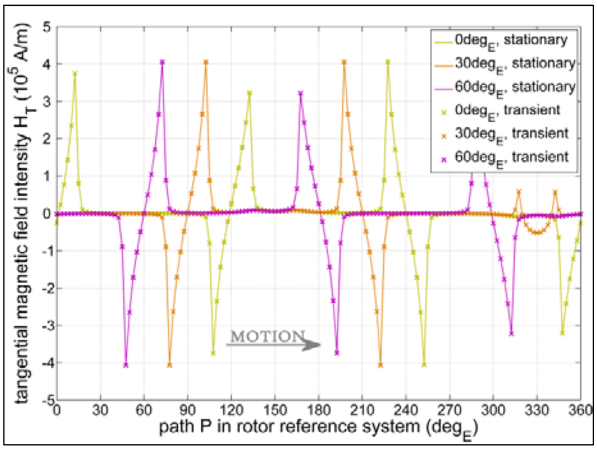

Fig. 2. Comparison of H_T between stationary and transient simulations for different rotor positions at open circuit condition.

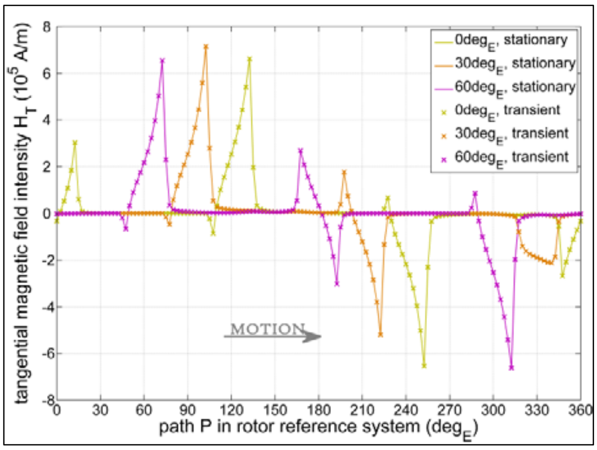

Fig. 3. Comparison of H_T between stationary and transient simulations for different rotor positions at nominal current condition.

IV. ACKNOWLEDGMENT

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