Inductance and Torque Calculation of Permanent Magnet Synchronous Machines using the Frozen Permeabilities Method with the Finite Element Analyses

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Abstract – **Permanent magnet synchronous machines with fractional slot stator windings using the tooth coil technology require detailed investigations on the electromagnetic parameters due to a very low number of slots per pole and phase. Finite element analyses can provide many results but a subsequent application of the frozen permeabilities method allows for a more detailed discussion of effects caused by both permanent magnets and armature stator currents in conjunction with angular rotor position and also different saturation levels. In particular, these detailed analyses are required for high performance electrical drive systems which operate under very fast changing load conditions and additionally run in deep field weakening ranges.**

I. Introduction

The electromagnetic torque of permanent magnet synchronous machines arises from the interaction of the linkage flux caused by the permanent magnets mounted in the rotor and the magneto motive force of the armature currents in the stator. With the design process of such machines, it is desirable to know the individual contributions from permanent magnets and stator currents in detail. In particular, this gains in significance with a rather high number of poles and consequently a fractional slot stator winding with a number of slots per pole and phase $q < 1$ as depicted in Fig. 1. The utilization of the frozen permeabilities method with the finite element analyses allows for these detailed investigations. Moreover, this method provides a straight-forward strategy for an evaluation of the apparent inductances of such machines in dependence of the stator currents and the rotor position even considering cross-coupling terms with the linkage flux components with respect to the dq axes of the rotor fixed reference frame.

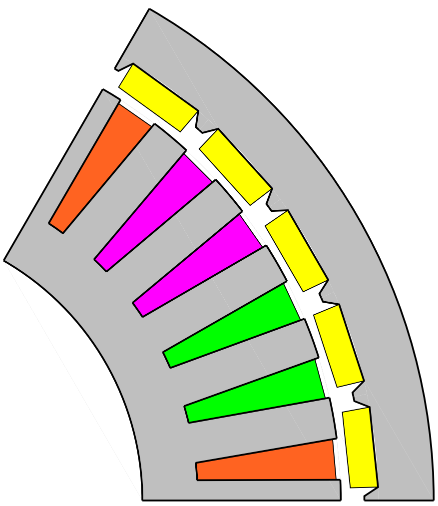

Fig. 1: Cross section of an external rotor permanent magnet synchronous machine with 30 poles and 36 slots

II. Sample Analysis Results

Fig. 2 depicts the load torque in dependence on the quadrature axis current. The numerical results are shown for both Y- and Δ-connected stator windings while the measurement results are obtained from the initial design with a Δ-connected stator winding.

Fig. 3 and Fig. 4 depict the current trajectories for a constant electromagnetic torque. Therefore, the design shows an inverse-saliency behaviour with a saliency ratio l_{dd}/l_{qq} of the apparent two-axes inductances slightly less than one. On the other hand, the saliency ratio l_{dd}/l_{qq} of the apparent two-axes inductances changes to values slightly greater than one in the deep field weakening range. This is caused by a desaturation mainly with the direct axis with these operational conditions.

Fig. 5 and Fig. 6 depict the total electromagnetic torque obtained directly as well as the components obtained from the frozen permeabilities method with rated quadrature axis current. With the Y-connected

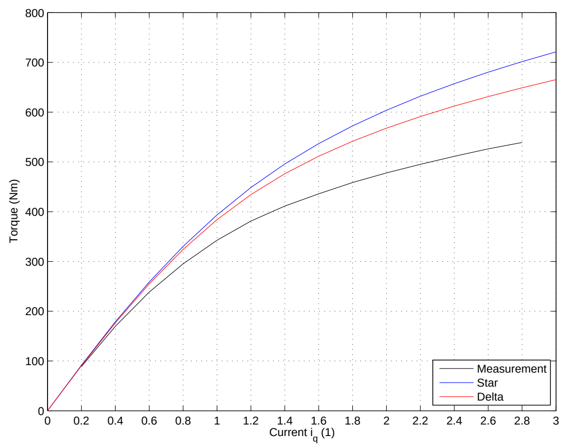

Fig. 2: Load torque, Y-connected and Δ-connected stator winding as well as measurement results

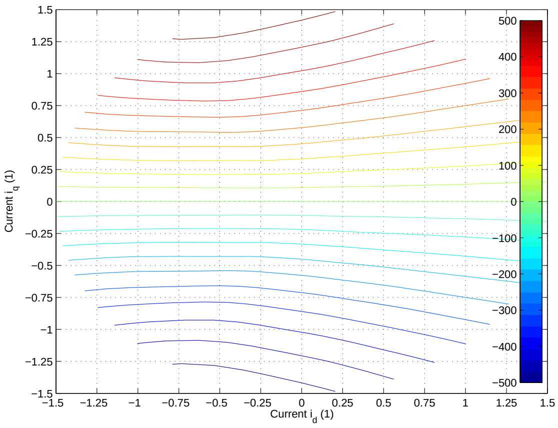

Fig. 3: Current trajectories for constant electromagnetic torque, Y-connected stator winding

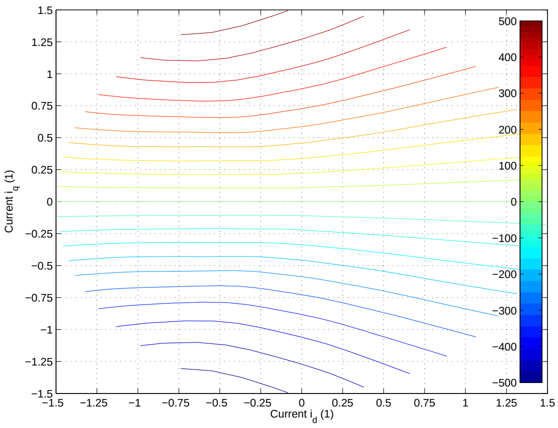

Fig. 4: Current trajectories for constant electromagnetic torque, Δ-connected stator winding

stator winding, the Maxwell stress tensor method yields four portions, the cogging torque of the permanent magnets denoted as $B_{rM}B_{pM}$, the reluctance torque of the stator currents denoted as $B_{rI}B_{pI}$ and the most significant two components arising from radial and azimuthal flux density components of permanent magnets and stator currents denoted as $B_{rM}B_{pI}$ and $B_{rI}B_{pM}$. With the Δ-connected stator winding, there are additionally the portion of the zero sequence current denoted as $B_{rZ}B_{pZ}$ and the respective four cross-coupling portions denoted as $B_{rM}B_{pZ}$, $B_{rI}B_{pZ}$, $B_{rZ}B_{pM}$ and $B_{rZ}B_{pI}$. With both winding connections, the portion of the stator currents $B_{rI}B_{pI}$ confirms a saliency ratio l_{dd}/l_{qq} slightly different from one.

III. Concluding Remarks

The full paper will additionally discuss the comparison of both apparent as well as differential inductances in dependence on stator currents and angular rotor position. Thereby, the differential inductances are deduced directly from the nonlinear analysis while the apparent inductances are obtained from the frozen permeabilities method carried out subsequently. As presented herein, both Y- and Δ-connected stator windings are concerned.

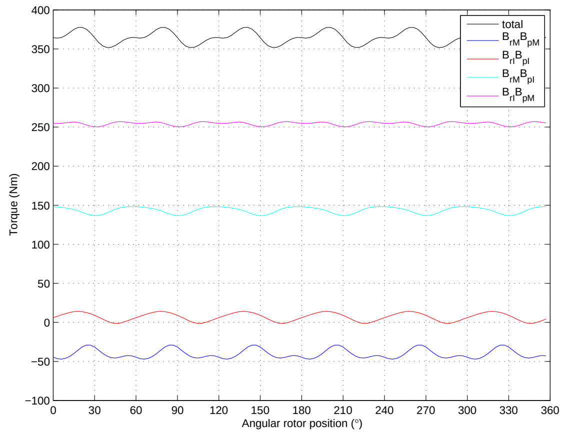

Fig. 5: Total electromagnetic torque and torque components, Y-connected stator winding

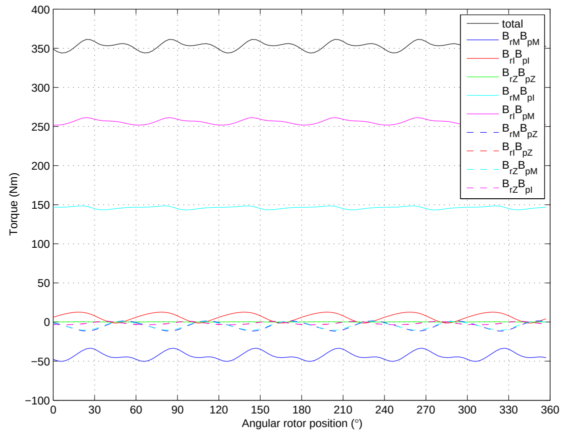

Fig. 6: Total electromagnetic torque and torque components, Δ-connected stator winding

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