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XXIII SYMPOSIUM ELECTROMAGNETIC PHENOMENA IN NONLINEAR CIRCUITS

July 2 – 4, 2014, Pilsen, CZECH REPUBLIC

Proceedings

EPNC 2014

University of West Bohemia • Pilsen, Czech Republic 2014

PTETiS Publishers • Poznań, Poland 2014

INFLUENCE OF NON-LINEAR FREQUENCY-DEPENDENT MATERIAL PROPERTIES ON THE OPERATION OF ROTATING ELECTRICAL MACHINES

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***Abstract*—High power density and a wide frequency range require particular attention regarding the machine design. This paper focuses on the frequency-dependent non-linear magnetization behavior of the soft magnetic material. The applied approach is based on measured material characteristics for various frequencies and magnetic flux densities. These are varied during the simulation according to the operational conditions of the rotating electrical machine. Therewith, the fault being committed neglecting the frequency-dependent magnetization behavior of the magnetic material is examined in detail. Effects on torque, iron losses and flux-linkage are presented.**

I. Introduction

The magnetization behavior of soft magnetic steel sheets is dependent on the applied frequency. However, during the Finite-Element (FE) simulation of electrical machines this frequency dependence is commonly neglected when using one magnetization curve [1], usually given for the frequency of 50 Hz. Hence, leaving the magnetization curve unchanged, the influence of the frequency is not considered, when simulating an electrical machine in the variable speed range [1].

The iron-loss calculation is strongly influenced by the magnetization characteristics, which may lead to an unfavorable selection of the material used in the machine.

As an example measured B/H characteristics of an M330-35A for different frequencies are shown in Fig. 1. From this characteristics a frequency-dependent behaviour of an electrical machine is expected. The purpose of this paper is to discuss the influence of the frequency-dependent material characteristics on the simulation results and the performace of the electrical machine. The full paper will present results for materials with different magnetization behaviors.

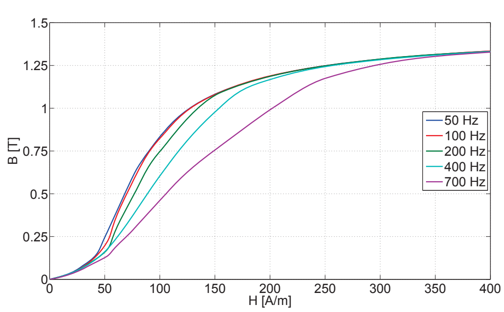


Fig. 1: Measured frequency-dependent non-linear magnetization curves.

II. Methodology

In order to evaluate the proposed methology a PMSM with buried magnets in the rotor is studied. The electrical machine is modeled in a rotor-flux-fixed dq-reference frame.

Figure 2 shows the trajectories of average electro-magnetic torque calculated with different current excitations. In order to calculate the operating points, the maximum torque per ampere (MTPA) control is used for the base speed range and the maximum torque per voltage (MTPV) for the field weakening range [2]. Figure 2 shows the calculated operating points from 0 Hz to 533 Hz fundamental electrical frequency and 0 Nm and 220 Nm inner electro-magnetic torque. The position of these operating points depends on the harmonic electro-magnetic torque and induced voltage, e.g., the differential of the flux linkage at different stator currents, for the MTPA and MTPV control.

In order to determine the influence of the frequency-dependent non-linear magnetization behavior of the soft magnetic material the electro-magnetic torque and the flux linkage are calculated and analyzed for different magnetization curves matching the fundamental frequency of the chosen operating point.

The effective operating points are identified considering the occurring losses, since the iron-loss calculation is directly dependent on the magnetization curve.

Subsequently the influence on the iron losses is examined using the IEM-formula, which allows a seperation of the different loss components and its corresponding frequency order with consideration of rotating field vectors [3]. The calculated fault area is compared to the effective operating points at the corresponding frequency spectrum. The results are verified by the solutions for the elements in the 2D-mesh.

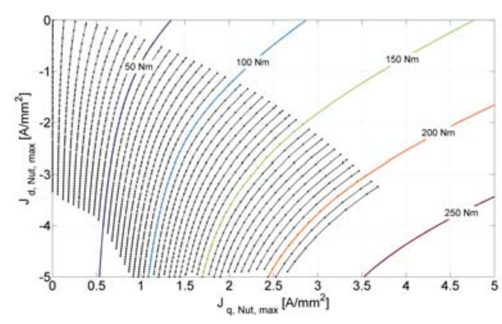
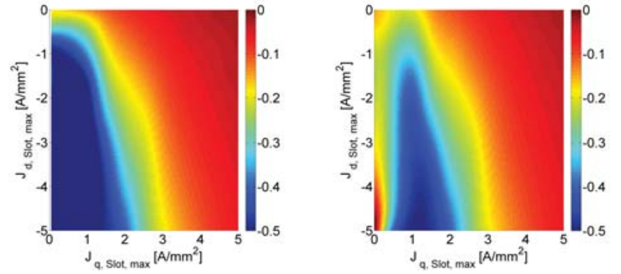


Fig. 2: Simulated map of the average torque in Nm with overlapping operating points.

III. Results

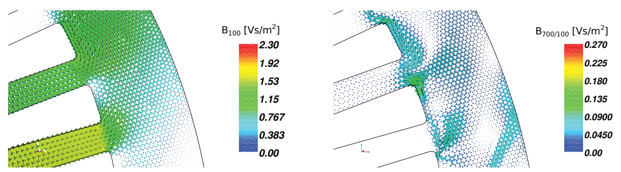
The applied control strategy and operating points depend on the harmonic electro-magnetic torque and the harmonic flux linkage, which causes the induced voltage. Figure 3 shows the deviation between the obtained results using the 100 Hz and 700 Hz magnetization curves to describe the magnetization characteristics of the material. It is apparent that the deviation



(a) Relative difference of the average torque in %.

(b) Relative difference of the total harmonic flux linkages in %.

Fig. 3: Deviation of torque (left) and flux (right) between results obtained using the 700 Hz and 100 Hz magnetization curve with different stator currents.



(a) Flux density distribution calculated for 100 Hz in T.

(b) Difference of flux density distribution between 700 Hz and 100 Hz in T.

Fig. 4: Behavior of the flux density distribution calculated with different magnetization curves.

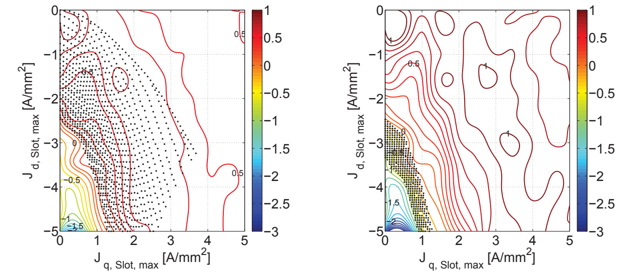
grows in the negative d-axis, i.e., the field weakening range. The obtained difference is less then 1 % for all simulated stator currents. This result shows that the magnetization curve has a minor effect on the calculation of the operating points for the considered PMSM. The reason for this is the high utilization and the saturation characteristics of the magnetic material.

Figure 4 (left) shows the flux density vector distribution for the 100 Hz magnetization curve and figure 4 (right) the difference in flux density distribution between 700 Hz and 100 Hz. It is apparent that the difference in the entire cross-section for the considered material is small and, as a result of this, the effect on the torque as already shown.

The influence of the material characteristics on the iron losses is analyzed using the IEM-formula [3], which allows for loss-separation. The relative differences in calculated hysteresis losses (Fig. 5) and classical eddy current losses (Fig. 6) using frequency-dependent magnetization curves corroborate the influence of the magnetization curve on the calculated iron losses. The operating points (black points, 200 Hz - 400 Hz left, 400 Hz - 600 Hz right) show the effective error, which is made using the magnetization curve of 100 Hz across the whole dq-range. The relative error lies between 0% and 1% for the hysteresis losses and between -1% and -3.5% for the classical eddy current losses for all operating points. Especially in regions where the flux density is low, e.g. in the yoke, the difference grows. As a result, the difference of the iron-loss distribution is shown in Fig. 7.

IV. Conclusion

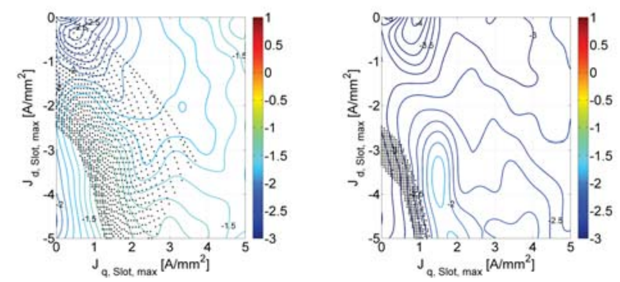
In this paper a methology to study the influence of the non-linear frequency-dependent magnetic material behavior on the operating characteristics of electrical machines, in particular the iron losses, torque and flux linkage is discussed.



(a) Relative difference of hysteresis losses in % between 400 Hz and 100 Hz magnetization curve.

(b) Relative difference of hysteresis losses in % between 700 Hz and 100 Hz magnetization curve.

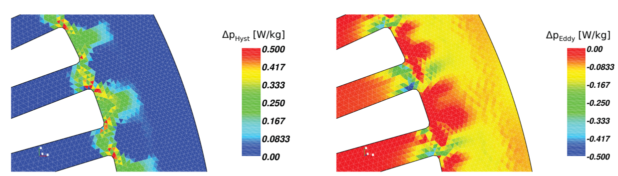
Fig. 5: Deviation of hysteresis losses calculated with different magnetization curves (operating points are indicated).



(a) Relative difference of clas. eddy current losses in % between 400 Hz and 100 Hz magnetization curve.

(b) Relative difference of clas. eddy current losses in % between 700 Hz and 100 Hz magnetisation curve.

Fig. 6: Deviation of classical eddy current losses calculated with different magnetization curves (operating points are indicated).



(a) Difference of hysteresis loss distribution between 700 Hz and 100 Hz in W/kg.

(b) Difference of classical eddy current loss distribution between 700 Hz and 100 Hz in W/kg.

Fig. 7: Difference of iron-loss distribution between 700 Hz and 100 Hz magnetization curve.

It can be seen that it is important to consider the frequency-dependency and saturation behavior of the material as well as its utilization, when selecting the most appropriate magnetic material. The used iron-loss model plays a central role, since the change in magnetization behavior with frequency leads to a change in iron loss. This will be presented in detail in the full paper comparing iron losses calculated using the fundamental component of the magnetic flux density to a summation over all harmonic components.

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