Temperature Influence of NiFe Steel Laminations on the Characteristics of Small Slot-less Permanent Magnet Machines

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Abstract—High performance electrical machines can operate at temperatures of 100 °C and beyond in rotor and stator cores. However, magnetic properties are generally measured at room temperatures around 23 °C to 25 °C according to the standards, even if it is known that the magnetization of some materials is substantially influenced by increasing temperatures. This paper investigates the thermal influence on the magnetic properties and iron losses in the stator cores of small slot-less permanent magnet synchronous machines (PMSMs). The stator stack is made of thin nickel iron (NiFe) lamination sheets. Magnetic measurements of the stator core are conducted for different frequencies and flux densities at several temperatures between 25 °C and 105 °C. The obtained measurement data is afterwards used in finite element method (FEM) simulations to investigate the influence of the magnetic property change on the machine performance. For the PMSM in consideration, the FEM simulations show that an increased stator core temperature reduces the electromagnetic torque considerably; approximately 1/3 of the torque reduction due to increased rotor magnet and stator core temperatures (from 25 °C to 100 °C) can be attributed to the increased stator core temperature.

Index Terms—Iron alloys, loss measurement, magnetic hysteresis, magnetic losses, magnetic materials, permanent magnet machines, soft magnetic materials, thermal effects.

I. INTRODUCTION

Temperature investigations on electric steels for electrical machines are relatively rare in literature. It is well known and taken into account in machine simulations that the properties of permanent magnets change with temperature, which in turn changes the machine performance [1]. But the temperature influence on electric steels is commonly neglected in simulations and the electrical machine design process, even if the temperature fluctuation and maximum value are often higher in the stator, compared to the permanent magnets located on the rotor. Therefore, certain used materials can have an essential impact on the machine performance, depending on the machine design.

Magnetic properties for an electrical SiFe steel and two cold rolled general steels are investigated for temperatures up to 700 °C in [2] and [3]. It is shown, that the magnetic properties of SiFe are quite stable at typical electrical machine operating temperatures (between 20 °C to 120 °C). Since the conductivity of iron is decreasing with temperature, the eddy current losses are as well decreasing. But for other magnetic materials used in electrical machines, the temperature can have a significant influence on the properties and thus the machine performance and losses. Some general data about the temperature influence on crystalline and amorphous metals can be found in [4]. The magnetic properties of nickel-iron alloys (NiFe) are clearly changing with the temperature.

NiFe has the advantage of a very small magnetic field coercivity and high permeability values. Furthermore, it has low hysteresis and eddy current losses, which makes it a suitable candidate for small high power and low loss electrical machines.

This paper focuses on the temperature influence of NiFe in a small slot-less permanent magnet synchronous machine (PMSM). Since slot-less stator cores do not have magnetic teeth, simple ring core tests, as described in the following sections, have been used to investigate the magnetic material, following the IEC standard [5]. The magnetization curves and losses are measured for different stator cores. Afterwards, the results are used in finite element method (FEM) simulations to investigate the machine performance due to the change of the magnetic properties with temperature.

II. INVESTIGATED STATOR CORES

Stator cores of a small, slot-less PMSM are used in this study to investigate the change of the magnetic properties with temperature. Each stator core is 64.5 mm long and has an outer and inner diameter of 31 mm and 23.2 mm, respectively. This yields a cross sectional area of the test core of 251.55 mm² in the circumferential direction. The mean length of the magnetic path is determined to 84.55 mm. A sample core is shown in Fig. 1.

The three investigated cores are made from NiFe electrical steel sheets with thicknesses of 0.1 mm (1 core) and 0.2 mm (2 cores) and a nickel content of approximately 40%.

Each core is wound with an inner copper winding \( N_2 \) of 0.22 mm² (FKUX 7/0,2MM) and 8 turns, encased by a stranded wire excitation winding \( N_1 \) of 120x0.1 mm² (CLI 200/120) and 35 turns. The stranded wire is used to minimize the dc resistance and to enable the possibility for future...
investigations of the magnetic properties at higher frequencies. One test sample is shown in Fig. 2.

III. MEASUREMENT AND CONTROL SYSTEM

The measurement system is built up following chapter 8 of the IEC standard [5]. The control algorithm for the magnetic excitation field is digitally implemented. The only difference in the used measurement setup is, that the flux density is determined from the secondary voltage by an analog flux meter and not integrated digitally.

An overview of the complete measurement setup is shown in Fig. 3, in which the solid lines highlight the electrical power circuit and the dashed lines the measurement and data flow. The later described control algorithm is implemented on a National Instruments CompactRIO system consisting of a Power PC (NI-9022) running the LabVIEW real time operating system (RT System) and an FPGA (NI-9114) for controlling the I/O modules and for initial data processing.

A. Measurement System

The flux density is determined by a Lakeshore 480 Fluxmeter (FM) which integrates the voltage of the measurement winding (inner winding) of the ring core. Furthermore, a Yokogawa WT1800 power meter (PM) is used to determine the losses in the test sample during the measurement. An isolated material test chamber (Binder FP-115) is used to heat up the stator cores to the desired temperature. Two PT100 temperature sensors are used to check the temperature on the core surface and under the excitation winding.

B. Control System

The control system for the magnetic measurements is implemented in LabVIEW. Two different control algorithms are used for the investigations. For measuring the quasi-static initial magnetization curve, a control algorithm keeping a constant change of the flux density (small constant $\frac{dB}{dt}$) has been implemented as described in [6]. It takes approximately 20 s to reach the maximum point of the magnetization curve, which equals an equivalent full period frequency of 12.5 mHz. For AC tests the control algorithm from [7] has been adapted to the system for measuring complete BH hysteresis curves with a sinusoidal flux density at different flux density amplitudes. The LabVIEW system measures and stores the excitation current, the voltage over the measurement winding and the flux density determined by the fluxmeter.

C. Measurement Principle

For each measurement, first some initializing loops are run at a high magnetic field strength to determine the voltage offset of the fluxmeter integration. The determined offset stays constant during the measurement and is used in all measurements to remove the integration offset constant from the obtained magnetic flux density value ($B$). Then, starting from the high initial magnetic field strength, the test samples are slowly demagnetized by decreasing the field strength down to zero over several loop cycles.

For determining the initial magnetization curve, the current, voltage and magnetic flux density as well as the iron loss measurement is started after this demagnetization process. Then, the flux density is linearly increased by keeping the flux density change $\frac{dB}{dt}$ at a small controlled value (0.01 T/s to 0.1 T/s), until the maximum peak current in the excitation winding (approximately 9 A) is reached.

For the AC BH hysteresis curve measurements, the iterative algorithm is started after the demagnetization process. The algorithm regulates the excitation current waveform until a pure sinusoidal flux density $B$ with a form factor of 1.11 is reached. Then, the recording of the current, voltage and magnetic flux density as well as the iron loss measurement is started and it spans over several periods.

IV. MEASUREMENTS

The stator core test specimens are investigated at different temperatures between 27 °C and 106 °C. The measurements are applied at different magnetic flux densities (up to 1.3 T)
and at frequencies up to 100 Hz. When the core reaches a constant temperature distribution, the magnetic measurements, as described in Section III-C, are started. The maximum deviation between the measurement results of the two stator core samples with 0.2 mm lamination thickness is less than 0.9%. Thus, it is not possible to visualize the results individually and averaged values are presented in the following plots.

The initial magnetization curves of the test specimens of 0.1 mm and 0.2 mm lamination thickness are shown in Fig. 4 at different temperatures. It can be seen that the saturation magnetization is decreased with increasing temperature and that the saturation magnetization is slightly lower for the 0.1 mm lamination sheets.

The decrease in saturation for complete BH hysteresis curves at 100 Hz and a sinusoidal maximum flux density of 1.3 T is shown for 27.2 °C and 102.7 °C in Fig. 5. A magnification of the coercitivity field of Fig. 5 is presented in Fig. 6, where it is shown that the coercitivity decreases with increasing temperature.

The change of iron losses with temperature at different frequencies is shown in Fig. 7 for the 0.2 mm stator cores. The losses decrease with increasing temperature, especially at higher flux densities. At 1.3 T, the losses are equal to 212.2 mW at 27.2 °C and 159.2 mW at 102.7 °C, resulting in a loss decrease of 25%.

Fig. 6. Zoom of the coercitivity field from Fig. 5.

Fig. 7. Iron losses in the 0.2 mm stator core for different sinusoidal flux densities at 100 Hz.

V. FINITE ELEMENT METHOD SIMULATIONS

The machine in consideration has two poles and a three-phase air winding. The rotor consists of several stacked permanent magnet segments in the axial direction with a high remanence flux density (1.31 T at 20 °C).

Approximately one quarter of the stator core has a partly radial flux density direction. The flux in the rest of the stator core points essentially in the circumferential direction, as can be seen in Fig. 8. Because this flux density distribution is very similar to the distribution obtained during the stator core material investigation in Section IV, these measurements results are used for the stator core material data in the FEM simulations. Furthermore, 2D FEM simulations are sufficient.
The torque values at the minimum and maximum temperature of the stator core and permanent magnet are given in Table I. It can be seen that even if the temperature influence of the permanent magnet is more pronounced, the change of torque due to the temperature change in the stator core material is not negligible.

VI. CONCLUSIONS

The presented measurements and FEM simulations give detailed results about the temperature influences on the stator core of a small permanent magnet slot-less synchronous machine. It is shown that the temperature change influences mainly the magnetic properties in the saturation region, whereas the reversible part of the BH hysteresis curve is hardly influenced. This means that the maximum flux density in the stator core of the machine reduces with an increasing temperature and, in turn, also decreases the maximum output torque of the machine at a constant current. This adds up to the already reduced performance due to the manufacturing influence on the magnetic properties of the lamination.

As a conclusion, the variation of the magnetic properties with temperature should be taken into account for NiFe lamination cores in finite element method (FEM) simulations to achieve a higher modeling accuracy. This is especially important in coupled thermal and electromagnetic simulations, where the permanent magnet parameters are already depending on the temperature.

REFERENCES


