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PROBLEM ROZMAGNESOWANIA MAGNESOW Z ZIEM RZADKICH W SILNIKU PMSM Z UZWOJENIEM UŁAMKOWO-ŻŁOBKOWYM

PROBLEM OF DEMAGNETIZATION OF RARE EARTHS MAGNETS IN PMSM MOTORS WITH FRACTIONAL SLOT WINDING

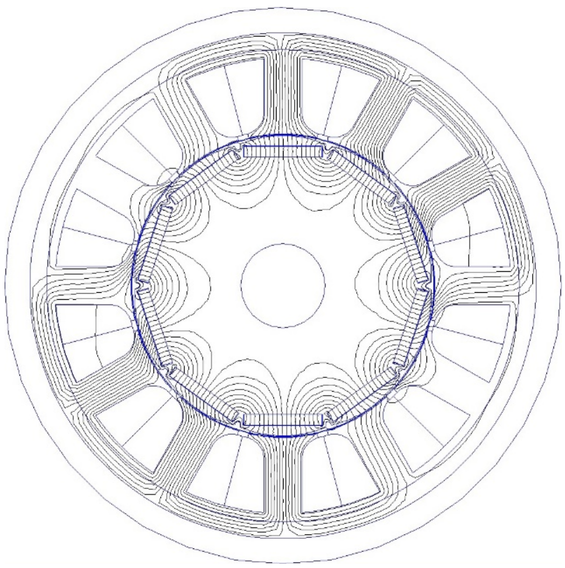
Streszczenie: W artykule przedstawiono zagadnienie rozmagnesowania magnesów z ziem rzadkich w silniku PMSM z magnesami zagłebionymi. Wstęp artykułu opisuje po krótce zagadnienia projektowe i eksploatacyjne dotyczące tego typu maszyn w zakresie mocy około 1 kW i prędkości 1500-3000 obr/min. Druga część artykułu pokazuje obliczenia magnetyczne wykonane metodą elementow skończonych w.w. maszyny, ze szczególnym naciskiem na pracę przy przeciążeniu oraz wypadnięciu z synchronizmu. Ostatnia część pokazuje wyniki badań rzeczywistych oraz porównuje je z wynikami obliczeń.

Abstract: Articles takes into consideration problem of demagnetization of rare earths magnets in PMSM with buried magnets. First part describes design and operation aspects of this type of machine with power around 1 kW and speed of 1500-3000 RPM. Second part shows electromagnetical calculations done with help of finite element. Especially overload and out-of-synchronism cases were investigated. Last part shows results of measurements of real machine and compares with calculations.

Słowa kluczowe: *PMSM, magnesy, odmagnesowanie, fractional slot winding*
Keywords: PMSM, magnets, demagnetization, fractional slot winding

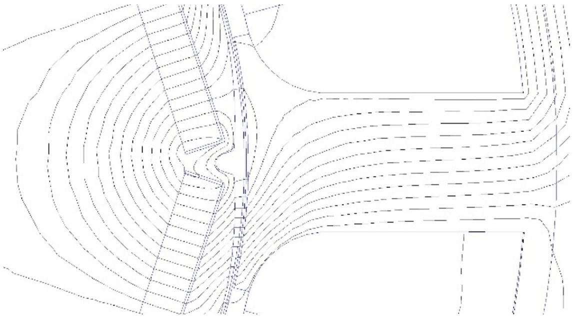
1. Introduction

Nowadays, due to higher efficiency regulations and requirements, synchronous machines with rare earths magnets are more and more common on the market. In industrial drives long lifetime and robustness are essential as well as price per unit. So in the mass production, cheap and well optimized product is important. Typical industrial motor must work in ambient temperature up to 40°C with overload factor around 2-3. This temperature and factor are also typical for industrial frequency converters and gearboxes. In these conditions motor must work with no risk of damage. When wire insulations class F (150°C) is used, the most critical elements in motor are magnets [1]. In PMSM motors with buried magnets and concentrated, fractional slot winding, it is possible to push the design to the limit. Construction is easy to be manufactured, assembly process is failure safe also for not trained workers, what is very important when the production must be set quickly. Efficiency is high (90-92%) thanks to relatively low winding resistance (due to short end connections) even when current density is relatively high (6-8 A/mm^2). Such machine is heavy exploited at nominal point. Especially the edges of magnets work in a high demagnetizing field. Picture 1 shows magnetic field flow in cross section of a 10 poles, 12 teeth, fully loaded machine. Picture 2 is a close-up on the corner of the most critical magnet. What is obvious – in this machine, at the certain moment of time, not all magnets create torque at the same level.



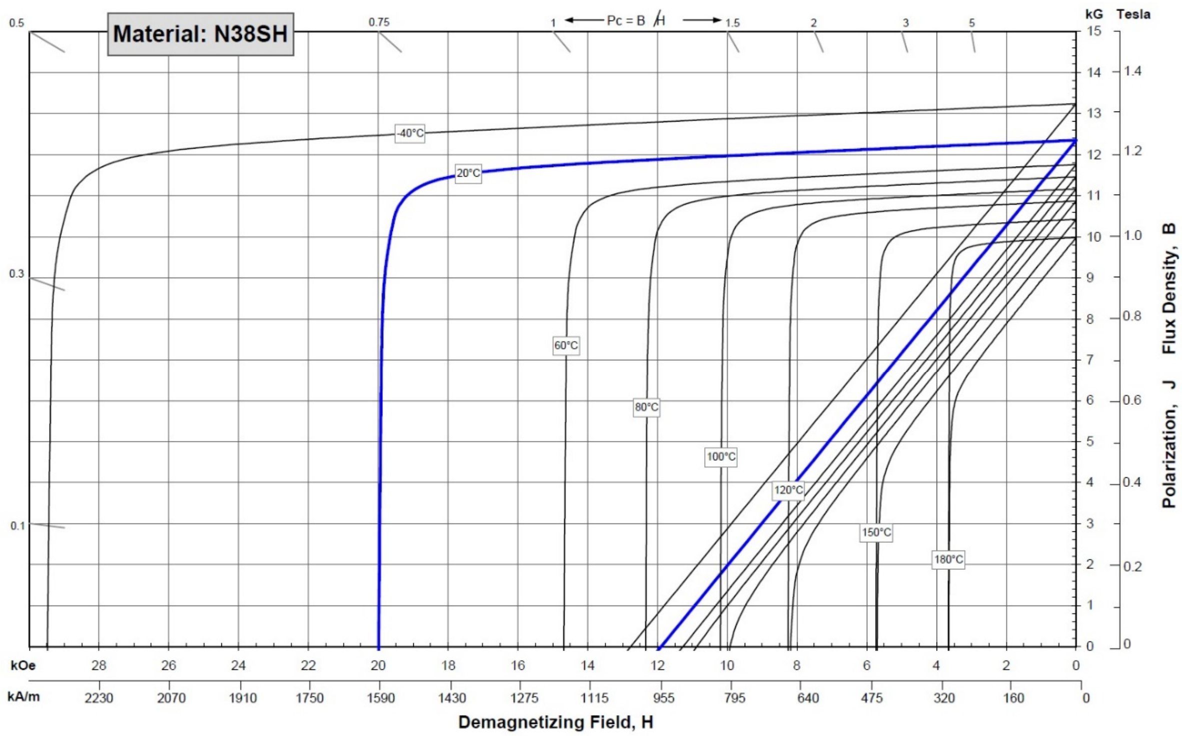
Picture 1. Filed inside fully loaded machine.

This phenomena and a way of investigation will be explained in the next paragraph. In article motor with magnets made of N38SH material is



Picture 2. Enlargement of the most critical magnet – upper one (90° electrical duty).

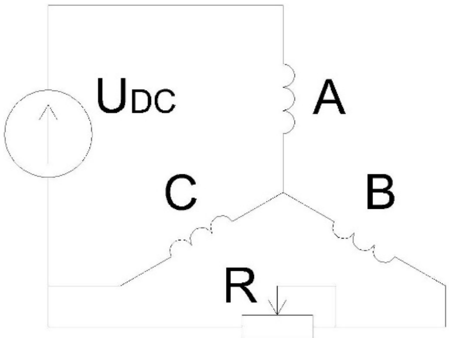
calculated and investigated. Of course there are already materials with higher H_{cJ} and H_{cB} so they can work safer either with higher overload or at higher temperature. The second square of magnetization curve for N38SH material is presented in picture 3. Investigation tries to summarize and give the answer whether simple, freeware program for finite element calculations of electromagnetic filed together with post processing script are able to deal with demagnetization problem at different temperatures. In commercial software, developed by well know companies there are several different demagnetization toolboxes. But these programs are out of reach of free designers and small, low-budget design groups.



Picture 3. II quadrant of hysteresis (picture - Arnold Company).

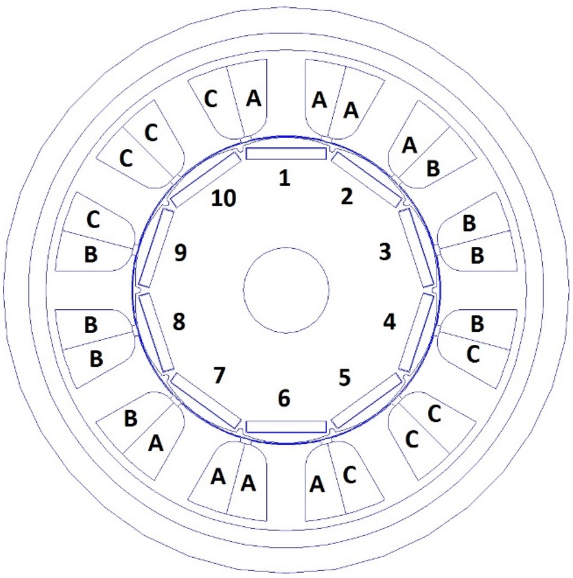
2. Problem definition and finite element calculations

The aim of this research is to find and check an easy method which says whether the designed construction of PMSM is safe under load and at certain temperature or not. The rule in industrial drives is that drive must work in all, defined on the nameplate conditions also with some safety (overload) factor. The test idea is to create similar load conditions like during real duty but on software simulation platform. In construction with buried magnets, due to pole shoe, field lines round magnet's corner are just smoother than in machines with magnets on surface. During finite element simulation the field strength was sampled along all magnets then in post processing script, temperature coefficient was added and it was checked if values of field strength along magnets are below H_{cJ}. If yes – it is considered as unacceptable case. Next step was to compare the results with tests, done with real motor. Normally, PMSM motors are fed by frequency converters. Fields in stator rotates as well as the rotor, load angle is usually constant, sometimes is dynamically changed and load dependent [2]. Because of PWM modulation and harmonics, there are ripples in current and it doesn't have pure sinusoidal shape. It is not easy to set and clearly measure load angle and three phase currents, especially when emergency case is studied - what is defined here as a "worst case scenario" - machine creates no torque and stator's flux is opposite to rotor's field. Solution was to create with real motor the conditions like during finite element simulations.



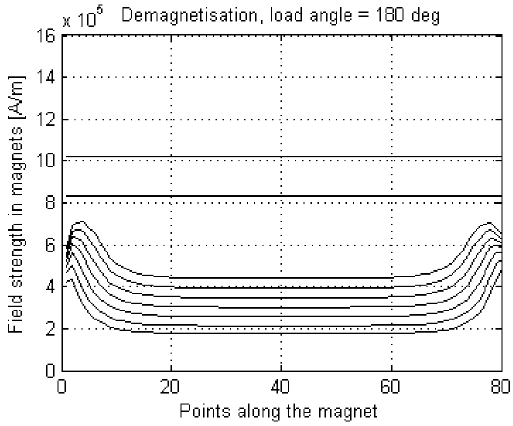
Picture 4. DC current supply circuit.

Three phases of winding were supplied with DC current source and the shaft was blocked by a precise worm gearbox with ratio 1:100. In this system virtual load at certain load angle was created. With help of resistive losses in supplied winding it was possible to warm up the motor so also the magnets. Such test circuit is very easy to be controlled. Test circuit is shown in picture 4. Cross section of motor is shown in picture 5. In this research two conditions were investigated: duty with load angle 90° and worst case, when load angle is equal to 180°.

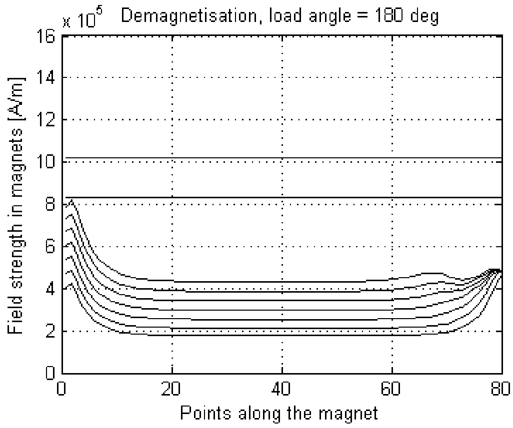


Picture 5. Cross section of motor with designated phases and magnets.

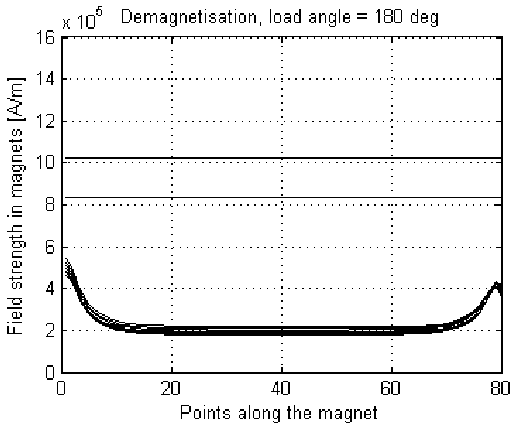
What could be predicted, with the currents described in Table 1 – at 180° (with rotor in position like in picture 5) or at 90° load angle (rotor turned 18° mechanical, clockwise from position in picture 5), the most endangered are magnets 2 and 7.



Picture 6. Field strength, magnet no. 1.

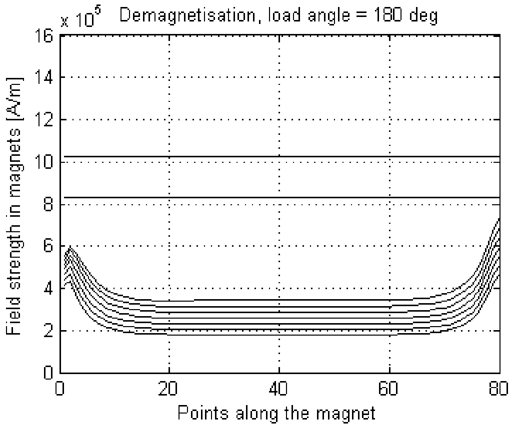


Picture 7. Field strength, magnet no. 2.

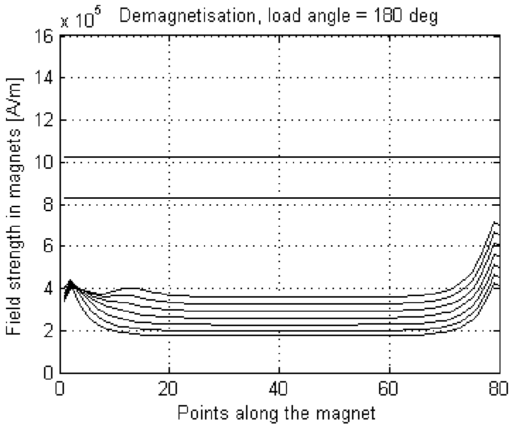


Picture 8. Field strength, magnet no. 3.

In finite element simulations it was arbitrarily chosen to sample the field strength 0,1 mm under the surface of magnets. This place of sampling is the most critical in the magnets. Due to mesh size in this area, there is no reason to reduce this distance. To decrease this distance the mesh size should be also decreased so the number of elements of mesh rises dramatically but final effect is very similar.



Picture 9. Field strength, magnet no. 4.



Picture 10. Field strength, magnet no. 5.

As it was mentioned – field in all magnets was analyzed - at the beginning of simulation it was not sure which magnet and what points are the most critical.

	50 %	100 %	150 %	200 %	250 %	300 %
Ia	1.54	3,09	4,64	6,18	7,72	9,27
Ib	0,41	0,82	1,24	1,65	2,07	2,48
Ic	1.13	2,27	3,40	4,53	5,65	6,79

Table 1. Currents in [A] for different load points, DC test.

In pictures 6, 7, 8, 9, 10 fields' strengths for magnets 1 to 5 are shown. Always, the lowest line is for no current case and the highest – at 3 times nominal current. Step is 0.5 times nominal current. Additionally, in each picture three levels for $H_{cJ} = 0$ are shown at 100°C, 80°C and 20°C (just on top) respectively. In all these pictures, only component normal to surface of magnet is presented; component parallel to surface of magnet is neglected [3].

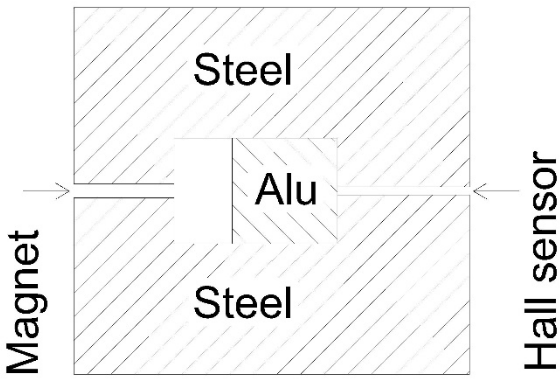
3. Real motor tests.

To validate simulations, three phases were connected like in picture 4. With help of variable resistor the balance of currents in phase B and C was set. It was essential to have a variable resistor because of variable temperature of winding so also temperature dependent winding's resistance. Table 2 describes what tests were done. Range of tests was wide because it had to be sure at which load point magnets would be demagnetized.

		2 x IN	2,5 x IN	3 x IN
90° load angle	20°C	ok	ok	ok
	40°C	ok	ok	ok
	60°C	ok	ok	ok
	80°C	ok	ok	ok
	90°C	ok	ok	ok
180° load angle	20°C	ok	ok	ok
	40°C	ok	ok	ok
	60°C	ok	ok	ok
	80°C	ok	ok	ok
	90°C	ok	ok	ok

Table 2. Test routine for magnets and results.

Temperature of magnets was measured with thermocouple placed along one magnet. Time of temperature rise was about 2 hours. So it was sure that all magnets had the same temperature. After each test point motor was disassembled and magnets were checked in magnetic circuit shown in picture 11. Device was made of standard C45 steel.



Picture 11. Magnetic circuit for testing magnets.

Magnetizing curve of this steel was unknown but due to big air gap for hall sensor (1 mm) and oversized dimensions, steel was working fairly below saturation point (measured flux density, in the air gap, was around 275-285 mT for all magnets, at 20°C). This device gives possibility to test only one point of magnetizing characteristic of magnets but it is enough to compare good magnet with partially demagnetized. As it could be seen, magnets stayed magnetized during whole tests (Table 2).

4. Conclusions.

In table 3 the most important parameters of investigated motor are shown. More detailed parameters and features are described in [4].

Parameter	Value
Nominal torque	5 Nm
Efficiency at speed	91.2% at 1500rpm
Stator outer diameter	120 mm
Stator inner diameter	68 mm
Air gap	0.5 mm
Package length	30 mm
End winding high	9 mm
Active part length	48 mm
Magnet thickness	2.5 mm
Magnet type	N38SH
Amount of magnets	0.102 kg
Amount of steel	1.6 kg
Steel type	M330-35A
Amount of copper	0.55 kg
Nominal temp. (magnets)	80°C

Table 3. Parameters of the tested motor.

As it was calculated with help of finite element software, and then proved during tests – this construction is fully safe under required conditions. During all tests magnets stayed fully magnetized. Tests at higher temperature were not done because of exceeded maximum allowed temperature of winding. It is hard to say if this simulation and calculations method gives vary accurate results. In future it is planned to design and test motor with similar construction but with nominal torque around 15-20 Nm. Nominal temperature will be increased up to 100°C. Proposed method will checked again. Conducted investigation shows clearly that in small motors, with power around 1 kW it is possible to use very thin magnets. Magnet's manufacturers say that the limit of thickness is just around 2 mm. Below 2 mm, magnet becomes sensitive to any mechanical shock [5]. So the assembly process could be difficult. But even with little bit oversized magnets, PMSM motors with concentrated winding are cheaper (in range of power) than any other synchronous motors – for the same output power and efficiency. Of course this statement is correct assuming price of magnets around 100-150 Euro per kilogram [6].

5. Literature

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