TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ELECTRICAL ENGINEERING | ELEKTROTECHNIKA

1-E/2015

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THE INFLUENCE OF CRYOGENIC TEMPERATURES ON THE CHARACTERISTICS OF A BRUSHLESS MOTOR

WPŁYW TEMPERATURY KRIOGENICZNEJ NA CHARAKTERYSTYKI SILNIKA BEZSZCZOTKOWEGO

A b s t r a c t

This article presents the results of a study on the magnetic properties of soft magnetic powder composites at room temperature and at liquid nitrogen temperature. The properties of a magnetoelectric motor with the power of 0.75 kW at room temperature and cryogenic temperatures are also presented in this article. The study of magnetic properties showed that magnetization curves at 20°C and -195.8°C temperatures are almost the same. Iron loss in the composite at liquid nitrogen temperature increased significantly in comparison to loss at room temperature. The study of the magnetoelectric motor showed that the back electromotive force at liquid nitrogen temperature decreases insignificantly in comparison to the back electromotive force at room temperature. Electromagnetic torque at liquid nitrogen temperature increases in comparison to room temperature.

Keywords: *electrical machines*, *powder metallurgy*, *cryogenic condition*

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań właściwości magnetycznie miękkich kompozytów proszkowych oraz parametry silnika magnetoelektrycznego o mocy 0,75 kW w temperaturze pokojowej i kriogenicznej. Badania właściwości magnetycznych kompozytów pokazały, że krzywe magnesowania określone w temperaturach 20°C i -195,8°C są zbliżone, natomiast straty mocy w schłodzonym kompozycie proszkowym znacznie się zwiększyły. W badaniach silnika magnetoelektrycznego wykazano nieznaczne zmniejszenie siły elektromotorycznej i przyrost momentu elektromagnetycznego w czasie pracy silnika w temperaturze ciekłego azotu w stosunku do parametrów w temperaturze pokojowej.

Słowa kluczowe: *maszyny elektryczne, metalurgia proszków*, *warunki kriogeniczne*

DOI: 10.4467/2353737XCT.15.049.3849

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1. Introduction

Electric drives for cryogenic temperatures below -150°C such as liquid gases: e.g. nitrogen, hydrogen, helium and natural gas are applied more often in the industry. Among others, cryogenic drives are applied in the cars supplied with hydrogen, rocket engines, cooling apparatus, devices for the storage and transportation of liquefied natural gas. Devices for storage, transport and processing should be employed in pumps and electric drives working in the atmosphere of liquefied gases. Electric machines applied in modern pumps of liquefied gases usually work whilst immersed and liquefied gas flows through the gap between the stator and the rotor.

Articles [1–2] show results of the study of a three phase induction motor working as a part of a pump immersed in liquefied natural gas. The article [3] presents computer simulations of a high voltage squirrel cage induction motor with 1 MW power working in liquefied natural gas (LNG) at a temperature of -162°C. The study showed that the induction motor immersed in liquid gas develops higher maximum torque and less change of rotational speed than the induction motor working at room temperature. The disadvantage of the cooled motor is a smaller starting torque resulting from lower resistance of an aluminum squirrel cage. Article [4] shows the study of a magnetoelectric motor applied for a pump drive of fuel in a new cryogenic drive for a rocket with low thrust.

Temperature changes of soft and hard magnetic materials lead to changes of their physical properties. The authors in publications [5] showed the results of measurements of magnetic properties of non-oriented steel sheets in cryogenic conditions. It was observed that at low magnetic field strengths, magnetic induction is lower in cryogenic conditions than at room temperature. At high magnetic strengths, magnetic induction is insignificantly higher for cryogenic conditions than at room temperature. The results of the measurements presented in article [6] showed that in liquid nitrogen immersion of iron based soft magnetic composites, their magnetic permeability is lower and their total loss is increased compared to when at room temperature.

In the case of Nd-Fe-B, permanent magnets lowering their temperature leads to an increase in remanence and coercivity. Manufacturers' catalogues of permanent magnets usually present the temperature coefficients of remanence and coercivity only for changes from 20°C to 100°C. For sintered Nd-Fe-B permanent magnets, values of the temperature coefficient of remanence is from -0.08 to -0.11%/K depending on the composition of the alloy. The temperature coefficient of coercivity of polarization of sintered Nd-Fe-B permanent magnets is from -0.5 to -0.6%/K. For isotropic bonded permanent magnets, the temperature coefficient of remanence is from -0.11 to -0.14%/K, for coercivity of magnetic polarization, the coefficient is about -0.4%/K [7].

In Tele and Radio Research Institute, the changes of magnetic parameters of bonded permanent magnets obtained from the Nd-Fe-B powder, type MQP-B produced by Magnequench Company, compressed and bonded by epoxy resin were measured. The measurements of the magnetic properties were carried out in a liquid nitrogen atmosphere at a temperature of -195.8°C and at room temperature. The temperature coefficient of remanence is -0.17%/K, whereas the coefficient of intrinsic coercivity is -0.39%/K determined for room and liquid nitrogen temperature [8].

The main aim of research was to determine the magnetic property changes of soft magnetic materials on parameters of the magnetoelectric motor.

2. Methodology of research

2.1. The research of magnetic properties of soft magnetic composites

The samples for the research were manufactured from commercially available soft magnetic powder called Somaloy 500 with the addition of lubricating binder LB1. The particles of iron powder are covered with a bonding agent that also ensures electrical insulation between particles. The composite samples were obtained by the cold compression moulding of powder with 800 MPa pressure. The green compacts that are mechanically weak were cured in air atmosphere at a temperature of 200°C for 60 minutes. The ring shaped samples for the magnetic measurements had the following dimensions: outer diameter 75 mm, inner diameter 55 mm, and height 10 mm.

The magnetization curves and the total power loss P_{tot} were measured by the measurements of dynamic hysteresis loops according to the IEC 60404-6 standard. The measurements of a hysteresis loop were carried out by the AMH-20K-HS system manufactured by the Laboratorio Elettrofisico Walker LDJ Scientific. The total power loss was determined for the frequency from 50 to 600 Hz for the amplitude of induction B_{max} = 1.0 T. The maximum error of measurements of total loss equals 3%. During the measurements of the magnetic properties, the back electromotive force induced in the measuring coil was sinusoidal with the shape coefficient equal to 1.111 ± 0.006. The measurements were conducted at room temperature and at liquid nitrogen temperature.

2.2. Measurements of properties of the brushless electric motor with the composite stator

Parts of the stator were cut using electric discharge machining from cylinders with a diameter of 63 mm and a height of 22.5 mm manufactured from Somaloy 500 + 0.6% LB1 (Fig. 1).

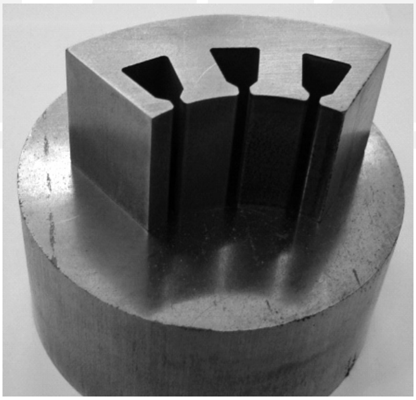

Fig. 1. Part of a stator and a half-finished product from iron powder composite

The obtained stator parts were glued with two component epoxy glue. In the research, the 4 pole motor with permanent magnets with 0.75 kW power and rotational speed 18 000 rpm was analyzed. The structure of this motor is presented in Fig. 2 [9].

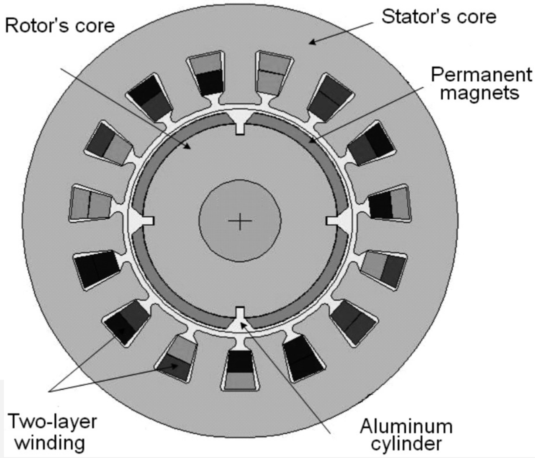

Fig. 2. The structure of analyzed motor

The analyzed electric motor consists of a stator with 15 slots, the rotor a 4 sintered Nd-Fe-B permanent magnets produced by Vacuumschmelze (VAC 669AP) and an aluminum cylinder. Typical parameters of permanent magnets obtained from the manufacturer's catalogue are the following: B_r = 1.16 T; H_{Cb} = 885 kA/m; H_{cJ} = 2000 kA/m; $(BH)_{\max}$ = 255 kJ/m^3. The temperature coefficient of remanence α_{Br} = -0.085%/°C, the temperature coefficient of coercivity β_{HcJ} = -0.57%/°C with changes of temperature from 20°C to 100°C. The analyzed motor should have higher magnetic flux density in the air gap resulting from lower temperature of permanent magnets in cryogenic temperatures. The motor has a two-layered, frictional-slotted winding with $q = 1\frac{1}{4}$ slots for a pole and a phase. A commercial motor housing from the motor manufactured by the Motor and Controller company, model MBL-92FT-300HA was used.

The measurements of parameters of the motor in the liquid nitrogen immersion needed the application of type C4 bearings with the enhanced bearing slackness. Before the assembly, sealants and lubricant were removed from bearings using acetone. The courses of interfacial back electromotive force and the electromagnetic torque in the function of rotor's position were measured. The back electromotive force was determined for the two rotational speeds of 1000 and 1500 rpm. During the measurements of the back electromotive force, the measured motor's rotor was moved by the three phase induction motor Skh-56-6B with the LG SV-iG5A inverter. The recording of the back electromotive force was carried out by the digital scope Tektronix TDS 210. The course of the electromagnetic torque was measured at the supply of the motor with direct current in brushless DC mode ($i_a = -i_b$ and $i_c = 0$). The measurements were done for two values of supply current i_a = 3 A and i_a = 5 A. DC supply GW Instek PSP-2010 was used in the research. The electromagnetic torque was registered with MW 2006-3S device co-working with the MT-3Nm torque meter manufactured by the Roman Pomianowski's Electronics Laboratory. During the recording of the electromagnetic torque, the measured motor was connected with 1 phase W&W Motor YJF61/16 with a gear-motor and the rotational speed was 0.8 rpm. Measurements were done at room temperature and next at the temperature of liquid nitrogen.

3. Results of measurements

In the first part of the research, the magnetic properties of soft magnetic composites were measured. The magnetization curves at 50 and 600 Hz frequency at room temperature and at liquid nitrogen temperature were measured. The magnetization curves almost overlap (Fig. 3).

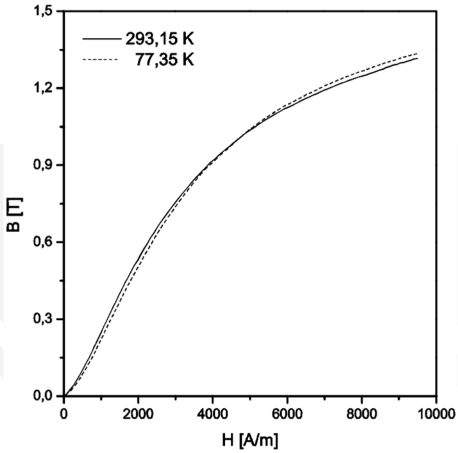

Fig. 3. The magnetization curves of powder soft magnetic composites measured at room and liquid nitrogen temperature, $f = 50$ Hz

The magnetization curves differ only in the speed increase of magnetic induction *B* which causes differences in the maximum magnetic permeability of the iron magnetic composite. Maximum magnetic permeability was equal to 215 for the temperature of 20°C and 202 for the temperature of -195.8°C at the frequency 50 Hz and 600 Hz.

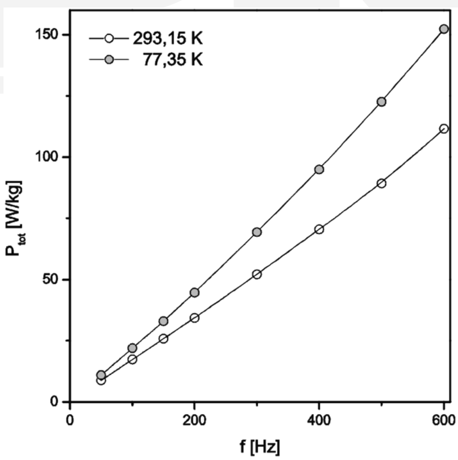

Fig. 4. The total power loss of iron soft magnetic composites measured at room and liquid nitrogen temperature, $B_{max} = 1.0$ T

The decrease in the sample's temperature to -195.8°C caused an increase of total power losses P_{tot} in the magnetic core. The increase in the loss of eddy currents is caused by the decrease of the resistivity of the material. The increase of coercivity causes the increase of hysteresis loss and magnetization energy due to a decrease of crystal lattice oscillations and a decrease of domain wall movements [8]. For example, at the magnetization frequency 50 Hz, the total power loss at liquid nitrogen temperature is about 25% higher than at room temperature, whereas at the frequency 600 Hz, it is more than 35% (Fig. 4).

In the second part of the research, the interfacial back electromotive force and electromagnetic torque was measured as a function of the angle of the rotor's rotation.

The analyzed magnetoelectric motor has asinusoidal back electromotive force at the 1000 rmp (Fig. 5a)) and 1500 rpm (Fig. 5b)) at room temperature and at liquid nitrogen temperature.

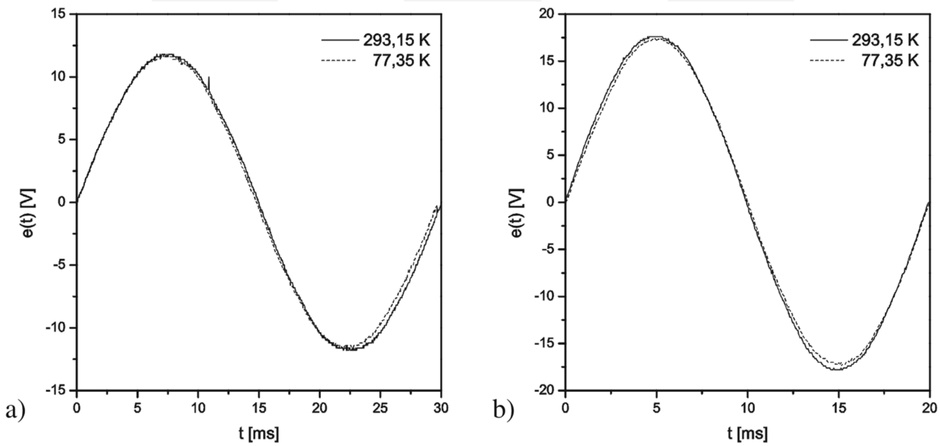

Fig. 5. The back electromotive force at the rotational speed: a) 1000 rpm, b) 1500 rpm measured at room temperature and liquid nitrogen temperature

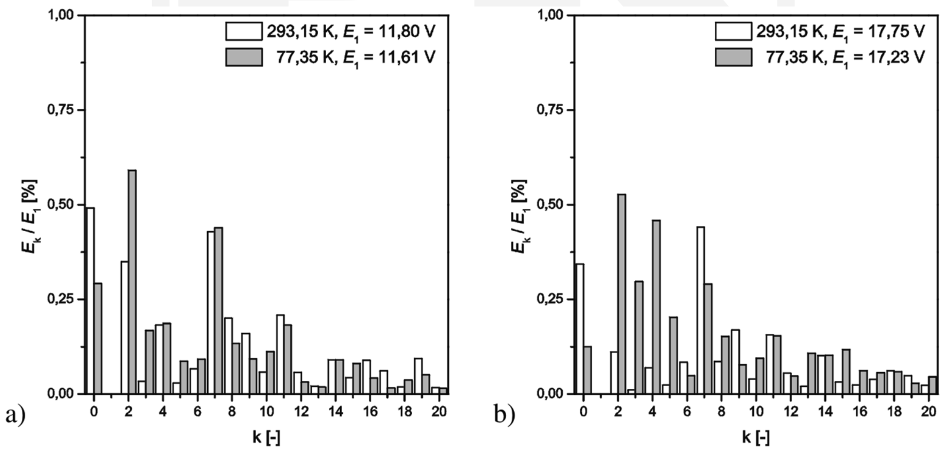

Fig. 6. Higher harmonics E_k in relation to the first harmonic E_1 at the rotational speed: a) 1000 rpm, b) 1500 rpm at room and liquid nitrogen temperature

After cooling the motor to liquid nitrogen temperature, the first harmonic of the back electromotive force decreases at the rotational speed 1000 and 1500 rpm but the change does not exceed 3%. Harmonics of 2, 3, 4 and 5 order increase their values (Figs. 6a) and b)). This effect leads to changes of total harmonic distortion (THD) coefficient. THD coefficient determined for rotational speed 1500 rpm at room temperature is equal 0.84%, whereas at liquid nitrogen temperature, it is 1.16%.

Table 1 shows the average rectified, effective-root mean square and maximum values of induced back electromotive forces for room temperature and liquid nitrogen temperature. Table 1 also presents shape and peak factors.

Table 1

Average rectified, effective-root mean square and maximum values, shape and peak factors of back electromotive forces

Room temperature (20°C)					
n (rpm)	U_{arv} (V)	U_{rms} (V)	U_m (V)	k_{rms} (-)	k_{peak}
1500	11.33	12.57	17.60	1.109	1.401
1000	7.52	8.35	11.80	1.110	1.414
Liquid nitrogen temperature (-195.8°C)					
1500	10.96	12.19	17.40	1.112	1.428
1000	7.41	8.22	11.80	1.109	1.436

The shape of the generated electromagnetic torque is sinusoidal (Figs. 7a) and b)).

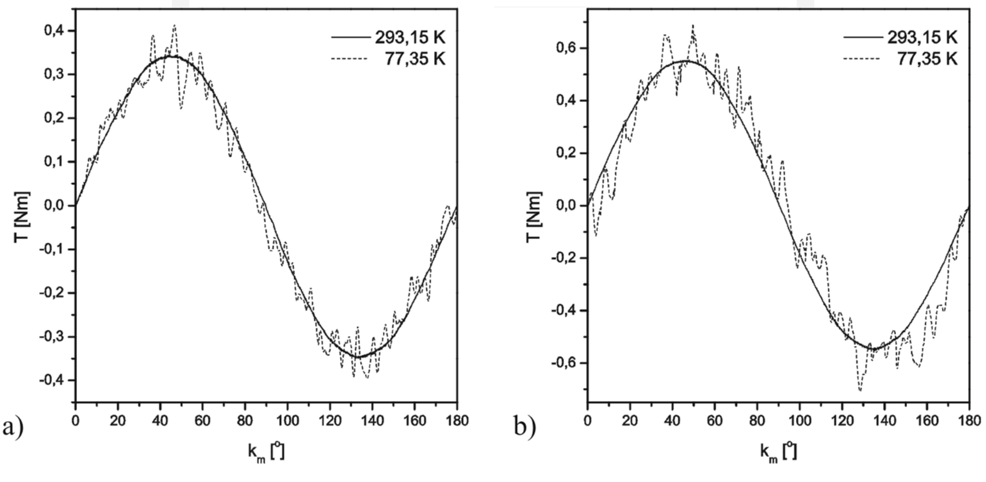

Fig. 7. The electromagnetic torque for: a) i_a = 3 A, b) i_a = 5 A measured at room and liquid nitrogen temperature

At the temperature of –195.8°C, unfavorable torque fluctuations caused by a bearing in a socket between a motor and a torque meter are seen in Figs. 7a) and b). This effect causes higher harmonics increase (Figs. 8a) and b)).

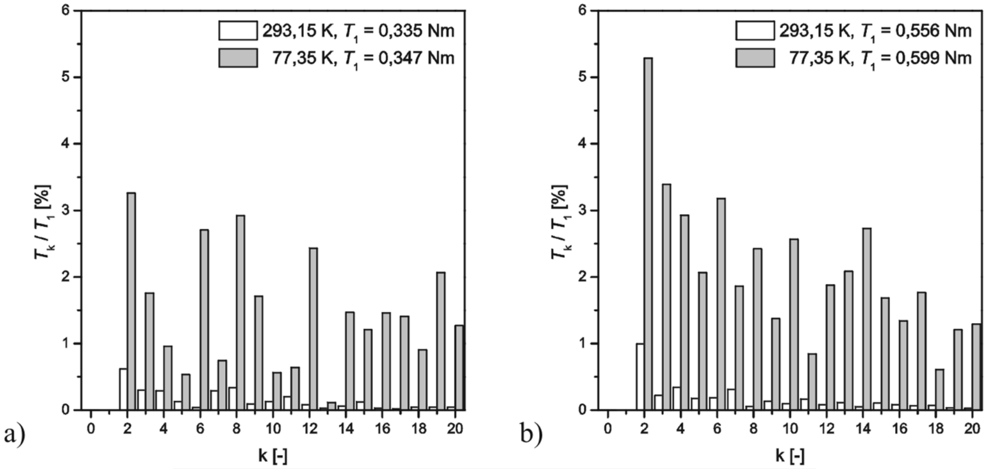

Fig. 8. Higher harmonics of electromagnetic torque T_k in relation to the first harmonic T_1 for: a) i_a = 3 A, b) i_a = 5 A measured at room temperature and at liquid nitrogen temperature

After the decrease of the temperature to liquid nitrogen temperature, an increase of the first harmonic of electromagnetic torque by 3% and 7% for i_a = 3 A and i_a = 5 A respectively, can be seen. In turn, the coefficient of total harmonics distortion THD described at room temperature changes from 1.44% at i_a = 3 A to 1.33% at i_a = 5 A.

4. Conclusions

The influence of temperature on the characteristics of the magnetoelectric motor with a stator manufactured from iron soft magnetic composites are presented in the article. Results of measurements of magnetic properties of soft magnetic composites showed that the influence of temperature on magnetization curves is very small. Significant differences can be observed in the measurements of total power losses at room temperature and at liquid nitrogen temperatures. The increase of total losses is caused by the increase of eddy current loss due to the lower resistivity of the iron based composite and increase of hysteresis loss due to higher coercivity of the iron based composite.

The back electromotive force induced in the motor after cooling in liquid nitrogen insignificantly decreases its value. Simultaneously, the increase of higher harmonics 2, 3, 4 and 5 can be observed.

It is observed increase of its first harmonic of electromagnetic torque after decrease of temperature of a motor. However, parasitic torque from bearings would not allow precise analyses.

The research shows that powder soft magnetic composites can be applied in devices working at cryogenic temperature conditions. Measurements of dynamic parameters of the analyzed motor should be the final tests of application of the powder magnetic composites in cryogenic temperatures.

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