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ANALYSIS AND MEASUREMENTS OF BRUSHLESS DC MOTOR WITH MAGNETIC CIRCUIT MADE OF SOFT MAGNETIC COMPOSITE AND ND-FE-B BONDED MAGNET

Summary. Magnetic composites made of powder are more often applied in modern electric machines as magnetic circuits. These magnetic materials can be divided into two groups: soft magnetic composites and bonded permanent magnets. The main purpose of the work was to design, manufacture and measure parameters of a brushless DC motor with powder magnetic circuits. The powder magnetic core has been prepared from iron powder bonded by resin and 4 pole permanent magnet which has been prepared from powder of Nd-Fe-B melt-spun ribbon bonded also by resin. Permanent magnet DC brushless motor with nominal power of 250 W and rotational speed of 6000 rpm has been designed based on measured parameters of powder materials. Measurements of brushless DC motor supplied from commercially available electronic commutator have been done.

Keywords: BLDC motor, powder materials, measurements of parameters of electric motor

ANALIZA I POMIARY BEZSZCZOTKOWEGO SILNIKA PRĄDU STAŁEGO Z PROSZKOWYM OBWODEM MAGNETYCZNYM I SPAJANYM MAGNESEM TRWAŁYM ND-FE-B

Streszczenie. Kompozytowe materiały magnetyczne wykonane z proszku spajanego tworzywem coraz częściej pełnią rolę obwodu magnetycznego w maszynach elektrycznych. Materiały tego typu można podzielić na dwie grupy: kompozyty magnetycznie miękkie i spajane magnesy trwałe. Celem pracy było zaprojektowanie, wykonanie, a następnie wyznaczenie parametrów silnika BLDC z proszkowym obwodem magnetycznym. Stojan maszyny wykonano ze sproszkowanego żelaza spajanego żywicą, a magnes z proszku z szybko chłodzonej taśmy Nd-Fe-B również spajanego żywicą. Bezszczotkowy silnik prądu stałego z magnesem trwałym o mocy znamionowej 250 W i prędkości znamionowej 6000 obr/min został zaprojektowany na podstawie zmierzonych właściwości fizycznych materiałów proszkowych. Wyznaczone w czasie pomiarów parametry silnika BLDC zasilanego z komercyjnego komutatora przedstawiono w artykule.

Słowa kluczowe: silnik BLDC, materiały proszkowe, pomiary parametrów silnika

1. INTRODUCTION

Soft magnetic materials and hard magnetic materials in the form of elements made from powder are more likely to be used in industrial electrical equipment. There are two basic technologies to prepare the magnetic elements: sintering and bonding by dielectric agent methods. The second method is becoming more widely used because of its advantages, one of which is the reduction of losses from eddy currents. The compression moulding method also allows creating components of magnetic circuit in complex shapes and with high dimensional accuracy. It is also possible to tailor the physical properties of elements by changing the physical properties of magnetic powder, amount of resin and parameters of technology used.

Many authors conducted a lot of research on soft magnetic composites [1-5] and bonded magnets [6-8] as magnetic materials for electric machines and other electromagnetic transducers. In latest years a lot of projects of electric machines have been done and many model motors have been designed, manufactured and measured, such as BLDC [9] permanent magnet [10], claw pole [11-13], linear [14], and slotless [15] motors.

Main task of research was to design, manufacture and measure parameters of brushless DC motor with powder magnetic circuits. Electromechanical parameters of motor should be better than series AC motor with mechanical commutator and electronic speed controller. Efficiency of such motors is about 40 %.

2. POWDER MAGNETIC MATERIALS

2.1. Bonded permanent magnets

In experiments, powder from Nd-Fe-B melt spun ribbon type MQP-A produced by company named Magnequench has been used as hard magnetic powder. This powder can be used as basic material for preparing permanent magnets, e.g. by compression. In this method grains of hard magnetic powder are bonded by a thermosetting modified epoxy resin. Figure 1 shows the demagnetization curves of bonded magnet from this Nd-Fe-B powder.

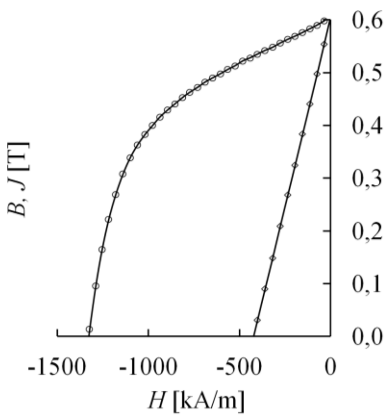

Fig.1. Demagnetization curves of bonded magnet of Nd-Fe-B powder
Rys.1. Krzywe odmagnesowania spajanego magnesu trwałego z proszku Nd-Fe-B

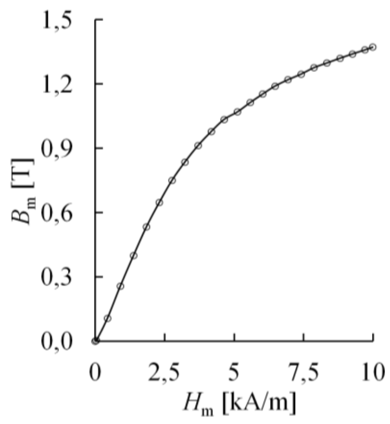

Fig. 2. Magnetization curve of iron powder composite made of Somaloy 500
Rys. 2. Krzywa magnesowania kompozytu z proszku Somaloy 500

2.2. Soft Magnetic Composites

Iron powder used in experiments has been produced by water atomization. It is called Somaloy 500 and is produced by Höganäs AB Company. Grains of iron powder for soft magnetic composites are covered chemically by thin inorganic insulation layer with thickness of a few nanometers. The soft magnetic material, which was used, was a commercially available iron powder with a binding agent. Soft magnetic composite (SMC) materials due to their parameters can be used in electric motor with high rotational speed that will improve the electrical efficiency. Figure 2 shows the magnetization curve of Somaloy 500.

3. BRUSHLESS DC MOTOR

3.1. Design and Magnetic Field Analysis of BLDC Motor

According to analytical methods brushless DC motor has been designed. Brushless DC motor has three phase, four pole permanent magnet and stator with six pole pieces. Each phase consists of two concentric coils placed on rounded pole body. Rounded poles decrease length of winding and decrease leakage flux. After design process of the motor analyses has been conducted using finite element method. This method allows analyzing the magnetic field distribution and electromagnetic torque calculation. Computer’s calculations have been performed for planar model using magnetostatic module using software FEMM 4.2. Model has been divided in 38360 surface elements and had 76145 nodes. Calculations have been done with prescribed the magnetic vector potential $\boldsymbol{A} = 0$ Wb/m along an external surface.

Figure 3 presents distribution of magnetic flux density and vectors of magnetic flux density and figure 4 presents distribution of magnetic field lines, calculation has been conducted for BLDC control mode (e.g. $i_a = -i_b$ and $i_c = 0$ A) and current value $i_a = 6.5$ A. In figure 5 is presented distribution of normal component of magnetic induction B_n in air gap of motor (current $i_a = 0$ A).

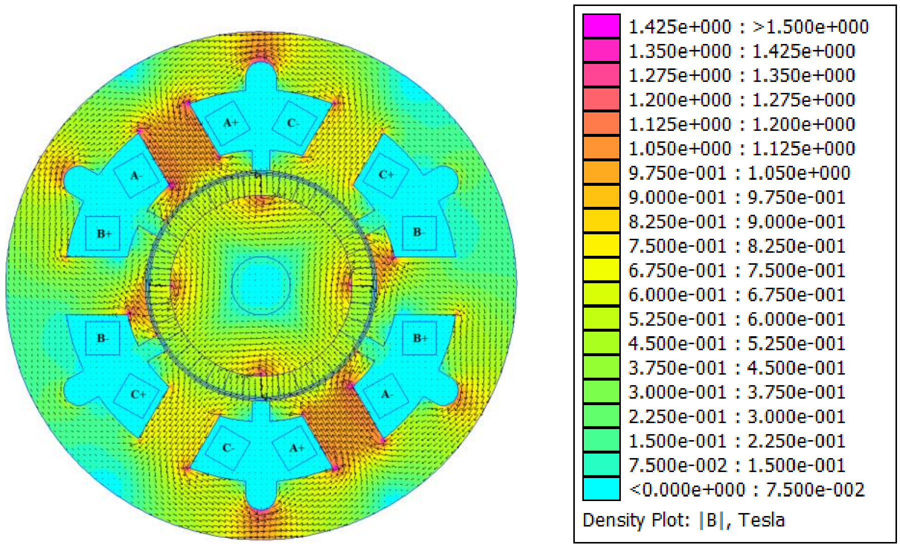

Fig. 3. Distribution of magnetic flux density and vectors of magnetic flux density
Rys. 3. Rozkład modułu i wektorów indukcji magnetycznej w silniku

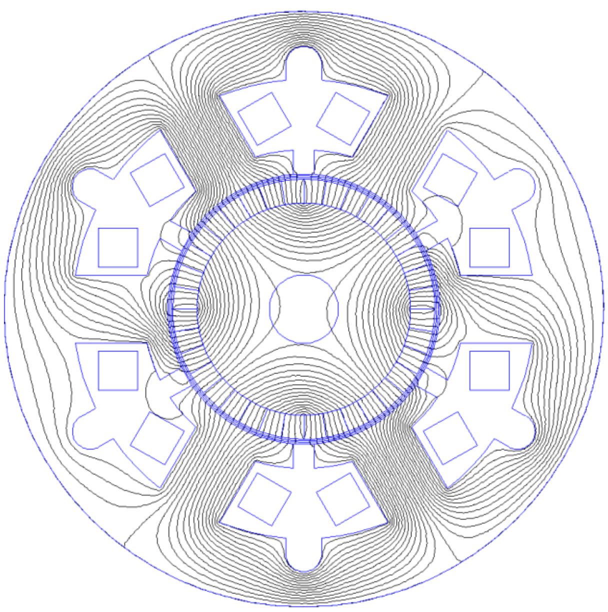

Fig. 4. Distribution of magnetic field lines
Rys. 4. Rozkład linii sił pola magnetycznego w silniku

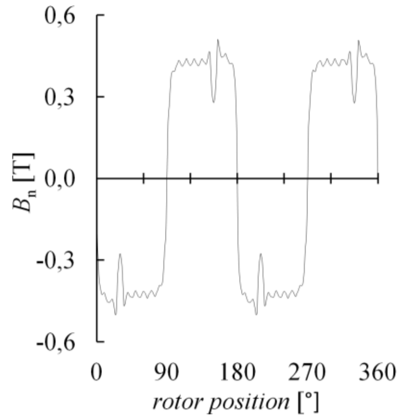

Fig. 5. Distribution of normal component of magnetic flux density in the air gap
Rys. 5. Rozkład składowej normalnej indukcji magnetycznej w szczelinie powietrznej

3.2. Construction of BLDC Motor

Figure 6 presents soft magnetic core manufactured in Tele and Radio Research Institute. It is made of iron powder Somaloy 500 with resin. Complicated shapes for model electric motor were obtained by electrical discharge machining. Six parts of a stator have been glued before winding. In production process a form with shape of stator's core has to be designed and manufactured. Figure 7 presents four pole bonded magnet made of Nd-Fe-B powder. Magnetization of permanent magnet has been conducted using impulse magnetizer and magnetization fixture designed and manufactured in Tele and Radio Research Institute. Magnetization fixture for radial multipole magnetization comprises of two parts. First of them is placed inside the magnet and the second outside the magnet. They are connected in series. During magnetization impulse current of 11,7 kA is flowing through wires for mili seconds. Fig. 7 presents also configuration of magnetic poles obtained using magnetic field viewer. Dark places show magnetic poles and bright lines show neutral lines of permanent magnet. Figure 8 shows a photo of brushless DC motor with powder components. At the end of the shaft is placed rotor's position sensor with 4 pole Nd-Fe-B bonded magnet and 3 Hall sensors type SS411A produced by Honeywell. The permanent magnet for position sensor has been produced in Tele and Radio Research Institute.

Fig. 6. Soft magnetic stator core
Rys. 6. Stojan silnika z proszku magnetycznie miękkiego

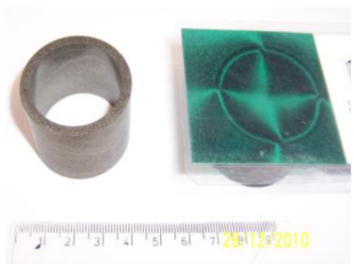

Fig. 7. Four pole Nd-Fe-B bonded magnets
Rys. 7. Czterobiegunowy spajany magnes z proszku Nd-Fe-B

Fig. 8. Brushless DC motor
Rys. 8. Bezszczotkowy silnik prądu stałego

4. RESULTS OF MEASUREMENTS

4.1. Electromotive force

Measurement of induced electromotive force (*emf*) has been conducted at 3000 rpm (a half of rated speed). The analyzed motor is characterized by trapezoidal electromotive phase force (Fig. 9). Total percentage of higher harmonics is equal to 9.18 % for *emf* induced in phase. Figures 10 presents the percentage of higher harmonic related to the first harmonic. Higher harmonics in the spectrum of *emf* can divide into two groups. First group is called a low-order harmonics of a magnetomotive force (*mmf*) (harmonic 5 and 7). Their existence is due to rectangular distribution of normal magnetic flux density in the air gap (Fig. 5). A Slot-harmonics belong to second group (harmonic 2 and 4), in order to determine the slot-harmonic, the following expression can be used $\upsilon = (2S/p) \pm 1$, where S is a number of a stator slots, p is a number of poles.

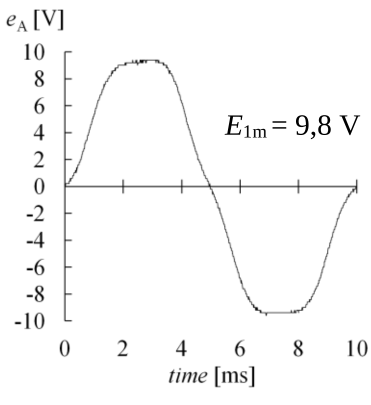

Fig. 9. Phase *emf* e_A waveform determined at rotor speed of 3000 rpm
Rys. 9. Fazowa siła elektromotoryczna e_A wyznaczona dla prędkości 3000 obr/min

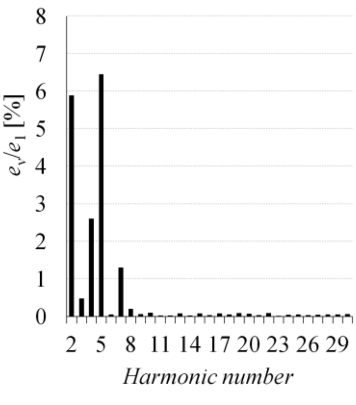

Fig. 10. Percentage higher harmonic e_v related to first harmonic e_1 of *emf* waveform
Fig. 10. Procentowa zawartość wyższych harmonicznych e_v odniesiona do harmonicznej podstawowej e_1

4.2. Load analysis

Model brushless DC motor has been supplied from 4 rechargeable batteries with capacity 65 Ah each, connected in series with nominal voltage U=48 V by a commercially available electronic commutator. In production motor commercial commutator is assumed to be replaced with new commutator designed especially for this brushless DC motor. Electric motor was supplied by servo amplifier SCA-B4-70-10 produced by Electrocraft company. Measurements of brushless DC motor have been conducted with an eddy current brake. Electromechanical characteristics of motor have been taken from no load speed of 6000 rpm and then with increasing torque up to 0.5 Nm.

As it can be seen in figure 11 rotational speed is decreasing linearly after exceeding torque of 0.1 Nm.

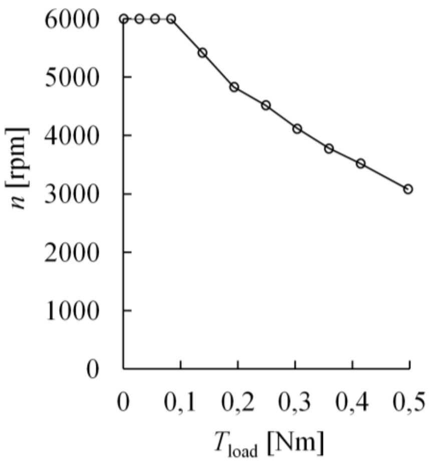

Fig. 11. Load characteristic of BLDC motor
Rys. 11. Charakterystyka mechaniczna silnika BLDC

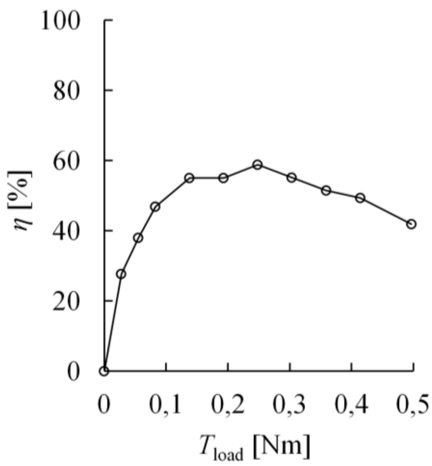

Fig. 12. Motor efficiency
Rys. 12. Sprawność silnika

The highest value of efficiency of the system consisting of the analyzed motor and the servo amplifier is equal to 59 % (Fig. 12). The analyzed system has reached this value of efficiency at rotor speed of 4520 rpm and at load torque of 0.25 Nm. At rated load torque (0.2 Nm) the rotor speed is approximately 20 % less than its synchronous speed.

In figure 13 torque-angle characteristic of BLDC motor is presented, measurement has been conducted for BLDC control mode (i_a = -i_b and i_c = 0) and current value i_a=6.5 A. A beam with a length of 100 mm has been installed on the end of the motor shaft. Measurement of the force has been done using a dynamometer.

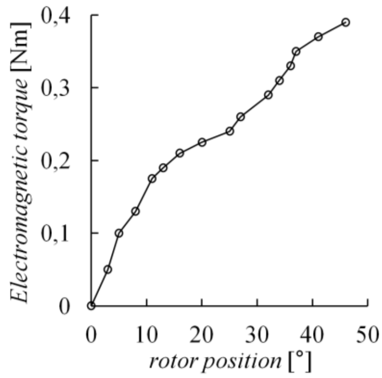

Fig. 13. Torque-angle of BLDC motor
Rys. 13. Charakterystyka momentowo-kątowa silnika BLDC

Current and voltage have been recorded in A phase of brushless motor using Tektronix TDS 210 oscilloscope and are presented in Fig. 14. Measurements have been done at torque 0.41 Nm and rotational speed 3460 rpm, supply current 6.65 A.

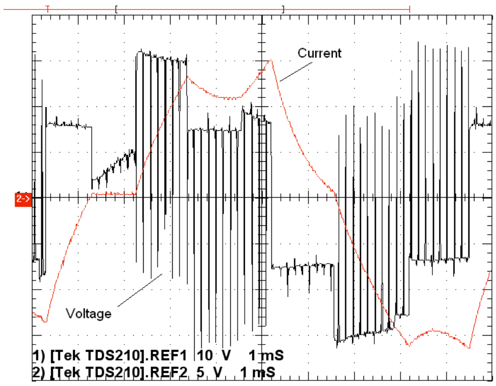

Fig. 14. Phase A voltage and current of brushless DC motor, 1 div=10 V, 1 div=5A, 1 div=1 ms
Rys. 14. Napięcie i prąd w fazie A silnika BLDC

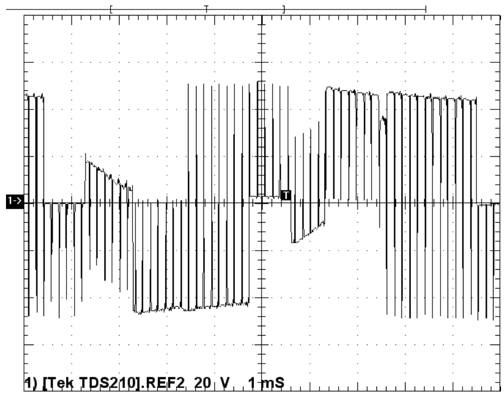

Fig. 15. Phase A to phase B voltage of brushless DC motor, 1 div=20 V, 1 div=1 ms
Rys. 15. Napięcie międzyfazowe silnika BLDC

As it can be seen in figure 14 the phase current is trapezoidal in shape. The maximum value of current is 15 A.

Figure 15 presents phase A to phase B voltage recorded at torque 0.41 N·m and rotational speed 3460 rpm, supply current 6.74 A. Line-to-line voltage is rectangular in shape (Fig. 15).

5. CONCLUSION

Brushless DC motor with powder magnetic circuit has been designed and manufactured. After measurements it turned out that electric motor did not obtain assumed parameters. Power at 0.4 Nm should be about 250 W, but has been obtained 150 W. This may be due to several reasons: the number of turns has been reduced during the winding process because of hand winding; the density of the magnet was lower than it has been assumed; results of the gluing are additional air gaps in the stator. Efficiency of motor is about 60 %. This is about 20 % more than for a AC electric motor with speed controller with the same motor dimensions. This motor was a first attempt in application of such magnetic circuits in BLDC motors. Optimization of motor is assumed to be conducted and new inverter – electronic commutator will be designed and manufactured. The research is still in progress.

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