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MAGNETOELECTRIC DC MOTORS WITH POWDER MAGNETIC CIRCUITS

ABSTRACT *Producers of electric machines permanently struggle to offer machines with better performance and operational parameters with simultaneous reduction of manufacturing costs. In case of transducers with magnetic circuits, application of powder magnetic materials offers wide opportunities for cost-effectiveness production and good operational parameters. The studies reported herein deal with a commutator-type DC motor where a conventional magnetic circuit was replaced with a one that was made by compaction of magnetic powders with an appropriate binder. The paper shows the measurements of DC motors with prepared powder magnetic circuits and traditional magnetic circuits.*

Keywords: *magnetoelectric DC motor, magnetic materials*

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1. INTRODUCTION

Development of magnetic materials makes it possible to introduce new design and manufacturing technologies to appliances with magnetic circuits. Magnetic materials that undergo rapid progress over the recent years, include soft magnetic materials and hard magnetic materials, are offered in the form of powders.

Nowadays, the machines with magnetic circuits usually comprise soft magnetic components that are made of electrotechnical steel whereas magnets of strontium ferrite serve as a source of excitation. Electrical steel exhibit very good magnetic properties although high price, related to high manufacturing costs of purposeful shapes for magnetic cores is a substantial hindrance. On the other hand, ferrite magnets applied as a source of excitation can be obtained for cheap, but their magnetic properties are pretty poor. Magnetic circuits made of modern powder-type magnetic materials, manufactured by compaction of powders with binders exhibit a number of advantages and their application area is being permanently expanded [1, 3, 4].

The new generation of magnetic circuits can be incorporated into electric machines on the designing stage, when parameters of new materials are taken into account. Substitution of conventional magnetic circuits with the ones of bound powders is also possible in appliances that are already manufactured and marketed. Magnetoelectric DC motors are considered as electromechanic converters that incorporate magnetic circuits. For instance, magnetoelectric DC motors PRMO 30-5D manufactured by Mikroma S.A. can serve here as an example.

Previous research and development efforts for electric motors of that type were focused on the influence of the applied magnets onto performances and operational parameters of such appliances [2].

The current studies are targeted to verify whether application of powder magnetic circuits in electric motors is feasible and purposeful. For the purposes of that study the electrotechnical steel of the rotor were substituted with the rotor manufactured of dielectromagnetics whereas dielectromagnets of pure Nd-Fe-B powder with radial-oriented and diameter-oriented magnetization were used instead of the permanent magnets comprising the mixture of Nd-Fe-B and ferrous powders.

2. POWDER COMPONENTS OF MAGNETIC CIRCUITS

For the purposes of this study the components of the magnetic circuits dedicated for the PRMO 30-5D motor were manufactured by means of a powder metallurgy method, e. g. compaction of metal powders. The method consists in high-pressure of mixtures that comprise magnetic powders and a binder. The compaction process is carried out in dies and then the powder compacts are hardened in furnaces or driers. Permanent magnets that are manufactured with use of that method are referred to as dielectromagnets whereas powder-based soft magnetic materials are called dielectromagnetics or Soft Magnetic Composites.

The examination process involved application of a hard magnetic material, namely it was powder from melt-spun ribbon of the Nd-Fe-B alloy. Samples for measurements of magnetic properties exhibited by dielectromagnets were shaped as cylinders with their diameter of 10mm and height of 4mm. Magnetic properties of manufactured samples were measured with use of the MCS-1 hysteresisgraph. The measured parameters of dielectromagnets are brought together in Table 1.

TABLE 1
Magnetic parameters of dielectromagnets at 20°C

The kind of a permanent magnet	B_r	H_{cB}	H_{cJ}	$BH_{\max}$
	[T]	[kA/m]	[kA/m]	[kJ/m^3]
Produced – 70% wt. Nd-Fe-B i 30% wt. Fe	0,60	203	393	27,6
Designed – 100% Nd-Fe-B	0,64	419	702	68,4

Permanent magnets applied for the motor have the shape of ring sectors with the outer diameter of 14.2 mm and the inner diameter of 10.9 mm, the angle of the magnet is 120° and axial length thereof is 24 mm. The magnets from the Nd-Fe-B alloy powder were magnetized in radial and diametrical orientation. Radial magnetization makes it possible to increase magnetic flux in the air gap of the motor.

Soft magnetic materials were used as a mixture of ferrous powder with 0.8% (by weight) content of thermosetting resin. The first type of samples was made for examination of magnetic properties of the material, other powder compacts were used for construction of the magnetic circuit of the PRMO 30-5D motor. Desired shape of the magnetic circuit of the rotor was achieved by the electrical discharge machining, however the treatment process did not allow to make inclined slots of the magnetic circuit of the rotor.

Samples for examination of magnetic properties of dielectromagnetics have the form of rings with their outer diameter of 55 mm, the internal diameter of 45 mm and the height of 5 mm. Magnetic properties of dielectromagnetics were measured in accordance to the standard PN EN-60404-6 at 50 Hz [5]. The amplitude magnetization curves $B_m = f(H_m)$ and $\mu = f(H_m)$ for the examined dielectromagnetics were measured. The curves are nonlinear. The measured maximum value for the relative magnetic permeability is 210 for H_m = 1750 A/m, whereas the same parameter of electrotechnical steel is 3200 for H_m = 200 A/m based on the catalogue reference.

3. EXAMINATION OF DC MOTORS

The DC motor of the type PRMO 30-5D is a driving unit with the following nominal parameters: power 5 W, rotation speed 5000 rpm, supply voltage 12 V DC, current 0.8 A. Dimensions of the motor are 32 mm in diameter and 60 mm in length. Magnetic cores of rotors electric motors currently comprise electrotechnical steel with their thickness of 0.5 mm. The excitation source is represented by two dielectromagnets made of the mixture of the 70% wt. Nd-Fe-B powder and 30% wt. Fe powders and expoxy resin. The dielectromagnets are magnetized in diametrical orientation and their magnetic parameters are similar to performances of sintered ferrite magnets that used to be applied to such motors. Parameters of the rotor winding for the electrical steel and powder-based magnetic core are as follows: number of coils = 8, number of turns per a singe coil = 49, diameter of the winding wire 0,26 mm. The rotor winding is the loop type with eight slots (the winding pitch is 1-4, 2-5, etc.). Each slot is filled with two sides of coils with the cross-section area 2 x 2,6 mm^2 = 5,2 mm^2. Resistance of each coil is ca. 1,35 Ω. The motor incorporates a conventional 8-sectored commutator made of copper and incorporating 2 brushes. The rotor winding resistance is 2.7 Ω. Nominal current for this type of winding is 0,8 A.

Initial measurements showed that winding of motors is not optimal for powder magnetic core of a rotor. New winding with the same cross section area was designed to increase output power of a motor with the same rotational speed as in motors in production. The same type of winding was prepared with changed only number of turns – 37 and diameter of wires – 0,3 mm. Nominal current for this type of winding is 1,1 A. Resistance of each coil is ca. 0,85 Ω. The rotor winding resistance is 1.7 Ω.

The extent of the research program included manufacturing and examination of 4 types of modelled motors and a produced motor for a comparison.

TABLE 2
Types of a DC motors

Type of a DC motor	Kind of a magnetic core of a rotor	Kind of a permanent magnet	Kind of a magnetization	Number of turns and diameter of wires
Model No. 1	dielectromagnetics	Dielectromagnets from pure Nd-Fe-B powder	diametrical	49 and 0,26 mm
Model No. 2	dielectromagnetics	Dielectromagnets from pure Nd-Fe-B powder	radial	49 and 0,26 mm
Model No. 3	dielectromagnetics	Dielectromagnets from mixture Nd-Fe-B and Fe powders	diametrical	49 and 0,26 mm
Model No. 4	dielectromagnetics	Dielectromagnets from pure Nd-Fe-B powder	diametrical	37 and 0,3 mm
Produced	electrical steel	Dielectromagnets from mixture Nd-Fe-B and Fe powders	diametrical	49 and 0,26 mm

Examinations of the prepared models and the production motor were conducted. The measurements of motor parameters were carried out on a workbench equipped with the Prony friction brake. The motors were also examined for reversed operation (as generators) for 1500 rpm obtained from synchronous motor at the idle run mode in order to find out the induced electromotive force in its windings and to evaluate the magnetic flux. Electromechanical parameters of the motors, such as rotation speed, input current, input and output power as well as efficiency of the examined motors were defined as a function of the load torque. Rotational speed was measured using a digital tachometer. Currents and voltages were measured using digital meters. The maximum current in the rotor winding was about 1,5 times higher than the nominal current. The maximum current in a rotor winding with 49 turns was 1,2 A and for winding with 37 turns was 1,6 A. No thermal test of motors was carried out.

During tests, electric motors with the powder magnetic rotor demonstrated increased level of noise. It results from a higher cogging torque of motors with straight slots. Anyway, a rotor with inclined slots can be designed and constructed when mass manufacturing of such motors is commenced.

The results of measurements of models, electromechanical characteristics, of a motor show Fig. 1. In Fig. 1 P1 represents input power, P2 output power, I current and n rotational speed.

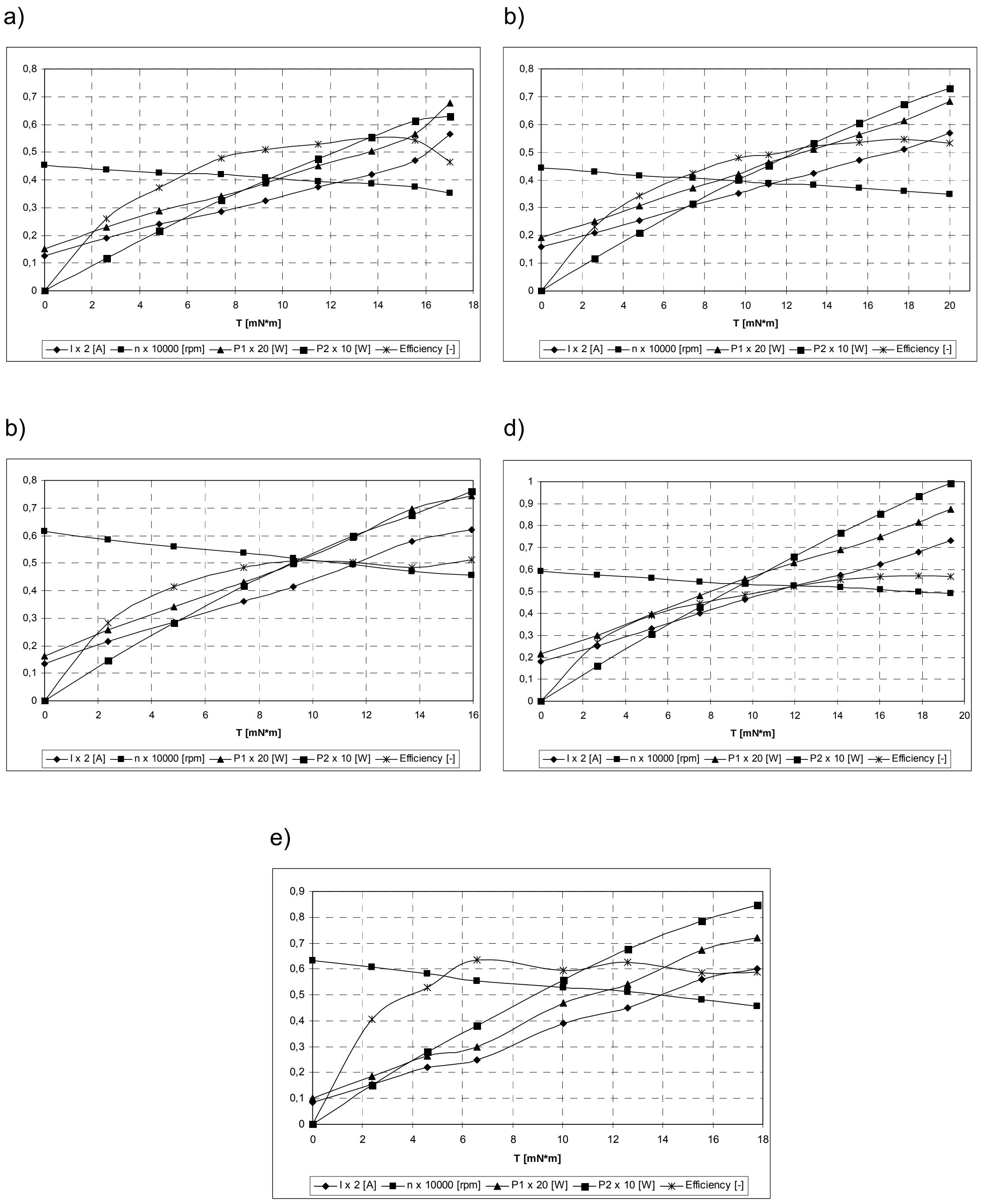

Fig. 1. Measured graphs of the DC motors:
a) motor No. 1, b) motor No. 2, c) motor No. 3, d) motor No. 4, e) produced

Parameters of measured motors were taken from the plotted curves and presented in table 3 and 4. Table 3 shows parameters of motors for load torque 10mNm and supply voltage 12 V and table 4 shows parameters of motors for nominal current for winding with 49 turns – 0,8 A and 1,1 A for winding with 37 turns, supply voltage 12 V.

TABLE 3
Measurements of DC motors for T = 10 mN·m and U = 12 V

Type of a DC motor	I	n	$P1$	$P2$	Efficiency
	[A]	[rpm]	[W]	[W]	[%]
Motor No. 1	0,68	4100	8,2	4,3	52
Motor No. 2	0,70	3915	8,4	4,1	49
Motor No. 3	0,88	5150	10,6	5,4	51
Motor No. 4	0,95	5250	11,2	5,5	49
Produced	0,78	5250	9,4	5,5	59

TABLE 4
Measurements of DC motors for I_n = 0,8 A for winding with 49 turns, I_n = 1,1 A for winding with 37 turns and U = 12 V

Type of a DC motor	T	n	P1	P2	Efficiency
	[mN·m]	[rpm]	[W]	[W]	[%]
Motor No. 1	13	3900	9,6	5,3	55
Motor No. 2	12	3850	9,6	4,8	50
Motor No. 3	9	5250	9,6	4,9	51
Motor No. 4	13	5150	13,2	7,0	53
Produced	10,5	5200	9,6	5,7	59

The results presented in table 3 and 4 show that it is possible to achieve the same power of DC motor with powder magnetic circuit – motor No. 4 as for production motor, but the value of current shows that it is possible to obtain 13 mN m and 7 W of output power for nominal current for this winding. Anyway the level of power for all motors is similar.

Figure 2 shows control characteristics of examined motors. The curves demonstrate variation of rotation speed vs. the supplying voltage when the load torque is unaltered and equals to 10 mN·m. The average input current for different voltages of the motor No. 1 was 0.70 A, for the motor No. 2 was 0.72 A, for the motor No. 3 was 0.84 A, for the motor No. 4 it was 0.9 A whilst for the production motor the input current was 0.78 A. The control characteristics demonstrate linear relationship between the supplying voltage and the rotation speed (rpm) of motors when the load torque is constant – 10 mN·m. The results point that that it is possible to control rotational speed of the rotor due to application in linear range characteristics.

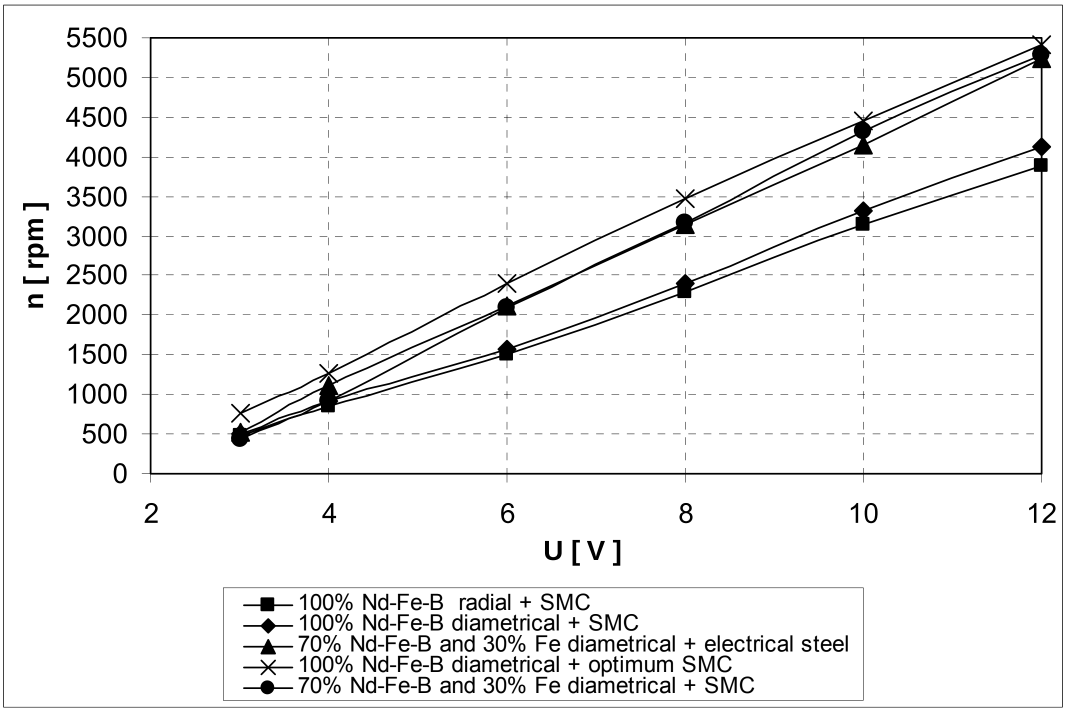

Fig. 2. Measured control graphs of the DC motors for all motors

The range of research covers observations and measurements using a digital oscilloscope of induced electromotive force as a function of time and currents and voltage as a function of time too. Figure 3 shows, for example, curves for produced motor – Fig. 3 a) and motor No. 2 – Fig. 3 b).

a) b)

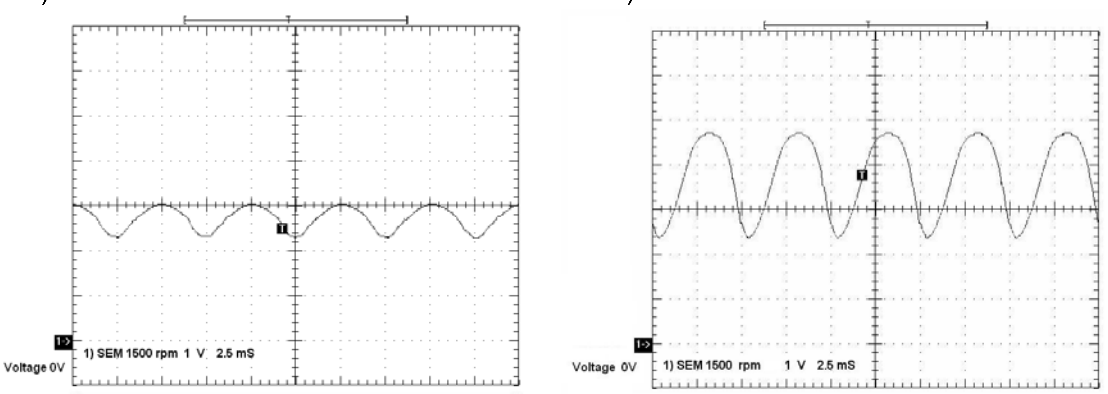

Fig. 3. Induced voltage as a function of time for generator state of
a) produced DC motor and b) motor No. 2. Rotors rotated 1500 rpm

As we can see from the curves the changes of voltage are smaller for production motor than for motor No. 2. It is a result of type of slots. In production motor slots are skewed and cogging torque is smaller than cogging torque for motor No. 2 with straight slots.

The same influences are observed for changes of currents in a function of time – Fig. 4 a) and 4 b). The reason is the same as for changes of induced voltage.

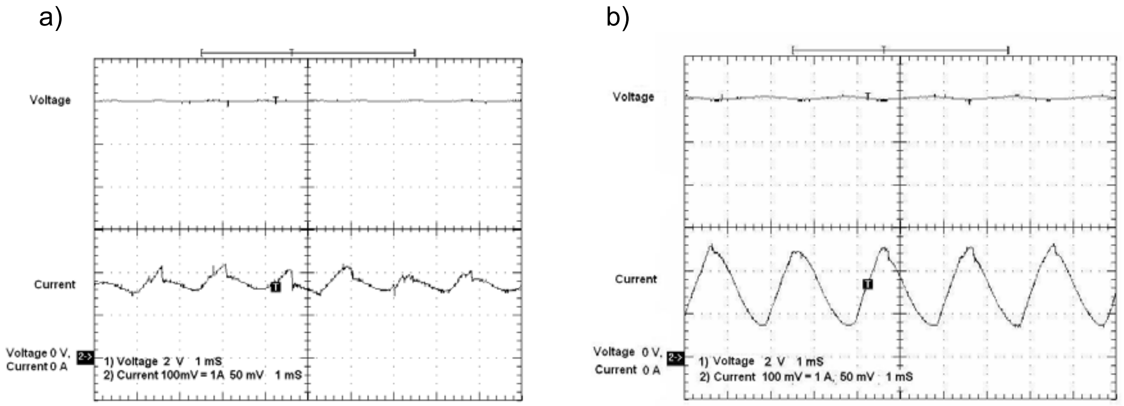

Fig. 4. Currents and voltage as a function of time for a) produced DC motor and b) motor No. 2
For produced motor U = 12 V, I = 0,85 A, n = 5110 rpm, torque = 11 mN·m.
For motor No. 2 U = 12 V, I = 0,77 A, n = 3880 rpm, torque = 11,5 mN·m

Table 5 gathers measured parameters of the motor PRMO 30-5D. It summarizes measurements of motors. The magnetic flux is higher for the newly designed motors No. 1 and No. 2, which is evidenced by the electromotive force (SEM) induced in motors. In these models are applied dielectromagnets with better magnetic properties than in production motors. The excitation sources in motor No. 4 are permanent magnets from pure Nd-Fe-B powder but in this motor winding is optimized for achievement the same value of electromotive force as in production motor.

Different types of dielectromagnets, magnetic cores of a rotor and windings cause the changes of values of constant torques.

TABLE 5
Measured parameters of DC motors type PRMO 30-5D

Type of a DC motor	Electromotive force for 1500 rpm	Back-EMF constant	Torque constant
	[V]	[V/1000 rpm]	[N·m/A]
Motor No. 1	3,56	2,37	0,016
Motor No. 2	3,74	2,49	0,017
Motor No. 3	2,64	1,76	0,011
Motor No. 4	2,72	1,81	0,012
Produced	2,75	1,83	0,013

4. CONCLUSIONS

Measurement results for models of DC motors provide the proof that conventional magnetic circuit of such motors can be substituted with a powder magnetic circuit.

The result of research confirmed that it is possible to tailor parameters of motors due to customers requirement. It is possible to tailor physical properties of dielectromagnets and dielectromagnetics and in result tailoring properties of powder magnetic circuit. Additional advantage of powder metallurgy technology is possibility to change design of a motor by changing dimension and shape of magnetic circuit with easier way than for traditional material.

Reduction of noise emitted by motors with powdered magnetic circuits is possible, if motor cores are executed with inclined slots, which assists to reduce cogging torque of motors.

The research program is still in progress.

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MAGNETOELEKTRYCZNE SILNIKI PRĄDU STAŁEGO Z PROSZKOWYMI OBWODAMI MAGNETYCZNYMI

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STRESZCZENIE *Rozwój nowych generacji materiałów magnetycznych pozwala na rozwój nowych urządzeń z obwodami magnetycznymi. Opracowanie technologii wytwarzania proszkowych materiałów magnetycznych umożliwia zmianę konstrukcji i technologii wytwarzania urządzeń z obwodami magnetycznymi. Ostatnie lata przyniosły rozwój proszkowych materiałów magnetycznie miękkich i magnetycznie twardych. W obecnie produkowanych maszynach elektrycznych, magnetycznie miękka część obwodu magnetycznego wykonywana jest z blach elektrotechnicznych, zaś jako źródło wzbudzenia stosowane są najczęściej magnesy ferrytowe. Blachy elektrotechniczne charakteryzują się bardzo dobrymi właściwościami magnetycznymi, ale ich wadą jest wysoka cena. W przypadku magnesów ferrytowych ich zaletą jest niska cena, ale wadą słabe właściwości magnetyczne. Proszkowe materiały magnetyczne mogą umożliwić poprawę parametrów eksploatacyjnych urządzeń z obwodami magnetycznymi a jednocześnie pozwolić na obniżenie kosztów ich produkcji.*

Celem prowadzonych badań jest sprawdzenie możliwości stosowania proszkowych obwodów magnetycznych w produkowanych silnikach elektrycznych prądu stałego z magnesami trwałymi. Przeprowadzono próby zastąpienia tradycyjnego obwodu magnetycznego proszkowym obwodem magnetycznym w silniku prądu stałego typu PRMO 30-5D produkowanym przez fabrykę Mikroma S. A. Badania symulacyjne pokazały, że możliwe jest zastąpienie produkowanego obwodu magnetycznego tego silnika proszkowym obwodem magnetycznym. Obwód magnetyczny wirnika został wykonany z proszku żelaza spajanego tworzywem – dielektromagnetyku, zaś magnesy wzbudzenia z proszku z szybko chłodzonej taśmy Nd-Fe-B spajanej tworzywem – dielektromagnesu (tab. 1). Wykonano modele silników z proszkowymi obwodami magnetycznymi (tab. 2). Przeprowadzono badania wykonanych modeli silników. Na rysunku 1. przedstawiono charakterystyki ruchowe silników. W tabelach 3-5 pokazano wybrane parametry badanych silników, natomiast charakterystyki sterowania na rysunku 2.

Przeprowadzone badania pokazały, że stosowanie proszkowych obwodów magnetycznych w maszynach prądu stałego jest możliwe i celowe. Stosowanie tego typu obwodów magnetycznych pozwala na sterowanie parametrami eksploatacyjnymi silników.