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The Comparative Analysis of Permanent Magnet Electric Machines with Integer and Fractional Number of Slots per Pole and Phase

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Abstract

The comparison of permanent magnet motors with integer and fractional number of slots per pole and phase was made. The torque developed by the motor and the torque ripples level were chosen as the major criterions. The comparison was made according to the results of equations of numerical calculation of magnetic field in active motors volumes using the finite element analysis. The recommendations on the choice of the most suitable option are given.

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Keywords: Permanent magnet motor; Torque ripples; Cogging torque; Fractional-slot winding; Finite element analysis

1. Introduction

The brushless permanent magnet DC motors are being developed fast over the years. Nowadays we can see a new intensive turn of their development. It is connected with the appearance and commercial exploitation of powerful and comparatively cheap high-coercive magnets, the development of power electronics.

By nature an electric machine is a quite conservative drive part which is upgrading slower than electronic components and program control logic. Nevertheless, optimization of this unit is very important as it is the motor which determines to a great extent energetic data and weight-size parameters of the drive on the whole.

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One of the last tendencies is application of the electric machines with fractional numbers of slots per pole and phase [1]. If a few decades ago such solutions were used for low power devices then now quite powerful motor electric drives appear with similar machines [2,3,4,5].

It should be noted that analysis and synthesis theory of conversion devices to be observed is behind of practice requirements that is connected with complication of electromagnetic processes in the machines with fractional numbers of slots per pole and phase. In the academic circles we can observe active disputes concerning effectiveness of such machines. This article is directed to partial settlement of these disputes. The analysis was carried out with the help of modern program means of finite element analysis of electromechanic and electromagnetic devices ANSYS Maxwell.

2. Task description

The primary objective of this work is research of winding distribution influence on the value and ripples of electromagnetic torque of the permanent magnet motor.

The electric motor DB-72 (variant 1) was chosen as a subject of research which is designed for usage in the respiratory medical device. The passport specifications are given in table 1. The number of motor stator slots is18, the number of poles of the inductor is 20. Then, the motor is made with fractional number of slots per pole and phase q=3/10. The motor has a converse construction: the armature is located inside, the rotating induction coil — outside.

Table 1. Nominal data of the motor DB-72

Parameter	Value
nominal power, (W)	25
DC nominal voltage, (V)	24
nominal speed, (rpm)	1000
nominal current, (A)	2.5
nominal torque, (Nm)	0.25
number of phases	3
phase connection scheme	Y

The specially designed motor with integer number of slots per pole and phase having the equal dimensions with the base motor was accepted as an alternative variant (variant 2). The inductor of the alternative motor is the same as the base model. The stator has the number of slots per pole and phase q=1. At that the number of machine slots turned out to be equal:

$$z = 2p \cdot m \cdot q = 20 \cdot 3 \cdot 1 = 60\,,$$

where p — poles pair number, m — phase number of the armature winding. Note that value q=1 turned out to be the most possible on design considerations for given sizes and polarity of the machine: slots number increase crushes the stator teeth dimensions unacceptably.

For comparison accuracy the number of phases ampere-turns of motors to be observed was accepted equal (180 turns in the phase, phases currents — nominal, according to the nominal data of the base motor). The total areas of slots and teeth of motors to be observed are equal accordingly.

3. Design models

The designing of magnetic field in active motors volumes was carried out according to the finite element analysis in 3D task description. It allowed to take into account a possible stator slot skewing while analysis. The developed models of the motors consider the properties nonlinearity of ferromagnetic materials, alternation of electromagnetic quantity over time, machine members moving relative to one another. The magnets were made of alloy NdFeB (coercive force by induction H_c = 890 kA/m, residual flux density B_r = 1,23 T).

The motors phases power was carried out by current supply, it allowed to exclude the resistance of armature circuit from the number of factors affecting the electromagnetic torque. The direct currents (nominal specified current) for the phase A and the phase C with corresponding marks and zero current for the phase B were set in accordance with 120-degree commutation algorithm.

The models designed due to axial and radial symmetry of the electric machines are presented in fig. 1.

In the course of experimental testing the nominal speed was imposed to the rotor, the torque on the motor shaft was measured, the torque average value was calculated in the closed interval corresponding to the intercommutating interval.

The measurement of cogging torque caused by variability of the magnetic permeability of the air gap was carried out for the electromagnetic torque estimation. While the experiment the rotor was brought to rotation with nominal rate, the phases currents were accepted as equal to zero. The electromagnetic torque of the motors was calculated according to the results of conducted experiments by means of coordinatewise diminution of the cogging torque curve from the full torque curve:

$$M_{em}(t) = M(t) - M_c(t)\,. \tag{1}$$

4. The results of experiments

The total torque tracings obtained while the experiment are shown in fig. 2. The cogging torque tracings captured in the process of the rotor turning are shown in fig. 3. The electromagnetic torque curves obtained by the (1) are shown in figure 4.

The average torques values for each motor in intercommutating interval were calculated by the equation:

$$M_a = \int_0^T M(t)dt\,, \tag{2}$$

where T — intercommutating interval size, $M(t)$ — torque dependence on instant.

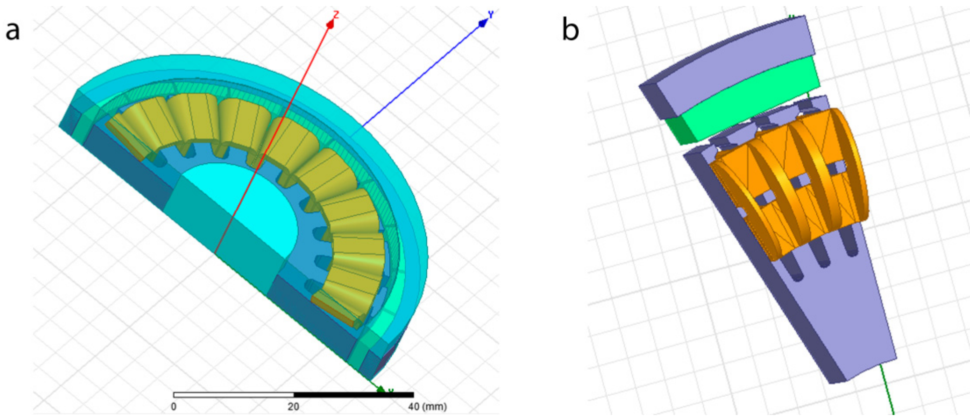

Fig. 1. Three-dimensional designed models of the motors to be observed:
(a) with fractional number of slots per pole and phase; (b) with integer number of slots per pole and phase.

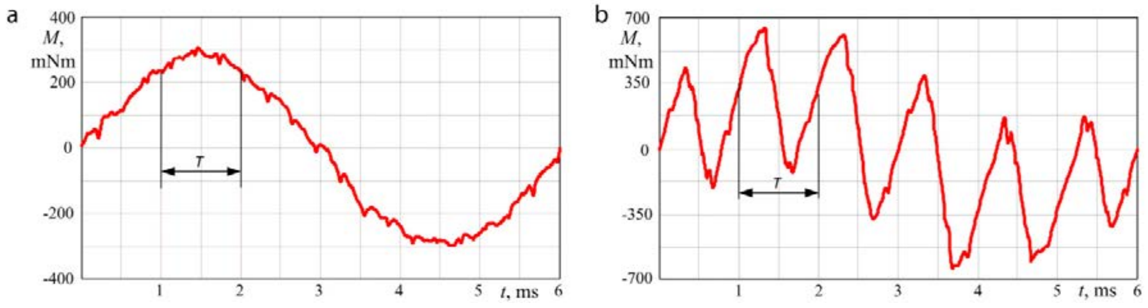

Fig. 2. The total torque tracing in the process of the rotor turn: (a) for variant 1; (b) for variant 2.

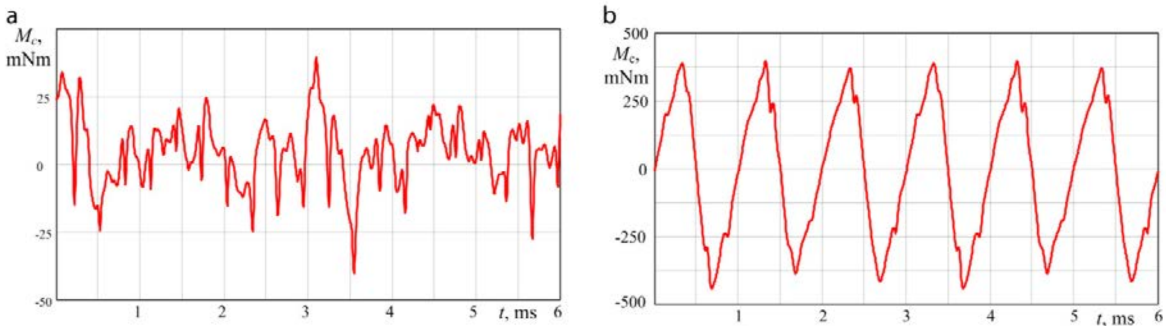

Fig. 3. The cogging torque tracing in the process of the rotor turn: (a) for variant 1; (b) for variant 2.

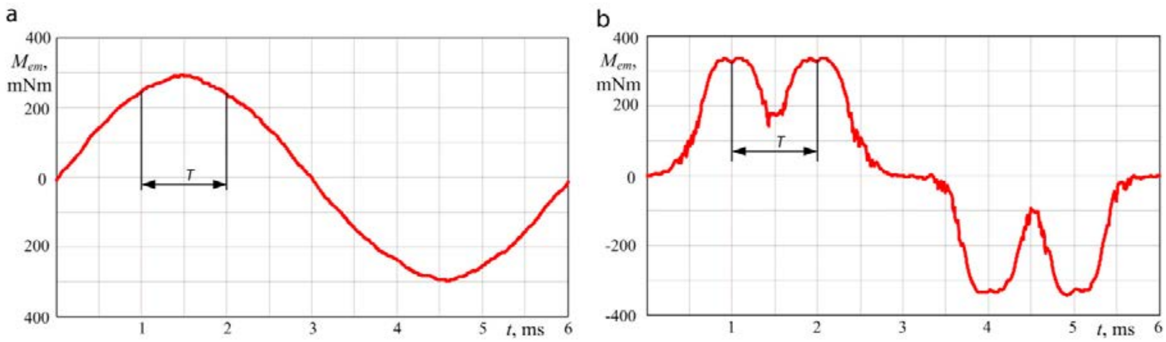

Fig. 4. The electromagnetic torque tracing in the process of the rotor turn:(a) for variant 1; (b) for variant 2

The ripple factor in the intercommutating interval was calculated for full and electromagnetic torques [6]:

$$k_r = \frac{(M_{\max} - M_{\min})/2}{M_a}, \tag{3}$$

where M_{max} and M_{min} — maximal and minimal torque value in the intercommutating interval respectively.

The cogging torque was estimated due to its maximum value. The calculations data were summarized in tab. 2, where: M_a — average torque on the motor shaft, $M^{em}{}_a$ — motor average electromagnetic torque, k_r — torque ripple factor on the motor shaft, k_r^{em} — motor electromagnetic torque ripple factor, $M^c{}_m$ — maximum value of motor cogging torque.

Table 2. Experimental data

	M_a, Nm	$M^{em}{}_a$, Nm	k_r	k_r^{em}	$M^c{}_m$, Nm
Variant 1	0.271	0.272	0.129	0.101	0.040
Variant 2	0.272	0.274	1.415	0.292	0.400

5. Discussion of the results

As the experiment showed both motors are approximately equivalent by the electromagnetic torque value but relating to torque ripples level variant 1 is ahead of variant 2 without doubt. It should be noted that torque ripples are common for all permanent magnet motors and connected with discrete behavior of position in vector space of armature magneto-motive force, however in this case the ripples have unacceptably high values.

According to the obtained data the essential cogging torque and, to a lesser extent, torques from the interaction of non-fundamental harmonics of the armature and induction coil fields are the primary reasons of high motor ripples torque with integer *q*. Actually in cogging torque generation in this case all stator teeth take part which are located equal on each polar pitch relative to poles.

In the motor with fractional *q* these factors are expressed weaker. Moreover, the cogging torque is lower due to the smaller number of teeth which are the reason of air gap variation and thanks to the fact that teeth are located on different polar pitches asymmetrically relative to the poles.

In the electric machine of variant 2 the winding has a full pitch, distribution is absent. In consequence of the specified characteristics of the motor winding in armature field curve except fundamental harmonic there are quite strong non-fundamental harmonics which are able to generate the electromagnetic torque ripples interacting with field harmonics of inductor .

Non-fundamental harmonics of the armature field in the machines with fractional *q* are significantly weakened due to teeth shift belonging to one phase in relation to one another in the limits of polar pitch and it affects like a pitch reduction and winding distribution by the slots in the windings with integer *q* [7].

For confirmation of these facts calculated dependencies of the time electromagnetic torques were expanded to harmonic series.

The electromagnetic torque of the motor with fractional number of slots per pole and phase is given as fundamental harmonic which has amplitude 0.287 Nm. The torque non-fundamental harmonics amplitudes do not exceed 1% of the fundamental harmonic amplitude.

The electromagnetic torque curve of the motor with integer *q* except the fundamental harmonic (0.290 Nm) contains a series of ultra ones, the strongest of them are the fifth (34% of the fundamental one) and the seventh (9.85% of the fundamental one). It should be noted that fundamental harmonics of the motors torques of both variants are approximately equal.

It is possible to decay torques ripples of the motor of variant 2 having weakened the non-fundamental harmonics of the armature field and having reduced the cogging torque. The reduction of non-fundamental harmonics amplitudes of the armature field which in this case are tooth harmonics is possible by increasing the number of slots per pole and phase and that does not seem possible with the specified dimensions without reducing the number of the machine poles. The increase of machine air gap that is connected with its increase in dimensions gives the other opportunity for reducing the torques from tooth harmonics.

The effective way of tooth harmonics influence reduction on the electromagnetic torque is a stator slot skewing [8,9]. At that the harmonics skewing of the armature field happens along the machine axis relative to similar harmonics of the induction coil field that weakens the torques to be generated by them. The slot skewing introduction affects favorably to the cogging torque reduction.

Let us estimate the slot skewing influence on the total and cogging torques of the machine of variant 2.

The research was conducted on the same model in the process of slot skewing alteration from 0 to 1 of the tooth pitch. Higher skewing values are not used as that increases leakage significantly [10]. The current loading in the process of the total torque determination remained also constant.

The best results were obtained in the process of the skewing to one tooth pitch. At that, the torque average value in the intercommutating interval was 0.279 Nm. The total and electromagnetic torques of the motor with integer q in the process of skewing to one tooth pitch are shown in fig. 5. The calculation results of the cogging torque maximal values and the results of the strongest harmonics amplitudes of the electromagnetic torque are given in Table 3.

The experiments revealed that in the process of slot skewing to one tooth pitch the cogging torque reduces significantly, being still slightly higher than the cogging torque of the motor with fractional *q*.

Table 3. The effect of the skew of slots on the torque of the motor with the integer *q*.

	M_{em}^{1}, Nm	M_{em}^{5}, Nm	M_{em}^{7}, Nm	M_c, Nm
Without skewing	0.290	0.098	0.029	0.400
Skewing to one tooth pitch	0.286	0.043	0.001	0.045

The non-fundamental harmonics of the motor electromagnetic torque are weakened quite effectively also. It should be noted that in spite of ripples decay by more than 50% their values remained still unacceptably high (k_r = 0,37).

Consequently taking into account all factors (value of total and cogging torques, ripples torque level) variant 1 is ahead of variant 2.

Moreover, the following advantages of variant 1 over variant 2 should be pointed out:

- shorter half-turn length as the end parts of different coils do not cross over each other but entail only one tooth; consequently the armature coil has a lesser active resistance that affects the electric losses favorably;
- better usage of machine volume due to a lesser area of slot insulation;
- more simplified manufacturing technique: a lesser number of slots simplifies the punches and mounting for the winding works.

6. Conclusions

The permanent magnet motors with fractional number of slots per pole and phase can compete successfully with equivalent motors with integer number of slots per pole and phase having acceptable value of the electromagnetic torque, lesser values of the cogging torque, lesser torque ripples, copper losses in simplified manufacturing technique.

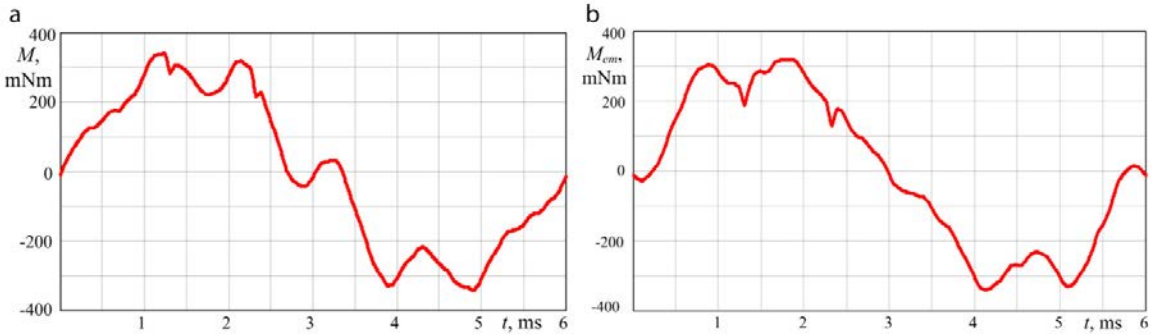

Fig.5. The tracings of full (a) and electromagnetic (b) torques in the process of the rotor turn for the motor variant with integer number of slots per pole and phase and slot skewing to one tooth pitch

In particular the distinct advantages of the machines with fractional number of slots per pole and phase should occur in extensively used electrical machines when the severe space restrictions are imposed on the requirements of high energy data of the motor.

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