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MASZYNA TARCZOWA O WZBUDZENIU HYBRYDOWYM – PRACE PROJEKTOWE

AXIAL FLUX MACHINE WITH HYBRID EXCITATION – DESIGN WORKS

Abstract: The article presents design of a disc-type surface mounted permanent magnet machine with flux control capability. The paper shows 3D-FEM model of FCAFPM machine developed to obtain predicted armature winding back-emf waveforms and field weakening/strengthening performance of the machine. Moreover, non-magnetic shaft with iron bushing, a rotor's yoke with iron poles and half-cross-section view of a concept of machine are presented in details.

Streszczenie: W artykule przedstawiono projekt maszyny tarczowej z magnesami trwałymi mocowanymi powierzchniowo, która posiada możliwość regulacji strumienia wzbudzenia. W pracy pokazano model polowy maszyny FCAFPM opracowany w celu otrzymania przewidywanych przebiegów SEM w uzwojeniach twornika oraz regulacji pola wzbudzenia maszyny. Ponadto, szczegółowo pokazano wał niemagnetyczny z żelazną tuleją, jarzmem i biegunami wirnika oraz przekrój koncepcji całej maszyny.

Keywords: *axial-flux electrical machine, permanent magnet, magnetic field control, finite-element analysis*
Słowa kluczowe*: maszyna tarczowa, magnes trwały, regulacja wzbudzenia, analiza polowa*

1. Introduction

Presently used solutions based on axial flux permanent magnet machines have a high torque and are characterized by high efficiency and favorable relationship of weight and volume to processed power [1-3]. Machines with permanent magnets characterizes inherently the high level of the torque ripple. Many research related to the minimization of the cogging torque have been reported in the literature, for example [4-8]. However, as an electrical vehicles drives, they have a major disadvantage which is inducing high-voltage at high rotational speeds, making it difficult to appropriate powering and control of the machine. In order to reduce these effects different techniques of controlling the magnetic flux are used. The articles [9-17] show how to regulate flux excitation in cylindrical machines with an additional coil powered direct current. This paper presents selected simulation and design results of a field controlled axial-flux permanent magnet (FCAFPM) machine, based on the Finite Element Method (FEM). The armature winding back-emf waveforms at three different additional DC control coil current has been also shown. The paper moreover presents a structure of the experimental model which is under construction. The presented design of the FCAFPM machine is based on an earlier conception and simulation results shown in papers [18, 19], in which the author among others explained the principles of strengthening and weakening of the excitation flux in axial-flux hybrid machines.

2. 3D-FEM model and results of simulating research

The 3D-FEM model of the FCAFPM machine, prepared with using the Flux-3D software, is shown in Fig. 1.

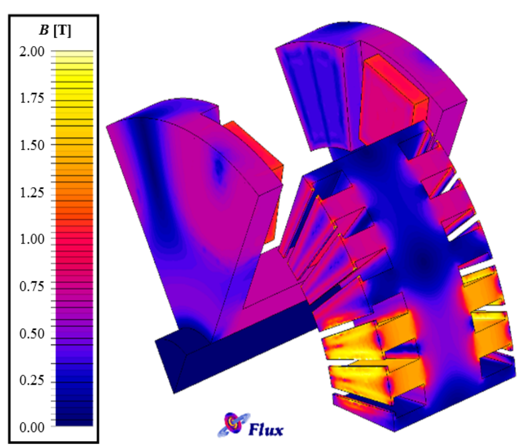


Fig. 1. 3D-FEM model of FCAFPM machine

Structure is composed of two rotor parts and an inner stator. One of the rotor's parts contains six permanent magnets magnetized in the *S* direction and the second – in the *N* direction. Each of the disks has also six iron poles placed alternating with permanent magnets. Important in this concept of machine is that the rotor shaft in the inner part is made from non-magnetic material – in order to reduce magnetic flux leakage.

The main parameters (physical and mechanical) of the 3D-FEM model are shown in Table 1.

Table 1. The main data of the FCAFPM machine

Main	Predicted nominal power	20 kW
	Maximal speed	5000 rpm
Stator	Stator outer diameter	300.0 mm
	Stator inner diameter	180.0 mm
	Stator axial length	100.0 mm
	Stator number of slots	36
	Width of the slot opening	4.0 mm
	Slot area	296.6 mm^2
	Number of turns in slot	20
Rotor	Rotor outer diameter	300.0 mm
	Rotor disc axial length	20.0 mm
	Rotor's bushing inner diameter	100.0 mm
	Rotor's bushing outer diameter	62.0 mm
	Number of poles	12
	PM type	NdFeB
	PM B_r	1.2 T
	PM relative permeability	1.05
	PM thickness	12.0 mm
	PM width	50.0 mm
	PM height	50.0 mm
	Iron pole thickness	15.0 mm
	Air gap PM	4.0 mm
	Air gap iron pole	1.0 mm
Control coil	**Turns**	**1000**
	Resistance	**6.0 Ω**
	Weight	**5.2 kg**
	Fill factor	**0.8**

The back-emf waveforms of the three additional coil power states (I_{dc} = -2.5 A, I_{dc} = 0 and I_{dc} = -2.5 A) at rotational speed n = 1000 rpm are shown in Fig. 2.

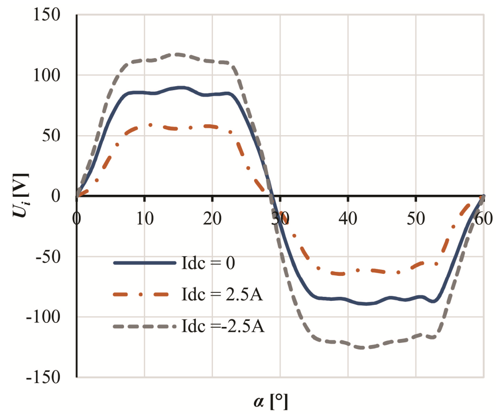


Fig. 2. Back-emf waveform for three different values of the DC control coil current at rotational speed 1000 rpm

Table 2 shows root mean square values of back electromotive force U_i for the three mentioned above different values of the current in DC control coil at rotational speed 1000 rpm.

Table 2. Back-emf values at different current in additional control coil

	strength ening		**weakening**
***I_{dc}* [A]**	-2.5	0.0	2.5
***back-emf* [V_{rms}]**	101.2	74.4	49.0
$u_{i\%}$	136%	100%	66%

From the research, shown in Fig. 2 and Table 2, result that DC control coil current I_{DC} = -2.5 A increases the value of the back-emf from 74.4 V to 101.2 V (up 36%), while at I_{DC} = 2.5 A voltage decreases by approx. 34%.

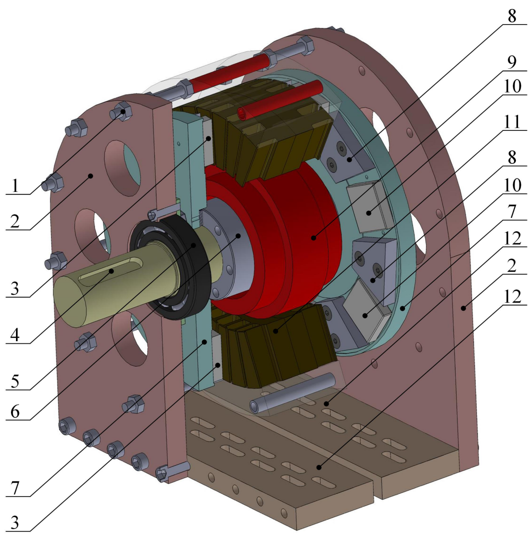
Using a simple formula defining the power loss of the DC control coil P_l:

$$P_l = I_{dc}^2 \cdot R_{dc} \tag{1}$$

where: R_{dc} – DC control coil resistance, it can be concluded that with the power loss of approx. 37.5 W (about 0.2% of predicted nominal power), the back-emf value in the FCAFPM machine can be controlled in the range of approx. ±35%.

3. Prototype of the FCAFPM machine

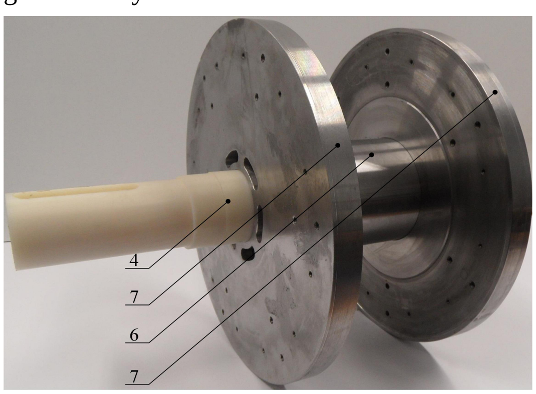
Based on simulation results and addition technical constrains the prototype of field controlled axial-flux permanent magnet machine design has been developed. In Fig. 3 a prototype of FCAFPM machine is shown in details.



1 – Bolt	5 – Bearing	9 – Control coil
2 – Housing	6 – Rotor bushing	10 – Magnet *N*
3 – Magnet *S*	7 – Rotor disc	11 – Stator core
4 – Non-magnetic shaft	8 – Iron pole	12 – Housing base

Fig. 3. Half-cross-section of the FCAFPM machine

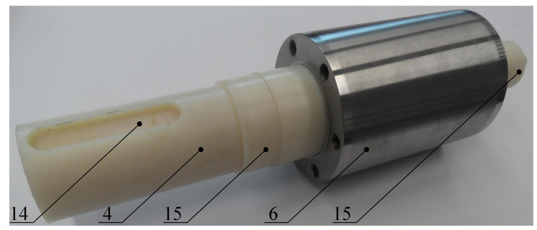
Figure 4 shows a picture of the prototype rotor's core with non-magnetic shaft. On the each of two discs, visible on the figure, six iron poles alternating with permanent magnets will be placed on the disc's plate. It should be noted that, the rotor's bushing belongs to the rotor yoke of the machine and conducts field generated by current in DC control coil.



4 – Non-magnetic shaft 6 – Rotor bushing 7 – Rotor disc

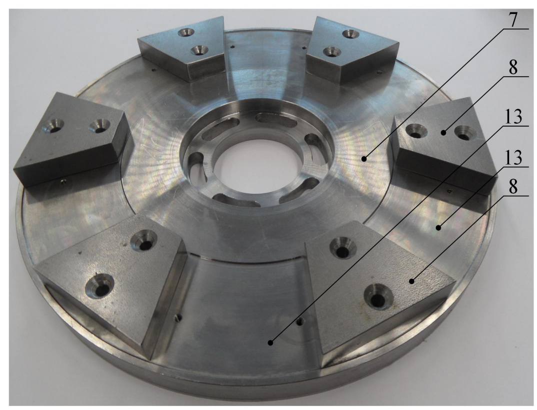
Fig. 4. Rotor's core of the FCAFPM machine mounted on a non-magnetic shaft

The next Fig. 5 shows built non-magnetic shaft of the rotor with bushing made of steel. Ultimately the two parts of rotor with iron poles, which are shown in Fig. 6, will be mounted on the rotor bushing. After assembling of all parts and attaching permanent magnets in places 13 (Fig. 6), whole will form the rotor of CFAFPM machine. Next Fig. 7 shows a view of FCAFPM machine's housing and rotor.



4 – Non-magnetic shaft 14 – Place for square key
6 – Rotor bushing 15 – Place for bearing

Fig. 5. Non-magnetic shaft with iron bushing



7 – Rotor disc 8 – Iron pole 13 – Place for magnet

Fig. 6. Rotor's disc of the FCAFPM machine with iron poles

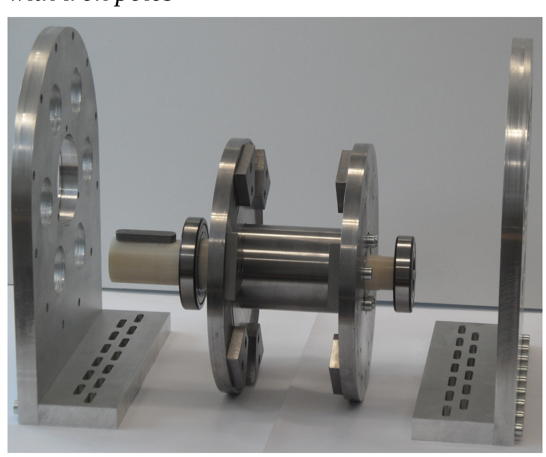


Fig. 7. FCAFPM machine's housing and rotor with bearings and square key

4. Summary

The paper presents selected simulation and design results of FCAFPM machine which is under construction. The preliminary simulating results prove that it is possible to control field excitation in wide range with low power losses in the DC control coil. In next works the authors plan to perform a complete experimental study in order to validate predicted performance of the machine.

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