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Design and simulation of disk stepper motor with permanent magnets

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Abstract: In this paper the design and the magneto-static simulation of axial-flux permanent-magnet stepper motor with the disc type rotor is presented. Disk motors are particularly suitable for electrical vehicles, robots, valve control, pumps, centrifuges, fans, machine tools and manufacturing. The brushless machine with axial flux and permanent magnets, also called the disc-type machine, is an interesting alternative to its cylindrical radial flux counterpart due to the disk shape, compact construction and high torque density. This paper describes a design of four phase microstepping motor with the disc type rotor. The FEM modeling and the 3D magneto-static simulation of the disk stepper motor with permanent magnets is being subject of the article, too. Disc rotor type permanent magnet stepper motor for high torque to inertia ratio is ideal for robotics and CNC machines.

Key words: Stepper motor, disk rotor, permanent magnet, magneto-static field simulation

1. Introduction

The permanent magnets (PM) machines with axial flux are increasingly used machines with the cost of the high energy PM. These machines have many individualistic features. They are usually more efficient because of the fact that field excitation losses are eliminated resulting in significant rotor loss reduction. Thus, the motor efficiency is greatly improved and higher power density is achieved [2], in comparison with common motor with radial flux. Besides PM motors have small size which results in small dimension of magnetic circuit. As for the PM machines with axial flux, they have a number of advantages over machines with radial flux. PM machines with axial flux can be designed to have a higher power to weight ratio resulting in less core material and they have planar and easily adjustable air gaps.

Moreover the noise and vibration levels are less than in the conventional machines. These advantages prioritizing the machines with axial flux over conventional machines with radial flux in various applications.

The disk stepper motors, like cylindrical stepper motors, can be viewed as brushless machine. Typically, all windings in the motor are part of the stator, and the rotor is either a toothed block of some magnetically soft material, in the case of variable reluctance motors, or the permanent magnet.

Disc motors are permanent magnet stepper motors that exhibit performance comparable to that of hybrid motors. The rotors in disk motors are thin (typically less than 1-mm) discs, unlike the cylindrical rotors in hybrids and conventional permanent-magnet motors. The conventional permanent-magnet motors generally are limited to a minimum step angle of 30° for a maximum of 12 steps/rev.

2. Advantage of motor with disk rotor

When using a stepper motor with the disk rotor, the main disk rotor advantages must be known. The quantitative difference between motor with cylindrical rotor and disk rotor results from mutual comparison of their electromagnetic utilizations. Therefore is necessary to formulate the specific thrust in active layer as parameter, which creates the torque.

Electric machines parameter σ indicating of an average specific tension in the active layer of cylinder rotor on diameter *d* and length *l*:

$$\sigma = \frac{F}{\pi \cdot d \cdot l} = \frac{2 \cdot M}{\pi \cdot d^2 \cdot l}, \tag{1}$$

where *F* – is the force actuating on a cylinder and *M* is the torque.

The result from Equation (1) is the generally known fact, that dimensional criterion is cubature of the electrical machine. This cubic value and the torque of cylindrical electric machine are reciprocally proportioning.

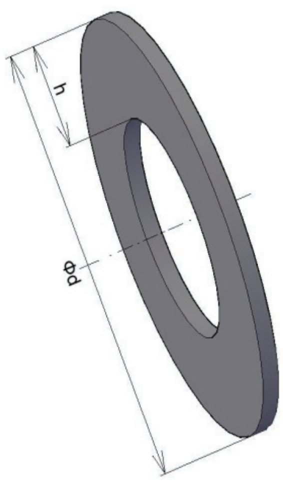


Fig. 1. Double layer disk rotor

The average specific tension in active layer of the disk rotor is doubled, therefore for two plan-parallel thicknesses is valid equation:

$$\sigma = \frac{F}{2 \cdot [\pi \cdot (d-h) \cdot h]} = \frac{M}{\pi \cdot (d-h)^2 \cdot h}, \tag{2}$$

where d – is outer diameter of the ring, h – is height of the annulus (Fig. 1), F – is the force value for total disk and M – is the motor torque.

From Equation (2) is the result, that dimensional criterion of the discoid motor is a planar quantity:

$$\pi \cdot (d-h)^2 \cdot h. \tag{3}$$

The motor torque M and the planar quantity (3) are then together proportional. From Equations (1) and (2) it stands to reason, that electric machine with the disk rotor can have small length, which is dependent only on designing production facilities of a disk and on its mechanical strength and length of the disk is not conditional by electromagnetic parameters.

3. Design of stepper motor with disk rotor

The merit of a design is determining the disk rotor main dimensions. Major task is then determining of the outer diameter and of the width annulus. Other quantity is data of stepping frequencies. With these quantities is close-knit step angle, the number of steps per revolution and the maximum rotation speed.

3.1. Basic measurements of disk rotor

Basic measurements of the disk rotor is possible to determine from planar parameters from modified Equation (2). On the basis of specific height h, the motor torque M and the average specific tension σ is calculated the diameter of disk rotor:

$$d = \sqrt{\frac{\frac{M}{\sigma \cdot \pi}}{h}} + h. \tag{4}$$

3.2. Number steps and stepping frequency of disk rotor

Stepper motors with the disk rotor normally are designed with the same number of poles $2p$ as the number of phases m. Therefore for stepper motors with disk rotor be of advantage as that of characteristic parameter used the number of phases and no the number of poles.

The number of steps per revolution K of the disk rotor is:

$$K = Q_2 \cdot 2m, \tag{5}$$

where Q_2 is the number of rotor slots (gears).

The stepping frequency f_s is in proportion to the electrical frequency f_e on output power unit of the stepper motor. One electric impulse of single phase is needed for one mechanical step, consequently after $2m$ steps oneself repeat the electric impulse in the same phase. Between mechanical, therefore stepping frequency and the electric frequency it's a deal:

$$f_e = \frac{f_s}{2m}. \tag{6}$$

The electrical frequency f_e according to Equation (6) is relatively low in compare with the stepping frequency. If we would select relatively high stepping frequency e.g. $f_s = 15\,000$ Hz, so for four-phase stepper motor $2m = 8$ is the electric frequency $f_e = 1875$ Hz, what's value acceptable for construction of power unit stepper motor.

For standard produced stepper motors with cylindrical rotor of this power stepping frequency is e.g. $f_s = 5000$ Hz and appropriate electric frequency $f_e = 1250$ Hz.

From hereinbefore aforesaid comparison is so confessedly, that stepper motor with cylindrical rotor has a third stepping frequency and the electrical frequency of the disk stepper motor is about 50% higher in comparison with the stepper motor with cylindrical rotor.

3.3. Rotational speed of stepper motor with disk rotor

The rotational speed of stepper motor with cylindrical and disk rotor are calculated from equation

$$n = \frac{60 \cdot f_s}{K} \text{ [rpm]}. \tag{7}$$

The standard stepper motor with cylindrical rotor for $K = 200$ steps on rev and $f_s = 5000$ Hz from Equation (7) has $n = 1500$ rpm.

For stepper motor with disk rotor is advisable formularize the rotational speed from modified Equation (7) with using Equations (5) and (6)

$$n = \frac{60 \cdot f_s}{Q_2} \text{ [rpm]}. \tag{8}$$

The equivalent stepper motor with disk rotor for $Q_2 = 24$ and $f_e = 1250$ Hz from Equation (8) has $n = 3125$ rpm.

The result from hereinbefore aforesaid is, that disk stepper motors have more than double speed in compare with stepper motors with cylindrical rotor.

4. Electromagnetic circuit of disk stepper motor with PM

The basic measurements of the electromagnetic circuit disk stepper motor were designed by means of equations, that are be presented in chapter 3.1 and 3.2.

The main parameters of the machine are given in Table 1.

Table 1. Stepper motor main parameters

Parameter	Value
Rated voltage	64 V
Rated current	5.0 A
Rated torque	4 Nm
Number of phases	4
Number of steps per revolution	200
Step angle	1.8°
Number of rotor magnets	50
Number of slotted stator poles on phase	4
Number of slotted stator poles	16
Number of teeth on stator pole	3
Winding turns in series per phase	196

In an axial flux permanent magnet motor with a two-stator and single-rotor construction, where the magnetic flux travels through the permanent magnets from one stator to another, the rotor of the machine can be kept totally ironless. This makes the manufacturing of the permanent magnet rotor very simple and inexpensive. The adverse effect is, of course, that two stators are needed. In a single rotor-two stators structure the permanent magnets are located in the rotor disk according to Figure 2.

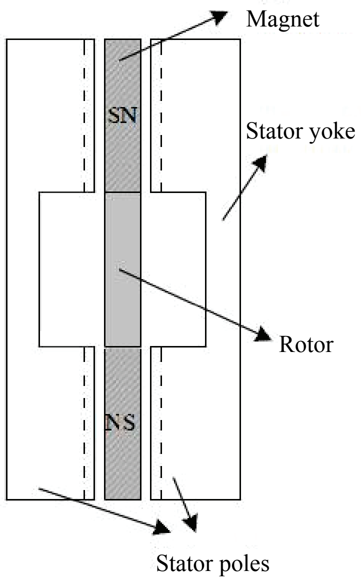


Fig. 2. Structure of the electromagnetic circuit disk stepper motor with PM

The basic dimensions of the electromagnetic circuit disk stepper motor with PM are given in Table 2.

Table 2. Stepper motor basic dimensions of the electromagnetic circuit

Parameter	Value
External diameter of the stator and rotor disk	140 mm
Internal diameter of the stator and rotor disk	63 mm
Stator yoke height	10 mm
Total stator pole height	21 mm
Pole core height	16 mm
Pole core width	16 mm
Pole core length	18.5 mm
Pole extension height	5 mm
Length of air gap (on both sides of the rotor)	0.3 mm
Thickness of PM (rotor disk)	3 mm
Rotor magnet Arc	3.6°

The design of motor electromagnetic circuit was developed by traditional analytic calculation (Table 1 and 2).

Figure 3 shows the schematically developed cut of magnetic circuit stepper motor with PM disk rotor across mean diameter of electromagnetic circuit.

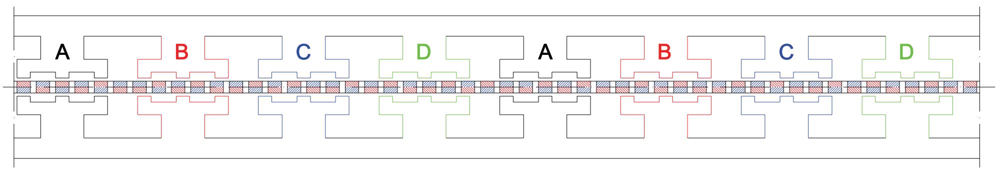


Fig. 3. Schematically developed cut of the electromagnetic circuit stepper motor with PM disk rotor

5. The magneto-static simulation of disk stepper motor with PM

According to the electrical parameters and dimensions specified in Chapter 4 there was developed a 3D model of a electromagnetic circuit for the stepper motor with PM disk rotor.

The stepper motor with axial flux permanent magnet disc-type slotless internal-rotor and two slotted external-stators was simulated. The basic measurements of the electromagnetic circuit are presented in Chapter 4.

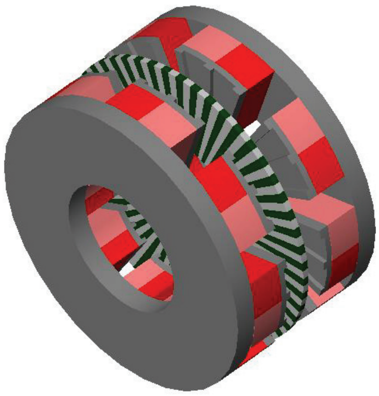
The rotor structure of this machine is formed by the axially magnetized surface magnets without iron yoke. The 3-d model of electromagnetic circuit stepper motor with disk permanent magnet rotor without iron yoke is created in a program ProEngineer and is displayed on Figure 4.

The flux then travels circumferentially along the stator core, returns across the air gaps, and then enters the disk rotor through the opposite polarity of the magnets.

The simulation is done in a program Cosmos/EMS. As boundary conditions is used the tangential flux. The parameters used for simulation:

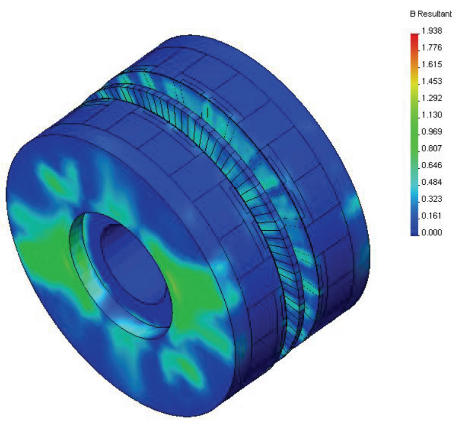
- global element size: 5.3697 mm; mesh control was used on the rotor and air gaps,
- total number of nodes: 20 463,
- total number of elements: 113 497,
- meshes type: standard.

Fig. 4. The electromagnetic circuit of disk stepper motor with PM disk rotor without iron yoke



The simulation of electromagnetic field disk stepper motor with PM disk rotor without iron yoke is shown in Figure 5.

Fig. 5. The electromagnetic field of disk stepper motor with PM rotor



Calculation of the motor torque determined by traditional method has been double-checked by applying the Finite Elements Method onto 3D model of the motor. By the Finite Elements Method calculated static torque in pre-step taking position is proved to be 4.08 Nm, and the difference represents only 0.08 Nm (i.e. 2%), which basically confirmed correctness of the analytical calculation (in Table 1 – the rated torque – 4 Nm).

6. Conclusion

In the present article 3D model of a step motor with permanent magnets rotor was designed also using analytic methods. When comparing the motor torque calculated by traditional method and by the Finite Elements Method applied to the motor 3D model, respectively, the difference of torques is amounted to only 2%. It would be appropriated to verify the calculated and simulated values of the proposed disc step motor with disc rotor through measurements performed on the motor physical sample.

In this paper, the design and magneto-static simulation in a program Cosmos/EMS of a motor with axial flux permanent magnet disc-type rotor have been presented. Its high torque-density was the parameter of concern. The aim was for maximum torque-density double-sided disk stepper motor with permanent magnets. Hence we can conclude that the disk step motor (specifically with small step of 1.8°) designed by the traditional method is sufficiently precise, which was confirmed also by 3D FEM analysis.

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