

*stepper motor, disk rotor, permanent magnet,
axial flux, electromagnetic field simulation*

Ján KAŇUCH*, Želmíra FERKOVÁ**

DESIGN AND ELECTROMAGNETIC FIELD SIMULATION OF DISK STEPPER MOTOR WITH PERMANENT MAGNETS

This paper presents the design and the electromagnetic field simulation of axial-flux permanent-magnet stepper motor with the disc type rotor.

The stepper motor with disc type permanent magnet rotor shows the advantages of higher torque at high speed, low moment of inertia, high torque to weight ratio, low power consumption and iron-less rotor having minimum iron loss using permanent magnets and prepregs.

This paper describes a design of four phase microstepping motor with the disc type rotor. The FEM modeling and the 3D electromagnetic field 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.

1. INTRODUCTION

The permanent magnets (PM) machines with axial flux are increasingly using machines with the cost of the high energy PM. These machines have many individualistic features. They are usually more efficient and higher power density is achieved. Besides PM motors have small magnetic size which results in small magnetic dimensions. 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 airgaps.

* Department of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, e-mail: jan.kanuch@tuke.sk

** Department of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, e-mail: zelmira.ferkova@tuke.sk

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

Stepper motors are widely used in printers, automated machine tools, disk drives, automotive dashboard instrument clusters, and other applications requiring precise motions using computer control. A stepper motor can be a good choice whenever controlled movement is required. They can be used to advantage in applications where you need to control rotation angle, speed, position and synchronism.

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. ADVANTAGES OF STEPPER MOTOR WITH DISK ROTOR

When using a stepper motor with the disk rotor it must be know the main disk rotor advantages.

The quantitative difference between stepper motor with cylindrical rotor and disk rotor flow from mutual comparison them electromagnetic utilizations. Therefore is needs formulate the specific thrust in active layer as parameter, which creates the torque.

2.1. AVERAGE SPECIFIC TENSION OF CYLINDER ROTOR

In electric machines building is established parameter σ indicative of a average specific tension in the active layer of cylinder on diameter d and length l :

$$\sigma = \frac{F}{\pi \cdot d \cdot l} \quad (1)$$

where F is the force actuating on a cylinder.

Provided that for the force F actuating on the cylinder is valid equation $F = M/d/2$, where M is the torque, so then after substitution into equation (1) we get for the specific tension equation

$$\sigma = \frac{2 \cdot M}{\pi \cdot d^2 \cdot l} \quad (2)$$

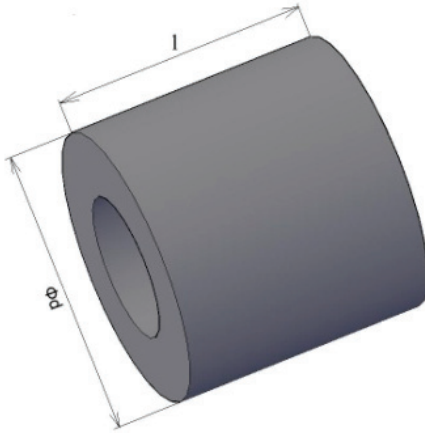


Fig. 1. Cylinder rotor

The result from equation (2) 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.

2.2. AVERAGE SPECIFIC TENSION OF DISK ROTOR

The average specific tension in active double layer of the disk rotor, therefore for two planparallel thicknesses is valid equation

$$\sigma = \frac{F}{2 \cdot [\pi \cdot (d - h) \cdot h]} \quad (3)$$

where d is outer diameter of the ring and h is height of the annulus (Fig. 2).

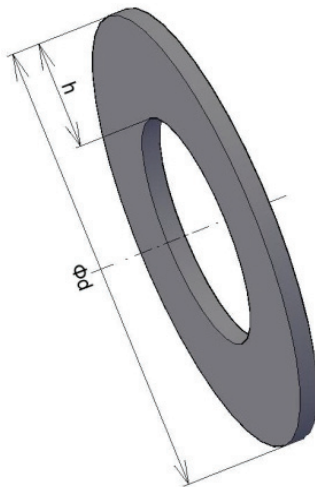


Fig. 2. Double layer disk rotor

The force F is value for total disk, therefore because of both parties disk. For the force F is valid equation

$$F = \frac{2 \cdot M}{(d - h)} \quad (4)$$

where M is the motor torque.

After substitution (4) in an equation (3) because of the specific tension disk motor we get equation

$$\sigma = \frac{M}{\pi \cdot (d - h)^2 \cdot h} \quad (5)$$

From equation (5) is the result, that dimensional criterion of the discoid motor is a planar quantity

$$\pi \cdot (d - h)^2 \cdot h \quad (6)$$

The motor torque M and the planar quantity (6) are then together proportioning. From equations (2) and (5) it stands to reason, that electric machine with the disk rotor can have minute length, which is dependent only on designing production facilities of a disk and on his mechanical strength and length disk is not conditional by electro-magnetic parameters.

3. DESIGN OF STEPPER MOTOR WITH DISK ROTOR

The merits of a design is determining of the disk rotor main dimensions . Major task is then determining the outer diameter and of the width annulus. By other quantity are data of stepping frequencies. With these quantity is close-knit step angle, the number step on rev and the maximum rotation speed.

3.1. BASIC MEASUREMENTS OF DISK ROTOR

Basic measurements of the disk rotor is possible determine from planar parameters from modify equation (5)

$$(d - h)^2 \cdot h = \frac{M}{\sigma \cdot \pi} \quad (7)$$

On the basis of specific height h , the motor torque M and the average specific tension σ , from modified equation (7) is calculated the diameter of disk rotor

$$d = \sqrt{\frac{M}{\frac{\sigma \cdot \pi}{h} + h}} \quad (8)$$

3.2. NUMBER STEPS AND STEPPING FREQUENCY OF DISK ROTOR

Stepper motors with the disk rotor normally to design with the same number of poles $2p$ how is 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 on rev K of the disk rotor is

$$K = Q_2 \cdot 2m \quad (9)$$

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. For one mechanical step be needed one electric impulse one's phase, consequently after $2m$ steps oneself repeat the electric impulse in the same phase. Between mechanical, therefore stepping frequency and the electric frequency it is a deal

$$f_e = \frac{f_s}{2m} \quad (10)$$

The electrical frequency f_e according to equation (10) is relatively low in compare with the stepping frequency. If we would select relatively high stepping frequency e.g. $f_s = 15000$ Hz, so for four-phase stepper motor is the electric frequency $f_e = 1875$ Hz, what is value acceptable for construction of power unit stepper motor.

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

From therein before 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 STEPPER MOTOR WITH DISK ROTOR

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

$$n = \frac{60 \cdot f_s}{K} \quad [\text{rpm}] \quad (11)$$

For stepper motor with disk rotor is advisable formularize the rotational speed from modified equation (11) with using equations (9) and (10)

$$n = \frac{60 \cdot f_s}{K} \quad [\text{rpm}] \quad (11)$$

The stepper motor with disk rotor for $K = 200$ steps on rev and $f_s = 15000$ Hz from equation (10) has rpm.

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

3.4. ADVANTAGE OF DISK STEPPER MOTOR WITH PERMANENT MAGNETS

Development and design of classic stepper motors has been divided to two application directions:

- the first direction has been stepper motor without excitation in rotor, who worked on variable reluctance principle,
- the second direction has been stepper motor with homopolar permanent magnet excitation.

The experience of applications stepper motors remitted at this, that stepper motors with homopolar permanent magnet have a larger torque and more perfectly conform to the commutation conditions of the semiconductive power circuits in compare with stepper motor of variable reluctance type, i.e. without permanent magnet. The self (excited) magnetic flux and the internal induced voltage are in this case user benefits parameters.

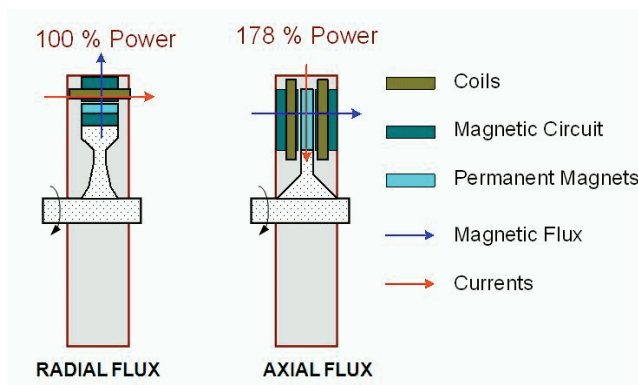


Fig. 3. The comparison of disk motor power with radial and axial magnetic flux [3]

However, if we compare a power of disk motor with axial magnetic flux with power in whiteness of same disk motor, but design solution like this, but with so much design solution, that magnetic flux flows in radial direction, so at holdback about equally of volume, the power of the motor with axial magnetic flux is cca more how 50% higher than the power of the motor with radial magnetic flux (Fig. 3).

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 toothes 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 and the permanent magnets are located in the rotor disk is schematic according to Fig. 4.

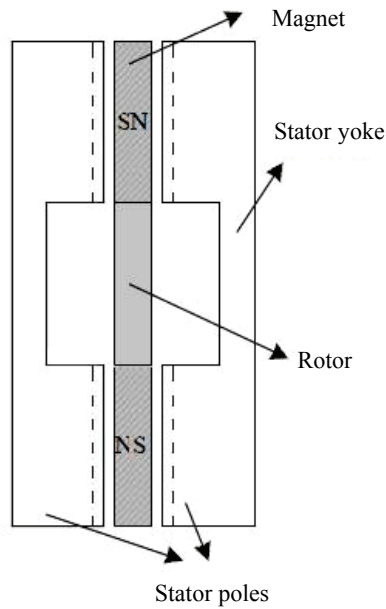


Fig. 4. Structure of the electromagnetic circuit disk stepper motor with PM

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	5mm
Length of air gap (on both sides of the rotor)	0.3 mm
Thickness of PM (rotor disk)	3mm
Rotor magnet Arc	3.6°

Figure 5 shows the schematic developed cut of electromagnetic circuit stepper motor with PM disk rotor across mean diameter of electromagnetic circuit. The winding of motor in the figure is not drawing.

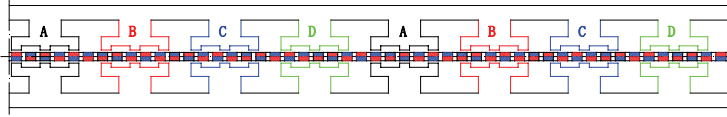


Fig 5. Schematic developed cut of the electromagnetic circuit stepper motor with PM disk rotor

5. ELECTROMAGNETIC FIELD SIMULATION OF DISK STEPPER MOTOR WITH PM

The stepper motor with axial flux permanent magnet disc-type nonslotted internal-rotor and two slotted external-stators was simulated. 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 Fig. 6.

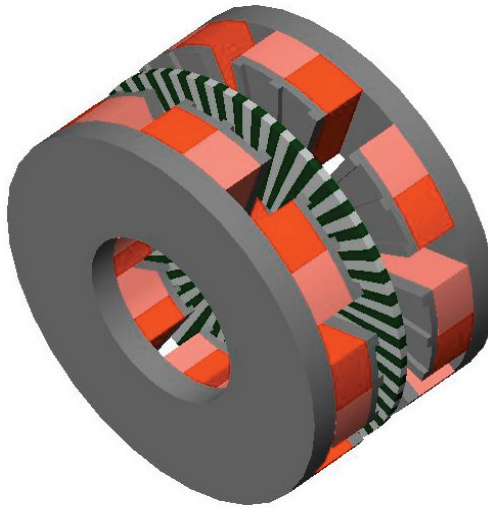


Fig. 6. The electromagnetic circuit of disk stepper motor with PM disk rotor without iron yoke

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 of electromagnetic field is made in a program Cosmos/EMS. As boundary conditions is used the tangential flux. While simulation is all model of the electromagnetic circuit containerised of an air. The parameters used about simulation:

- global element size: 5.3697 mm; mesh control was used on the rotor and air gaps,
- total nodes: 20463,
- total elements: 113497,
- meshes type: standard.

Fig. 7 shows of density meshes at simulation. On the right is air, that is at simulation hidden.

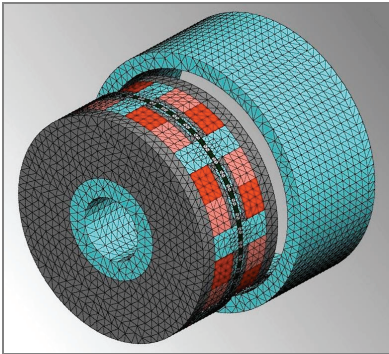


Fig. 7. The meshes at simulation

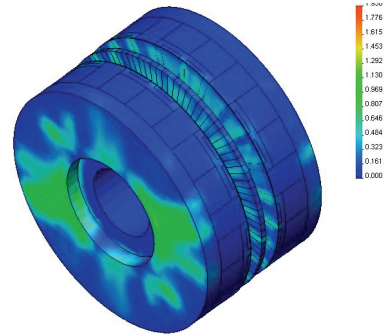


Fig. 8. The electromagnetic field of disk stepper motor with PM rotor

The simulation of electromagnetic field disk stepper motor with PM disk rotor without iron yoke is shown in Fig. 8 and Fig. 9.

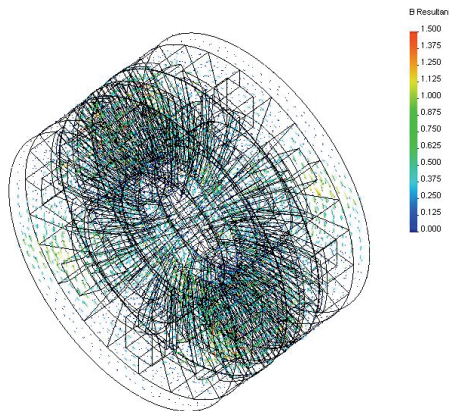


Fig. 9. The electromagnetic field of disk stepper motor with PM rotor

7. CONCLUSION

In this paper, the design and electromagnetic simulation 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.

The motor is ideally suited for measurement and control applications. The step resolution and performance of these motors can be improved through a technique called microstepping and used to disk rotor with permanent magnets.

Results of design and simulation electromagnetic field in a program Cosmos/EMS have been reviewed in this paper.

ACKNOWLEDGEMENT



We support research activities in Slovakia/Project is co-financed from EU funds. This paper was developed within the Project "Centrum excelentnosti integrovaného výskumu a využitia progresívnych materiálov a technológií v oblasti automobilovej elektroniky", ITMS 26220120055.

The financial support of the Slovak Research and Development Agency under the contract No. APVV-0138-10, is acknowledged.

REFERENCES

- [1] Available on: < <http://www.portescap.com> >
- [2] AYDIN M., HUANG S., LIPO T.A., *Axial flux permanent magnet disc machines: a review*, University of Wisconsin – Madison, 2004 .
- [3] GIERAS J.F., WANG R.J., KAMPER M.J., *Axial Flux Permanent Magnet Brushless Machines*, Kluwer Academic Publisher, 2008.
- [4] HRABOVCOVÁ V., JANOUŠEK L., RAFAJDUS P., LIČKO M., *Moderné elektrické stroje*; University of Žilina press, 2001, Slovakia. (in Slovak).
- [5] HRABOVCOVÁ V., RAFAJDUS P., FRANKO M.: *Measuring and modeling of the electrical machines*; University of Žilina press, 2004, Slovakia.
- [6] KAŇUCH J., „*Rokový motor s diskovým rotorom s axiálnym magnetickým tokom s krokom $\alpha < 1$* “. Technical University of Kosice, TUKE, 2003.
- [7] PARVIAINEN A., *Design of axial-flux permanent magnet low-speed machines and performance comparison between radial-flux and axial-flux machines*, Lappeenranta teknillinen yliopisto Digi-paino 2005.
- [8] RAHIM N.A., HEW W.P., MAHMOUDI A., *Axial-Flux Permanent-Magnet Brushless DC Traction Motor for Direct Drive of Electric Vehicle*. International Review of Electrical Engineering (I.R.E.E.), March–April 2011, Vol. 6, No. 2.

- [9] WIAK S., *Disc Type Motors for Light Electrical Vehicles*, ACEMP'2001, June, 2001, Turkey, invited paper, 447–452.
- [10] WIAK S., NADOLSKI R., LUDWINEK K., GAWĘCKI Z., *DC Permanent Magnet Motor for Electric Bike and Their Impulse System for Battery Charging*, Proceedings XVI International Conference on Electrical Machines ICEM 2004, 3–6 September 2004, Cracow, Poland; 1057–1058.
- [11] WIAK S., WELFLE H., *Electromagnetic Field Analysis of 3D Structure of Disk-Type Motors*, Electro motion, September, 1999, Vol. 3, 336–337.
- [12] WIAK S., WELFLE H., KOMEŹA K., DEMS M., *Comparative study of 3D structure of disk type motor*, Proceedings COMPUMAG'99, Sapporo, Japan, 25–28 October 1999.