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DESIGN AND CONSTRUCTION OF BLDC MOTOR WITH AXIAL MAGNETIC FLUX FOR DIRECT DRIVE

PROJEKT I KONSTRUKCJA SILNIKA BLDC O STRUMIENIU MAGNETYCZNYM OSIOWYM DO NAPĘDU BEZPOŚREDNIEGO

Abstract: The paper deals with suggested concept of direct drive for small electric vehicle, using a three-phase double disc BLCD motor. Presented and described in the article are results of electromagnetic design and construction of a disc brushless motor with central slotted stator and double outer rotor with permanent magnets that has been found to be suitable for its positioning within wheel of small electric vehicle.

Streszczenie: W artykule omówiono koncepcję bezpośredniego napędu małego pojazdu elektrycznego z wykorzystaniem trójfazowego tarczowego silnika BLCD. Przedstawiono i opisano wyniki projektu elektromagnetycznego i bezszczotkowego silnika tarczowego z centralnym szczelinowym stojanem i podwójnym wirnikiem zewnętrznym z magnesami trwałymi, który został umieszczony w obrębie koła małego pojazdu elektrycznego.

Keywords: *BLCD motor, small electric vehicle, brushless motor, disc electric motor, external rotor, construction, design*
Słowa kluczowe: *silnik BLDC, mały pojazd elektryczny, silnik bezszczotkowy, silnik elektryczny tarczowy, wirnik zewntrzny, projktowanie, konstrukcja*

1. Introduction

Today, DC motors with permanent magnets (DCPM), internal rotor and mechanical commutator present an industry standard for the electric drive of small electric vehicles. The resulting efficiency of such a drive (inverter, engine and gearbox) without load is about 80%. The overall efficiency of the drive is also greatly influenced by battery attributes, such as capacity, peak current and battery life.

The speed and operating range of a small electric vehicle depend on the condition of the battery. Design of the electric drive, the motor type, the weight and the type of the battery affect the resulting vehicle parameters, such as its operating range, maximum speed, load capacity, total weight, width and height. The design elements such as gears and other transmission elements, for example drive axles and bearings, are frequent sources of noise and generate resistance for electric drive, thereby reducing its efficiency. The use of DC motors with mechanical commutators requires regular maintenance or replacement and also creates noise.

The propulsion system of powered small electric vehicle typically consists of a pair of motors, one for each drive wheel, and a drive train consisting of gears, belts and other mechanical elements that couples the motor's shaft to the drive wheel shaft [2]. Most small electric vehicles utilize two DC permanent magnet motors (DCPM motors), with two 12 V batteries providing a 24 V supply. DCPM motors have a linear torque-speed profile making them easy to control.

Under loads typical for small electric vehicles, the DCPM motor can attain lower efficiency. The drop in motor efficiency increases the current drawn from the battery and decreases battery life and capacity [2].

The drives system of a commonly used electric vehicle consists of DC motor and a drive train consisting of gears or belts or other mechanical elements that couple the motor's shaft to the drive wheel shaft.

A converter (DC–DC) supplies motor with a high frequency and square-wave pulse train. Microprocessor based control unit controls the speed and torque generated by motor through independent PWM signal (Fig. 1).

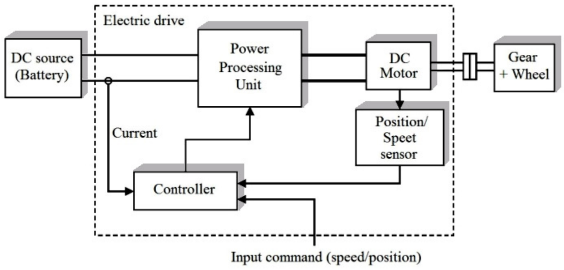

Fig. 1. Block diagram of an electric drive system for small electric vehicle

Generally, the control module of the vehicle converts the speed required information into power signals to the motor. Many control modules utilize feedback to sense whether the motor is responding properly to the required speed.

2. Drive concept of electric vehicle with inverse BLDC motor

Hub motors are called the motors incorporated into the wheels of the vehicle. In the case of hub motors, the torque transmission elements from motor to wheel are eliminated. The cylindrical motor is attached directly to the wheel rim. The main advantages of gearless drives are as follows:

- improved system reliability and system performance,
- lowers installation costs and reduction of system components,
- fits the wheel units for a variety of wheelchairs,
- eliminated is the use of transmission elements like chains and belts.

Basic elements of the drive with a brushless DC motor are: BLDC motor, inverter, driver and controller. The simplified block diagram is shown in Fig. 2.

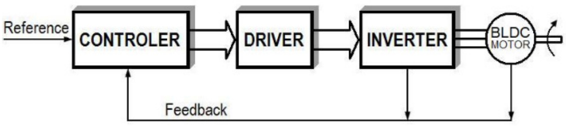

Fig. 2. Block diagram of an electric drive with BLDC motor

The BLDC control drive system is based on the feedback of rotor position. So, the operation of BLDC motor requires a control system and position sensors to estimate rotor position [3, 4].

Nowadays, quite widely used is double-sided disc structure BLDC motor with a central stator without slots (Fig. 3).

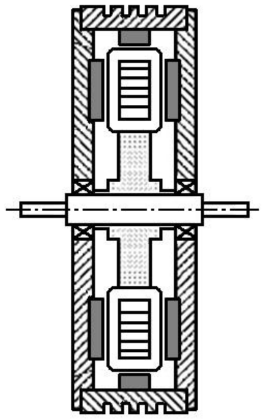

Fig. 3. The disc BLDC motor with a central stator

The BLDC motor has a multi-phase toroidal stator winding wound on the stator ferromagnetic core. The stator core is made up of laminating steel tape or by powder metallurgy (sintering). Due to the relatively large air gap the maximum magnetic induction in the motor does not exceed 0.65 T. The magnetic circuit is unsaturated. For higher induction values, a large volume of permanent magnets is required.

3. Electromagnetic and construction design of the BLDC motor with axial flux

The increasing popularity of brushless DC permanent magnet motors in recent years is due to use of high energy magnets and to drop in the price of electronic devices. The brushless PM motors perform better and have higher efficiency than the machines with electro-magnetic excitation.

Selected for driving the small electric vehicle is a disc BLDC motor with three phase stator winding connected in star (Y). This connection is compared with a delta connection (D) suited to drive on battery power and has a lower Joule loss in the same dimensions of the motor. The selected BLDC motor has two external disc rotors with PM and one central mutual slotted stator. This motor with axial magnetic flux is thinner and more powerful than a motor with radial magnetic flux of the same volume. In this construction, it requires only half the volume of PM, and the magnets are the most expensive elements in the construction of the motor.

A proposal of three-phase disc BLDC motor with dual external rotor and central grooved stator was necessary to define the basic parameters of the drive and performance requirements. The calculation of all parameters, coefficients, and dimensions was performed by using a debugged m-file in MATLAB 2013a. This m-file contains all initial performance requirements of drive and all equations necessary to calculate the final dimensions and characteristics of the disc BLDC motor with dual external rotor (with permanent magnets) and a central grooved stator. To calculate the required parameters in terms of power and torque of the disc BLDC motor with axial flux, which are located in wheel, a simplified model of dynamics of a small electric vehicle was used.

3.1. Basic specification Torque and Speed of BLDC motor

Detailed vehicle parameters are provided in Table 1.

Table 1. Basic Vehicle parameters

Parameter	Value
Vehicle mass	130 kg
Required vehicle speed (at nominal torque)	10 km.h^{-1}
Acceleration	1 m.s^{-2}
Maximum slope	5 %
Wheel radius	0.3048 m
Angular velocity	9.02 rad
Rolling resistance factor	0.0212
Gravitational acceleration	9.81m.s^{-2}
DC Supply Voltage	24 V

To calculate the power and torque of the BLDC engine, a simplified model of vehicle dynamics was used. The forces which the electric machine of the vehicle must overcome are the forces due to gravity, wind, rolling resistance, and inertial effect. The total tractive force required for drives of vehicle consists of the following components:

- Inertial force of the vehicle,
- Rolling resistance force of the wheel,
- Gravitational force of the vehicle
- Force due to wind resistance.

The traction force of a vehicle (calculated from vehicle parameters shown in Table 1) is $F_t = 220.45$ N. The traction force for one BLDC motor is $F_{t1} = F_t /2 = 110.22$ N.

The traction torque of one BLDC motor is $T_{t1} = F_{t1} * r_{whell} = 34$ N.m. Total required traction power of one BLDC motor is $P_1 = T_{t1} * \boldsymbol{w}_{whell} = 307$ W. Nominal speed of BLDC motor is $n = v_t /(2.\boldsymbol{p}.r_{whell}) = 1.44$ rev/s = = 86 rpm.

3.2. Electromagnetic design of the BLDC motor

Calculations of dimensions and parameters of the BLDC motor were implemented by use of m-file in MATLAB 2013a. For the design and electromagnetic calculations of three-phase disc BLDC motor with dual external rotor and central grooved stator the basic equations and information were used with support of references [5 - 10].

The calculation of rotor disc dimensions depends mainly on the achievable magnetic induction on the surface of the permanent magnets and on the maximum flux density in the rotor yoke. The selected material of the permanent magnets is NdFeB (class N38) [11]. The main resulting design parameters of BLDC motor are provided in Table 2.

Table 2. Main parameters of three-phases BLDC motor

Parameter	Value
Power	310 W
Supply voltage	24 V DC
Nominal current	14.2 A
Nominal torque	34.0 N.m
Nominal speed	86 rpm
Number of phase	3
Type of windings connection	"Star" (Y)
Number of pole pairs	32
Total length of motor	106.5 mm
Length of air gap	0.5 mm
Outer diameter of the stator	224.0 mm
Inner diameter of the stator	130.0 mm
Effective length of the stator core	47.0 mm
Number of turns per phase	130
Wire diameter of the stator windings	1.8 mm
Coil spacing (in the number of coils)	1
Number of stator slots (on the one side of stator disc)	48
Opening width of the stator slot	2.0 mm
Magnetic induction in air gap	0,85 T
Permanent magnet material	NdFeB (N38)
Height permanent magnets	47.0 mm
Angle of the permanent	7.5 °

magnets	
Maximum (minimum) width of permanent magnets	14.65 (8.5) mm
Thickness of the permanent magnets	3.0 mm
Magnetic induction of magnets	1.22 T

The three-phase 32-pole two-layer winding placed in the stator is grooved on both sides. The final positioning of coils stator in the slots is shown schematically in Fig. 4.

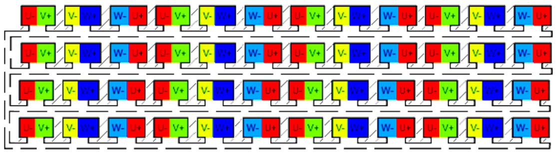

Fig. 4. Final placement of two-layer winding in stator slots

3.3. Construction design of the BLDC motor

The 3D model of the stator core created in the PTC Creo Parametric 3.0 M060 is shown in Fig. 5 and its dimensions are shown in Fig. 6.

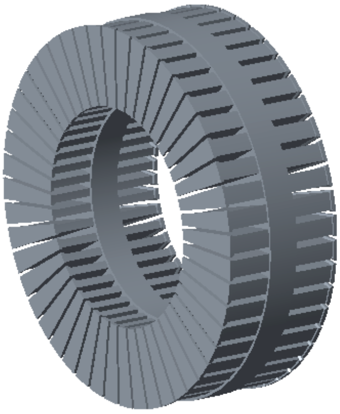

Fig. 5. Model of central grooved stator

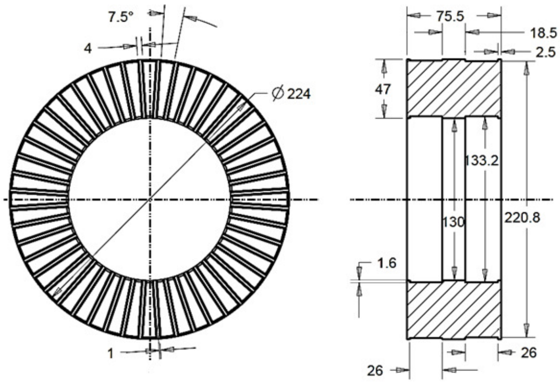

Fig. 6. Dimensions of stator core

Fig. 7 presents the geometry and dimensions of stator slot with winding.

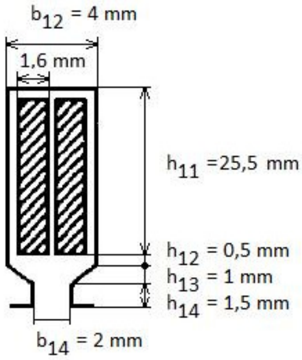

Fig. 7. Dimensions of stator slot with winding

The calculation of the rotor disc dimensions depends mainly on the achievable magnetic induction on the surface of permanent magnets and on the maximum magnetic induction in the rotor core. The maximum magnetic induction in the rotor core (low carbon steel grade SAE 1117) is 1.5 T [12]. 3D model of rotor disk in two views without permanent magnets is shown in Fig. 8.

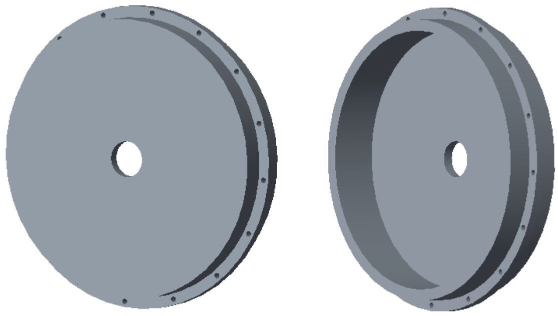

Fig. 8. Model of rotor core motor without permanent magnets

Fig. 9 presents the geometry and dimensions of the rotor core without permanent magnets.

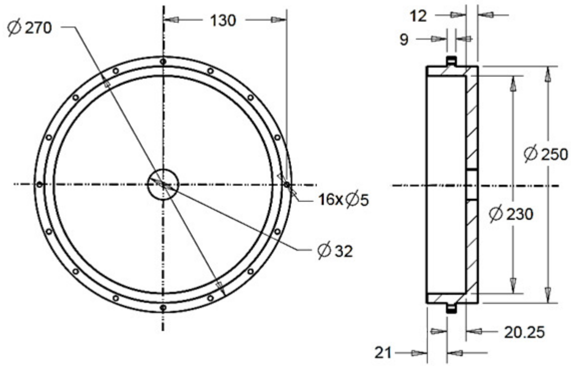

Fig. 9. Dimensions of rotor core

The dimension of permanent magnets depends on the geometry and dimensions of stator. The thickness of permanent magnets depends on the volume of permanent magnets required for the given engine power. The permanent magnet material is NdFeB class N38 [11].

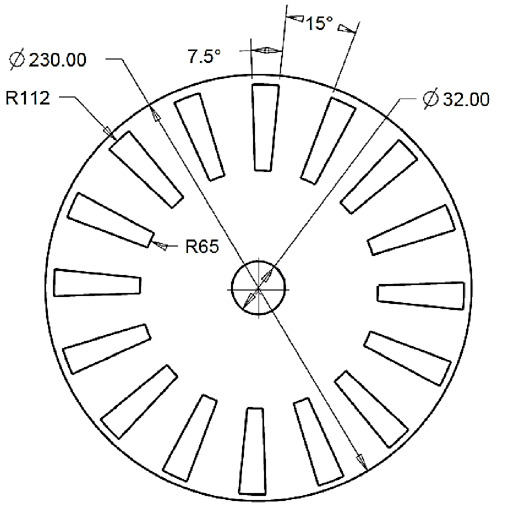

Fig. 10. The permanent magnets on the rotor disc

The arrangement of permanent magnets on the rotor disc and their dimensions are shown in Fig. 10. The main dimensions of permanent magnet are provided in Table 2.

The fixed shaft of motor with outer rotor is shown in Fig. 11.

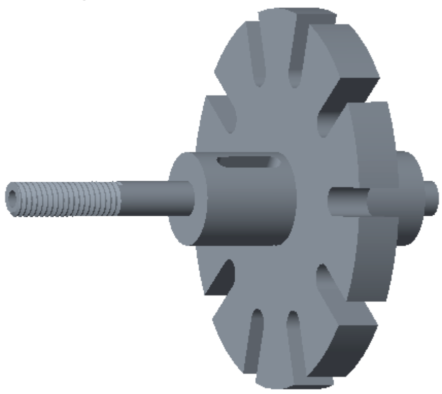

Fig. 11. The 3D model of fixed shaft

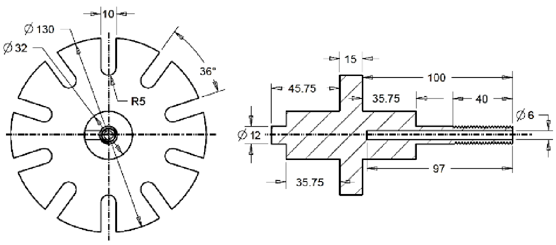

Fig. 12. Dimensions of fixed shaft

Fig. 13 presents the final 3D-model of disc BLDC motor with dual external rotor in exploded view.

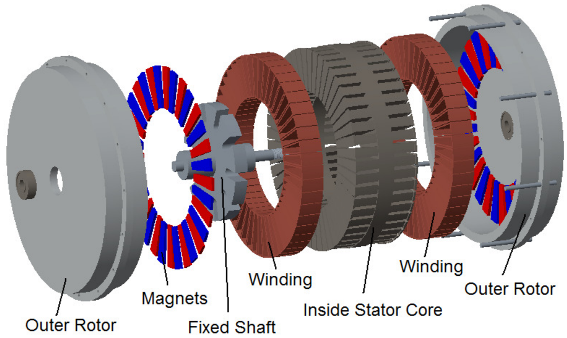

Fig. 13. Model of disc BLDC motor with dual external rotor

The final 3D-model of disc BLDC motor with dual external rotor created in the PTC Creo Parametric 3.0 M060 is shown in Fig. 14. Based on the 3D-model design parameters and dimensions of motor parts prototype of disc three-phase the BLDC motor can be manufactured.

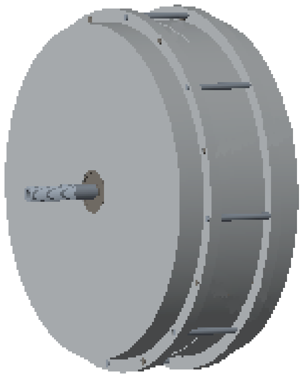

Fig. 14. Model of disc BLDC motor

4. Conclusions

Designed has been a double-disc BLDC motor with permanent magnet that is applied as the small gearless electric vehicle drive.

The main contribution of the research is a detailed electromagnetic proposal and design of double-disc brushless DC motor with external rotor and permanent magnets. Electromagnetic calculations, calculations of dimensions and parameters of the BLDC motor were realized by using the m-file in MATLAB programme. This m-file can be used at a future design of electric drive for other small vehicles by simply changing the desired properties and parameters. In the future, use of m-file can optimize the calculated dimensions and characteristics of the disc BLDC motor with a central slotted stator and outer double disc rotor with permanent

magnet for other drive application. Main electromagnetic parameters of a three-phase BLDC motor have been verified using electromagnetic simulation in the program type FEA/FEM (simulation with a finite number of elements).
For design of each element of the BLDC motor and its 3D model the program PTC Creo Parametric was used. Based on electromagnetic and construction design prototype of disc three-phase the BLDC motor is ready to be manufactured. After manufacturing the motor prototype the final parameters are verified by measurements.

5. Acknowledgment

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6. Bibliography

[1]. A Guide to Electric Wheelchairs [Online]. [cit. 2016-03-10], 2016, Available from: http://www.apparelyzed.com/wheelchair/electric-wheelchairs.html

[2]. Discussion Preparation for: Motors, Drive Trains and External Drive Motor Systems, 2016, Available from: http://www.wheelchairnet.org/WCN_WCU/Research/StakeholderDocs/PDFs/motors.pdf

[3]. Gieras J. F., Wing M.: *„Permament magnet motor technology."*, Marcel Dekker Inc., New York, 2002.

[4]. Gieras J. F., Wang R. J., Kamper M. J.: *„Axial flux permament magnet brushless machines."*, Kluwer Academic Publishers, USA 2004.

[5]. Glinka T.: *„Maszyny elektryczne wzbudzane magnesami trwałymi.",* Wydawnictwo Politechniki Śląskiej, Gliwice 2002.

[6]. Król E, Rossa R: „Silniki z magnesami trwałymi o dużej przeciążalności momentem". *Maszyny Elektryczne - Zeszyty Problemowe*, nr 81, pp 27-31, 2009.

[7]. Kołodziej, J., Kowol, M., Mendrela, E.: „Moment i siła elektromotoryczna w nowym synchronicznym silniku tarczowym z magnesami trwałymi o wydatnych biegunach stojana". *Maszyny Elektryczne – Zeszyty Problemowe,* nr 4 (104), pp 77-82, 2014.

[8]. Bernatt J.: *„Obwody elektryczne i magnetyczne maszyn elektrycznych wzbudzanych magnesami trwałymi.",* Wydawnictwo BOBRME Komel, Katowice, 2011.

[9]. Król E.: „Silniki synchroniczne w napędach pojazdów sportowo-rekreacyjnych", *Maszyny Elektryczne-Zeszyty Problemowe* nr 2, pp 23-27, 2014.

[10]. Hetmańczyk, J., Krykowski, K., Gałuszkiewicz, Z., Miksiewicz, R., Makieła, D.: „Porównanie właściwości wysokoobrotowego silnika PM BLDC ze stojanem bezżłobkowym i żłobkowanym", *Maszyny Elektryczne - Zeszyty Problemowe*, nr 90, pp 117-122, 2011.

[11]. Grades of Neodymium [Online], 2017, Available from: http://www.ndfebinfo.com/neodymium _grades.aspx

[12]. Gottipati P.: *„Comparative study on double-rotor PM BLDC motor with cylindrical and disc type slot-less stator.",* USA 2007. 97s.

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