Ján Kaňuch
Technical University, Letná 9, Košice, Slovakia

DIRECT DRIVE OF ELECTRIC WHEELCHAIR WITH DOUBLE DISC BLDC MOTOR

NAPĘD BEZPOŚREDNI WÓZKA ELEKTRYCZNEGO Z SILNIKIEM BLDC O KONSTRUKCJI Z PODWÓJNYM DYSKIEM

Abstract: In the first part of paper there are described various constructions of existing electric drives used in a wheelchair driven by an electric motor and also described is the most widely used current technology drive of the wheelchair. Further this paper describes a new design and technical solution of the concepts of the proposed drive with the choice of the type construction drive and steering, construction of the motor, battery and appropriate drive parameters. Results of construction and electromagnetic design of disc brushless motor with a central stator and double-tapping external rotor suitable for location in 24" rear wheels of a wheelchair are also described.

Streszczenie: W pierwszej części artykułu opisano różne konstrukcje istniejących napędów elektrycznych, używanych w wózku inwalidzkim napędzanym silnikiem elektrycznym. Następnie opisano nowy projekt i techniczne rozwiązanie koncepcji proponowanego napędu z wyborem napędu budowlanego i układu kierowniczego, konstrukcji silnika, akumulatora i odpowiednich parametrów napędu. Opisano również wyniki budowy i projektowania elektromagnetycznego bezszczotkowego silnika z centralnym stojanem i podwójnym zębatym wirnikiem, do zastosowania w tylnych kołach 24" wózka inwalidzkiego.

Keywords: *electric wheelchair, disc motor, brushless motor, external rotor, construction, design*
Słowa kluczowe: *wózek elektryczny, silnik z podwójnym dyskiem, silnik bezszczotkowy, projektowanie*

1. Introduction

Wheelchair is an essential assistive device for many individuals with disability. Manual wheelchairs provide a relatively low-cost solution to the mobility needs of such individuals. However, the manual wheelchairs have large mechanical losses, and thus the risk of user fatigue. Electric-powered wheelchairs provide a more convenient means of transportation of disabled people. However, they are relatively expensive. Electric wheelchairs are usually more heavier than manual wheelchairs because the frame has to be stronger in order to support the battery and motors [1]. The propulsion system of powered wheelchairs 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 wheelchairs utilize two permanent magnet DC motors (PM motors), with two 12 V batteries providing a 24 V supply. PM motors have a linear torque-speed profile making them easy to control.

Under loads typical for power wheelchairs, DC PM motor can attain lower efficiency. A drop in motor efficiency increases the current drawn from the battery and decreases battery life and capacity [2].

The way that electric wheelchairs are driven varies and different methods give different characteristics to the wheelchairs. The following are the four basic methods of propulsion [3]:

- Rear Wheel Drive Wheelchair (Fig. 1a) - This is the most common method of drive for an electric wheelchair. This drive makes the wheelchair fast, but can give a poor turning capability when compared to front and mid wheel drive wheelchair.
- Mid Wheel Drive Wheelchair (Fig. 1b) - The method of drive gives the best turning capability of all the wheelchairs. The wheelchair may not be suitable for uneven surfaces.
- Front Wheel Drive Wheelchair (Fig. 1c) - The method of drive gives a lower top speed than rear wheel drive, but offers a good turning capability.
- Mixes (all-terrain) wheelchair 4x4 (Fig. 1d). The wheelchair is designed to pass through doorways. The all-wheel-drive electric wheelchair (4x4) makes it possible to drive indoors

but its main benefit is in the country, in the garden and in the city [4].
Then, there are various special and experimental design electric wheelchairs designed for non-standard applications – wheel-chairs for overcoming obstacles (eg. curbs and stairs), drive the bands instead of wheels for movement on snow, constructions with different number and layout of wheels than usual and the like [5].

Fig. 1. Different types of drives electric wheelchairs [3,4,5]

2. Current technology drive of wheelchair

The drives system of a common used electric wheelchair consists of two DC motors (one for each drive wheel) and a drive train consisting of gears or belts or other mechanical elements that couple the motor's shaft to the drive wheel shaft (Fig. 2) [6-9].

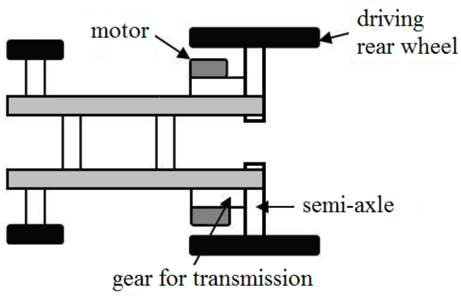

Fig. 2. Mechanical system for a wheelchair drive

A converter (DC–DC) supplies each motor with a high frequency and square-wave pulse train. Microprocessor based control unit controls the speed and torque generated by each motor through independently PWM signal (Fig. 3).

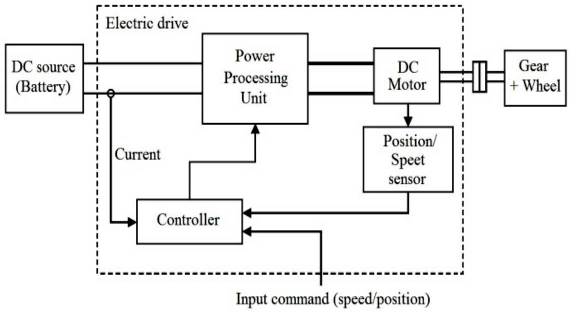

Fig. 3. Block diagram of an electric drive system for a wheelchair

Generally, to switch supply voltage polarity (to change the running direction of PM motor) are used relays. The control module of the wheelchair converts the positional information from the joystick into power signals to the motors. Many control modules utilize feedback to sense whether the motor is responding properly to the joystick position.

Fig. 4 (a, b and c) shows drives with and without gears. In gearless drives, the motors are incorporated within the drive wheels. Figure 4c shows a drive without gears.

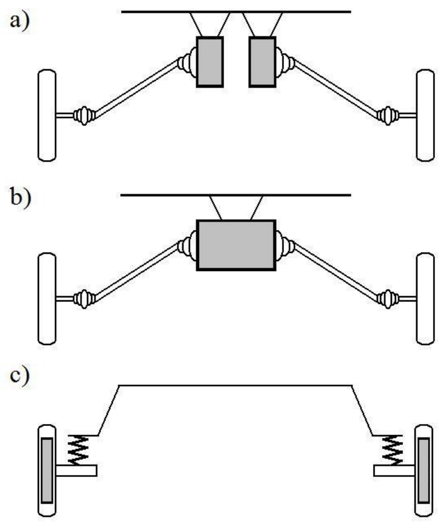

Fig. 4. Configurations of drives of electric wheelchair

Fig. 4a) shows two independent motors that are sprung from chassis. In Fig. 4b) there is one centrally placed motor with mechanical gear. Fig. 4c) shows another arrangement of the motors - they are two unsprung hub motors. A single motor with mechanical differential is used seldom [10].
The motors incorporated into the wheels of the vehicle are called hub motors. 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 advantages of gearless drives are as follows:

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

3. Drive concept wheelchair with a BLDC motor

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 they have higher efficiency than the machines with electro-magnetic excitation.

There are essential differences between the brush DC motor and brushless DC motor. The brush DC motor is equipped with a commutator, whereas in the brushless DC motor there is used an electronic commutator. When using of electronic commutator, the winding is placed on stator and the rotor contains permanent magnets. In case of the brush DC motor, the winding is placed always also on the rotor.

To drive the wheelchair selected is direct drive (without gearbox) with driven rear-wheels of standard size 24". This structure is also chosen because of its simplicity. In each rear-wheel placed there is one disc BLDC motor. Rear-wheel drive presents the most common construction for a motorized wheelchair with which the wheelchair can reach top speed, has good stability and relatively good driveability in indoor and outdoor areas. The rebuilding requires reconstruction of non-motorized wheelchair in order to replace rear wheels by the wheels with integrated disc BLDC motor, by adding battery, inverter and control (joystick) and with the necessary mechanical modifications. The advantages of direct drive as compared with indirect drive are as follows:

- elimination of gears and other transmission components,
- drive without gears is quieter,
- improvement of reliability and performance of such a system,
- reduction of the cost of conversion and of necessary components.
- system eliminates rewind of one wheel,
- increase of efficiency (meaning a larger operating range per battery charge and reduce of operating costs).

3.1. Final selection of the motor and control

Selected for driving the wheelchair 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 losses in the same dimensions of the motor. The selected BLDC motor has an external disc rotor with PM and central mutual slotted stator. This motor with axial magnetic flux is thinner and more powerful than a motor with radial magnetic flux at 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.

Control module and converter for the two BLDC motors with control using a joystick are chosen from Golden Motor Technology Co. Ltd., which is directly suitable for electric powered wheelchair [11]. Control module is designed for battery with a supply voltage of 24 V and can supply a current of 40 A for both motors, has five degrees of speed and allows regenerative braking. Electrical specifications and parameters of converter are listed in Table 1. Fig. 5 show control module and converter.

Table 1. Basic parameters of the converter (Golden Motor Technology Co.)

Parameter	Value
Supply Voltage	24 V DC
Operating Voltage	18 V ~ 28 V DC
Peak Voltage	38 V DC
PWM Frequency	19.5 kHz (±1 %)
Brake Voltage	24 V ~ 6 V DC
Brake Current	max 1 A; min 0.1 A (each)
Motor max. Drive Current	50 A (two)
max. Battery Charge Current	12 A
Operating Temperature	-25 °C ~ +50 °C
Humidity Level Permit	IPX4
Electronic reverse brake function	
Brake open-circuit automatically detects function	

Fig. 5. Converter and control module [11]

3.2. Selecting the battery pack

As the battery is one of the most expensive and most weighty element of the whole system, it is necessary to pay more attention not only to define individual battery parameters, but also to selection of the type. Improper selection of the battery can greatly increase the weight of the wheelchair or the battery will not have a sufficient capacity, resp. fails to provide sufficient power (current) to the motors, for example, at an increased load. The first issue is the use of maintenance or maintenance-free lead-acid traction batteries that are susceptible to charging and discharging, and the practice shows that their lifetime (number of cycles) is usually short. Another variant is the more expensive battery, which is based on NiCd and NiFe, or battery life is several times higher. Still further, there are LiFePO4 batteries where the price is double of that of lead-acid batteries, but lifetime is at least three times higher and have more highly preferred parameters [12]. For the power supply of the wheelchair selected was (mainly due to the weight and excellent specification) LiFePO4 accumulator (from Bioenno Power company) BLF-2420W with nominal voltage of 24 V and a capacity of 20 Ah (see Fig. 6) [13]. Parameters of the accumulator are listed in Table 2.

Fig. 6. Accumulator Bioenno Power BLF-2420W LiFePO4

Table 2. Parameters of the accumulator BLF-2420W

Parameter	Value
Nominal Voltage	24 V
Capacity	20 Ah
Nominal discharge current	40 A
Maximal discharge current (max. 2 s)	80 A
Width x length x height	222 x 92 x 136 mm
Weight	5 kg

The accumulator is possible, in case of increased requirements, be replace by another with higher capacity, but every increase capacity on about 20 Ah presents 5 kg increase in weight of the accumulator.

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

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 the performance requirements of a wheelchair. The calculation of all parameters, coefficients, and dimensions was done by using a debugged m-file in MATLAB 2013a. This m-file contains all initial performance requirements of the wheelchair and all equations necessary to calculate the final dimensions and characteristics of the disc BLDC motor with dual external rotor (with permanent magnets) and central grooved stator. To calculate the required parameters in terms of power and torque of the two disc BLDC motors with axial flux, which are located in 24" wheels, a simplified model of dynamics of a wheelchair was used.

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) [14]. Calculation of the thickness of permanent magnets depends on their surface and the volume of permanent magnets needed for stated power of the BLDC motor. Individual calculations of dimensions and parameters of the BLDC motor were realized by using of m-file in MATLAB 2013a. This m-file can be used in the next design by simply changing the desired properties and parameters. 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 [15 - 20]. The main resulting design parameters of BLDC motor are shown in Table 3.

Fig. 7 presents the 3D-model of disc BLDC motor with dual external rotor (with permanent magnets) and central grooved stator in exploded view.

Fig. 8 presents the 3D-model of disc BLDC motor and wheel in exploded view.

Table 3. 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
Permanent magnet material	NdFeB (N38)
Height permanent magnets	47.0 mm
Angle of the permanent magnets	7.5 °
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

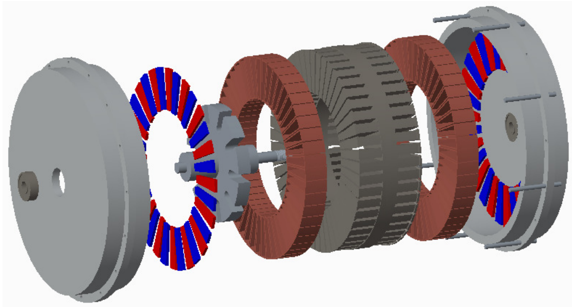

Fig. 7. Model of disc BLDC motor with dual external rotor and central grooved stator

The motor has three-phase 32-pole two-layer winding placed in the stator, which is grooved on both sides. The final positioning of coils stator in the slots is shown schematically in Fig. 9.

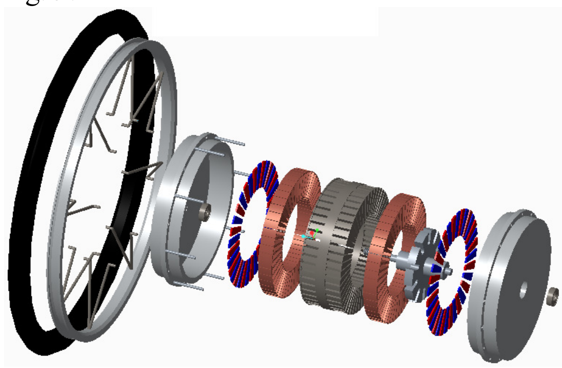

Fig. 8. Model of disc BLDC motor and wheel

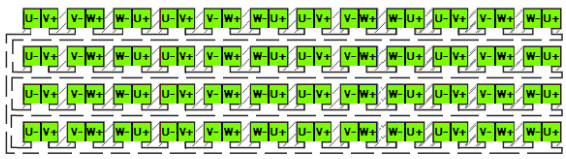

Fig. 9. Final placement of two-layer winding in stator slots

3.4. The final design of realized drive for the electrical wheelchair

The motor prototype, the subject of this paper, has been designed (chapt. 3.3). The motor is of a disc type permanent magnet brushless DC motor. The stator of motor is placed between the two rotor discs. The motor will be manufactured with the purpose to drive a wheelchair. Fig. 10 shows a 3D-model of the wheel of a wheelchair with three-phase BLDC motor and double external disc rotor with permanent magnets.

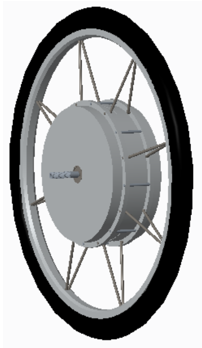

Fig. 10. The wheel with three-phase BLDC motor

The selection of battery pack as the above mentioned is in chapt. 3.2 and the selection of control module and converter is mentioned in chapt. 3.1. Resulting structure of concept electric drive for wheelchair, which consists of two disc BLDC motors in the rear-wheels of a wheelchair, the control module and converter for both BLDC motors and battery, is shown in Fig. 11.

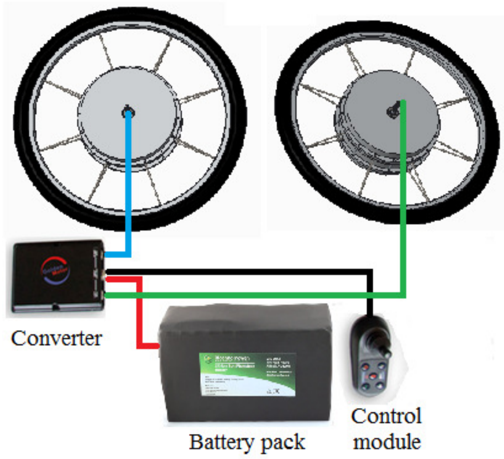

Fig. 11. Concept of electric drive for wheelchair

4. Conclusions

A double-disc BLDC motor that is applied as a gearless wheelchair drive has been designed.

The main contribution of the research consists 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 2013a. This m-file can be used at the next design of electric drive for a wheelchair and for other small vehicles by simply changing the desired properties and parameters. In the future, use of MATLAB programme 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. The 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 3.0 M060 was used. Based on electro-magnetic and construction design prototype of disc three-phase BLDC motor can be manufactured. Afterwards of manufacturing of the motor prototype the final parameters are verified by measurements.

In general, the brushless DC motor studied in this paper satisfies the requirements put on the electric wheelchair. The speed and torque of the wheelchair drive can be controlled easily by varying the input current.

5. Acknowledgment

This work was supported of the Slovak Scientific Agency under the contract No: VEGA 1/0121/15.

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]. MDA Quest Magazine: Front, Middle or Rear? [Online], [cit. 2016-03-11], 2016, Available from: http://quest.mda.org/article/front-middle-or-rear-finding-power-chair-drive-system-thats-right-you

[4]. Power4: P4 Country, [Online, cit. 2016-03-12], 2016, Available from: http://www.four powerfour.com/presentation-4x4-electric-wheel chair.asp

[5]. DEKA Research and Development: Technologies and Applications – iBOT, [Online]. [cit. 2016-03-12], 2016, Available from: http://www.dekaresearch. com/ibot.shtml

[6]. The Stakeholders Forum: Wheeled Mobility, May 26-27, in Pittsburgh PA, Available from: http://www.wheelchairnet.org/WCN/WCN_WCU/Research/WCN_stakehold.html

[7]. Medium-wheel drive [Online, cit. 2016-03-12], 2016, Available from: http://quest.mda.org/files/ images/Quest2/ 18.4/permobil_m300.jpg

[8]. Front-wheel drive [Online], [cit. 2016-03-12], 2016, Available from: http://www.caring-for-aging-parents.com/images/ motorized-wheelchair9.jpg

[9]. IBOT [Online], [cit. 2016-03-12], 2014, Available from: http://www.aidn.com/wp-content/ uploads/2014 /02/ibot.jpg
[10]. Stakeholder Forum on Wheeled Mobility [Online], [cit. 2016-03-13]. http://t2rerc.buffalo. edu/pubs/ forums/mobility/mobility.pdf
[11]. Golden Motor Technology Co Ltd.: Technology sheet, 2016, Available from:
[12]. Straka, M.: „Využití fotovoltaických systému v off-grid aplikacích", *Master's thesis,* Brno, University of Technology, 2012
[13]. Bioenno Power BLF-2420W [Online]. [cit. 2016-04-18], 2016, Available from: https://www. bioennopower.com/pages/ 24v-20ah-lifepo4-battery
[14]. Grades of Neodymium [Online], 2016, Available from:
http://www.ndfebinfo.com/neodymium_grades.aspx
[15]. Glinka T.: *„Maszyny elektryczne wzbudzane magnesami trwałymi.",* Wydawnictwo Politechniki Śląskiej, Gliwice 2002.
[16] Król E, Rossa R: „Silniki z magnesami trwałymi o dużej przeciążalności momentem". *Maszyny Elektryczne - Zeszyty Problemowe*, nr 81, pp 27-31, 2009.
[17]. 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.
[18]. Bernatt J.: *„Obwody elektryczne i magnetyczne maszyn elektrycznych wzbudzanych magnesami trwałymi.",* Wydawnictwo Komel, Katowice, 2011.
[19]. Król E.: „Silniki synchroniczne w napędach pojazdów sportowo-rekreacyjnych", *Maszyny Elektryczne-Zeszyty Problemowe* nr 2, pp 23-27, 2014.
[20]. 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.

Author

Ing. Ján Kaňuch, PhD. - he graduated with distinction at the department of Electrical Drives of the Faculty of Electrical Engineering at VŠT (now Technical University) in Košice in 1986. Since then, he has been working in this department (now Department of Electrical Engineering and Mechatronics) at the Faculty of Electrical Engineering and Informatics. He defended his PhD in 2006. His research interests include Electrical machines and apparatuses, Automotive electrical equipment and mechatronics, EMC and Industrial electronics.

Address: Department of Electrical Engineering and Mechatronic, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia.
Email: jan.kanuch@tuke.sk, tel.:+421 55 602 2275.