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ELEKTROS INŽINERIJA

Design of a Direct Sliding Gearless Electrical Motor for an Ergonomic Electrical Wheelchair

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Introduction

It is important to consider the needs of the user in the design and production of the wheelchair, to use quality materials, and to pay great attention to ergonomic criteria both in the design and production processes for the easy use of the electrical wheelchair. The purpose of this study is to develop a design appropriate for electrical motors driving electrical wheelchairs and adapt it in such a way as to obtain ergonomics in electrical wheelchairs. For this purpose, a gearless motor design with a permanent magnet that can be used in electrical wheelchairs was developed here. Traditionally, a DC motor with gears is used in an electrical wheelchair. These motors are installed on the spindle of the wheel with a gear box having 1/5, 1/10, 1/15 conversion rates. Thus, while the speed of the motor decreases 5, 10, 15 times, its torque increases at the same rates. The motor used in a combination of manual electrical wheelchair and electrical wheelchair is fixed on each hub of the rear wheels with 27:1 gear system [8]. Frequent break downs seen in the gear system are a big problem for the disabled user. Moreover, while geared DC motor works with 70% efficiency when unloaded, this percentage falls down to 45% when working loaded [1].

Gears are liable to erode and break and their repair is expensive. While operating, gears lose mechanical power and they make noise. Furthermore, brushes are eroded during the commutation of the brushed DC motor and they need maintenance. In order to get rid of these two problems mentioned, with the help of the advancements achieved in the field of magnet production and fast progress seen in the field of electronic control technology brushless DC motors with a permanent magnet can be used in electrical wheelchairs. In a study conducted for this purpose, it is suggested to use brushless and rare earth magnets in direct sliding motors without gears [2].

In the present study, the computer-assisted design of the motor located inside the wheel with low-speed and high-torque and not having any device for mechanical power transmission was and its performance analyses were conducted. Here, what is aimed is to develop a motor located inside the hub of a wheel of an electrical wheelchair, shaped with rare-earth magnet with external rotor and having phase flux in the form of square wave.

Motor Geometry and its Properties

The motor to be designed will be used for electrical wheelchair. The type of motor selected is brushless DC motor with a permanent magnet. As known, disc type brushless DC motors with a permanent magnet are the most suitable ones for gearless sliding. Among the disc type brushless DC motors with a permanent magnet, the commonly used one is torus type motor with a stator of axial flux [3, 4]. In a design the most fundamental elements are the selection of rotor type, determination of coil type, sticking magnets, and packaging of driving electronic card [5].

In this study, as low speed and high torque are desired, axial type of motor was selected. And as it is cheap and with high energy density and moreover as its volume is small and it has a low weight, NdFeB permanent magnet was selected.

The number of the phases in the motor designed in this study is three. If there were more than three phases, it would increase the number of the power switches and accordingly the cost. If the number of the phases were less than three, it would cause friction in the motor. This motor was designed as three-phased. The number of the poles in the design is 12, and the number of the slots was determined to be 36. The coils are in the form of two-storey (tow bobbin edges per slot) and mounting coil or one storey, yet they are in the form of concentric coil [6].

In Fig. 1, shape of stator coil of brushless permanent magnet DC motor designed is seen. In figure 1, stator coil, the number of stator slots, and the structure of layered mounting coil can be seen as well.

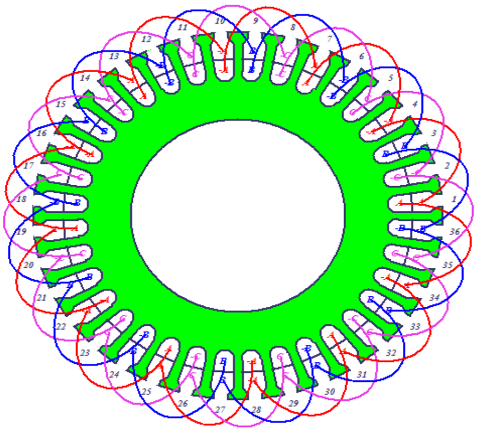


Fig. 1. Stator and coil structure of the designed motor

From the ratio of coil number of the designed motor to the number of the poles, the bobbin step is obtained to be 3. Phase coil enters through first slot and exits through the fourth slot. In table 1, torque waviness value of the motor, and its weight and volume are presented. The proportion of copper weight to copper losses, torque waviness, total weight and cogging torque values are also presented.

Table 1. Torque waviness value of the motor, its weight and volume

Properties of three-phased brushless DC motor	
Copper weight / Copper losses in rated power	1,35705kg/15,5068 *W*
Torque waviness	15 %
Total weight	11,9719 *kg*
Cogging torque value	$1{,}15349.10^{-11}$*Nm*

In Fig. 2, wave structures of three-phased square wave current showing the positions of transistor keys.

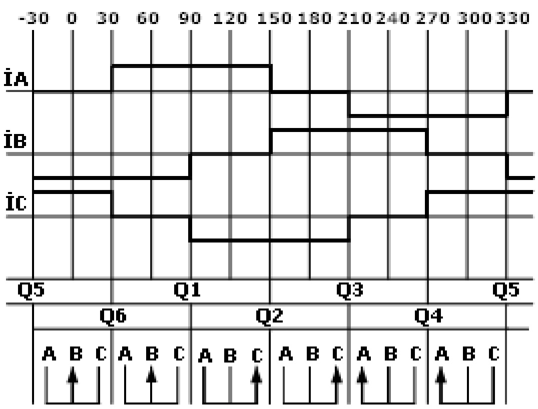


Fig. 2. Current wave forms versus switching angles of the transistors

This motor is driven by a circuit consisting of 6 transistors. The acquired square wave shapes can feed the stator without causing any breakdown. For the brushless permanent magnet DC motor to operate, it is necessary to have information about field-effective sensor giving the angular position of the rotor. Even when two of the three-phased currents pass, this is sufficient for sensors to obtain information related to location. Rotor position determines which phase is active. During each commutation, first coil is energized with positive power (current enters the coil), second coil is negative and the third coil is in the state of not energized. Torque is produced as a result of the interaction taking place in the area between the magnetic fields generated by magnets and stator bobbins. Ideally, when the phase angle between these two fields is 90^0, peak torque is produced [7].

As can be seen in the graphic given in figure 2, acquired DC energy feeds two motor coils at 60^0 periods. During that time, the third coil does not carry current and it is in the position without energy. At the end of each 60^0 period, the current changes its direction from one of the conducting lines towards unloaded line. While developing the design of the motor and performing its optimization, the steps followed are as follows: In the first step, the design of motor configuration and its geometry were found depending on required output power, speed, and sizes of the wheel. In the second step, motor parameters were calculated and obtained through finite element analyses. In the last step, the designs were redeveloped by changing the design geometry until a proper design was obtained. The design values of the motor after these steps were realized are given in Table 2. In Fig. 3, stator slot shape of the designed motor is presented and its measures are given.

Table 2. The design values of the motor

Electrical Features	
Rated current: 8,08 *A*	Rated speed:160 *rpm*
Rated output power: 160 *W*	Maximum speed: 170 *rpm*
Maximum torque: 120 *Nm*	Maximum output power : 484*W*
Stator Internal Features	
Rated voltages: 24V	Maximum current: 90 *A*
Internal diameter: 110 *mm*	Thickness: 0.2 *mm*
Conductive medium: Copper	Outer diameter: 178 *mm*
The length of air gap : 0.8 *mm*	Number of laps per bobbin: 32
The length of nub: 66 *mm*	Coil type: Double layered block coil
Wire diameter: 1.15*mm*	Resistance per phase: 0.13 ohm
Measures and properties of permanent magnet	
Magnet: NdFeB	Remanence (Bc): 1,23
Coercivity (Hc): 890000	Maximum energy production $(BH)_{max:}$ 273.675
Thickness of the magnet: 6.3 *mm*	
Outer rotor measures	
External diameter : 210 *mm*	Internal diameter: 181 *mm*
Pole number : 12	The length of nub: 66 *mm*

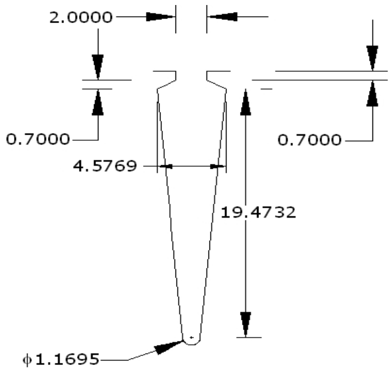


Fig. 3. Physical shape and measures of a slot (*mm*)

In Fig. 4, 2-dimensional iron sheet package view and measures (*mm*) of the designed brushless permanent magnet DC motor.

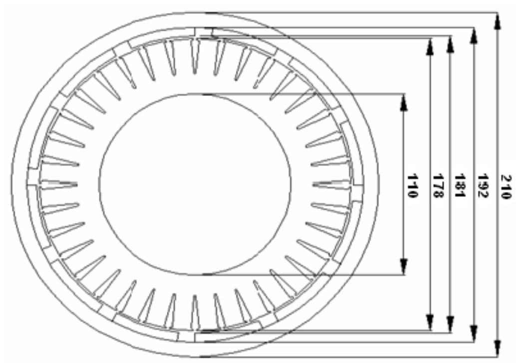


Fig. 4. 2–dimensional iron sheet package view of the designed motor.

Magnetic Examination Of The Motor Through Finite Element Analysis

In order to perform the electro magnetic analysis of the designed motor, Maxwell 2D field simulator was used. The simulation was completed in five steps.

i. *Determining the model of the motor:*

First, according to front design configuration of the designed motor, the model shown in figure 4 is formed. In this model, there is 12–poled rotor nub made up by NdFeB magnet material, air gap, stator nub with 36 slots coiled on copper conductor and spindle.

ii. *Selection of the material:*

For different parts of the motor, different magnetic materials were selected. It is presented in table 3.

Table 3.

Stator (Lamination)	Steel_1008B-H curve
Rotor (Lamination)	Steel_1008 B-H curve
Stator conductor type	Copper
Permanent magnet	NdFeB35 B-H curve
Air gap	Air (0.8 *mm*)
Spindle	Stainless steel

iii. *Determination of the border conditions:*

For this, currents passing through phase coils and other values according to the direction of the current.

iv. *Obtaining Performance Curves*

The results of the simulations were analyzed through curves and graphics. These curves are presented in figure 10-14. They showed that the rated working borders are within the acceptable levels.

v. *Solution Finding:*

After undergoing the first three steps, finite element mesh of the determined model is automatically obtained from Maxwell 2D. In Fig. 5, finite element mesh to be used in the calculation of coil energy is shown.

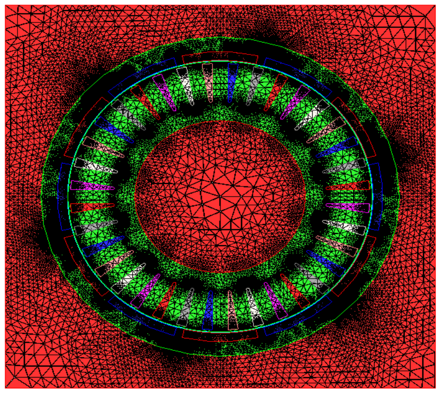


Fig. 5. Mesh production

Simulation Results and Performance Curves

Magnetic examination of the designed brushless permanent magnet DC motor according to iron sheet package structure was performed with Maxwell 2D program. From this electromagnetic analysis, actual potential magnetic flux intensity of the motor was obtained. The results of the magnetic analysis are presented in Fig. 6.

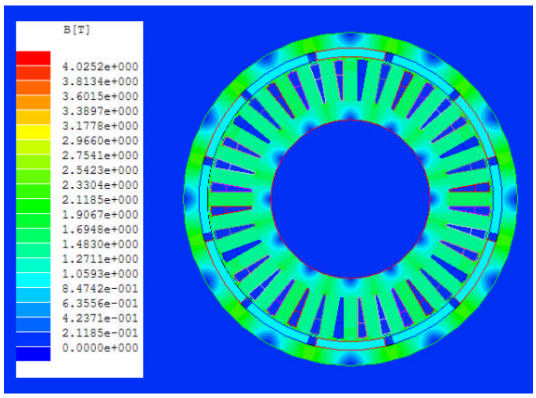


Fig. 6. The magnetic flux intensity view of the designed motor.

In Fig. 6, magnetic flux intensity distribution of the designed brushless fixed magnet DC motor. In figure 7, B/H characteristic curves of the 1008 steel material used for rotor and stator nubs, and in figure 8, the B/H characteristic curves of NdFeB magnet used are shown. It is seen in Fig. 7 that the steel_1008 material has a saturation point at 2–2.30. In the magnetic analysis conducted with Maxwell 2D, it was found that the magnetic flux intensity of rotor and stator is about 1.6–2.30

T. It can be seen from Fig. 8 that the saturation point of NdFeB magnet is 1.23 *T*. In Maxwell 2D analysis, the magnets functions between 1.05 and 1.27 *T*. This means that the motor is working at saturation point. At motor's 1000 *A* lap terminal current value, the torque value obtained with Maxwell 2D is 17.5215 *Nm*. When the motor works at saturation point, it produces high torque.

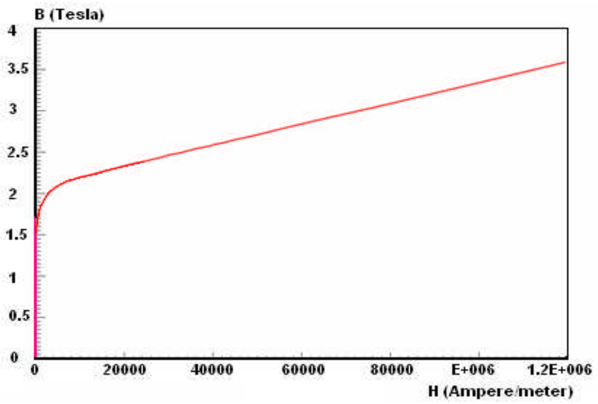


Fig. 7. B/H curve of the steel_1008 material used for rotor and stator nubs.

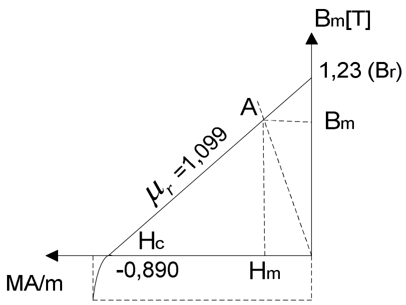


Fig. 8. B/H characteristic of NdFeB magnet used in the design

In Fig. 9, magnetic flux distribution of the designed brushless permanent magnet DC motor performed in Maxwell 2D is shown. From this, it is possible to see flux line distributions when two phases of the motor are energized and the third one is with zero value.

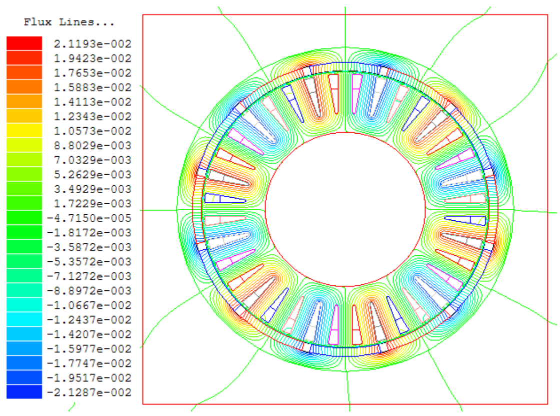


Fig. 9. Magnetic flux line distribution of the designed motor

Flux line distributions pass over stator and rotor and through the air gap. This shows that the designed motor works at appropriate air gap. The performance curves of the designed motor show that rated working gaps are at the acceptable levels.

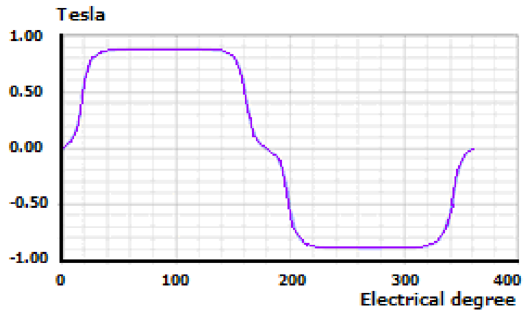


Fig. 10. Air gap flux intensity curve of the designed motor

In Fig. 10, air gap flux intensity of the designed motor is shown. Air gap flux intensity of the brushless DC motor is in the form of isosceles trapezoid.

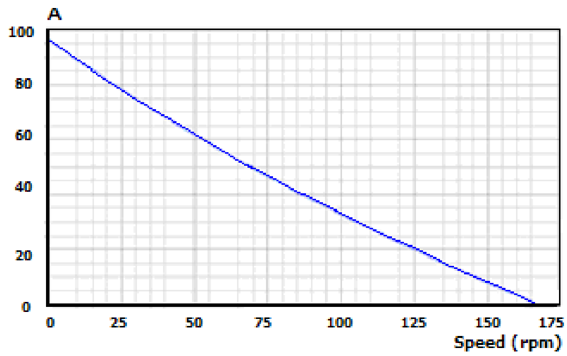


Fig. 11. Input current-speed graph of the designed motor

In Fig. 11, input current-speed graph of the designed brushless permanent magnet DC motor is seen. At the start, the motor draws 90 *A* current. When it reaches 153 *rpm* nominal speed, the current value is about 8.08 *A* on average.

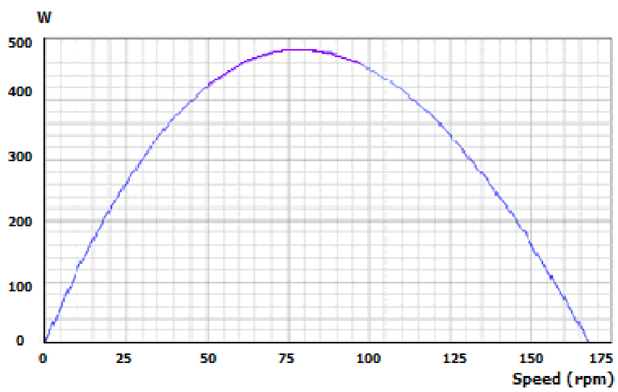


Fig. 12. Output power-speed graph of the designed motor

In Fig. 12, output power-speed graph of the designed motor is seen. In Fig. 13, it is seen that motor nearly draws 484 W maximum power at 75-80 rpm speed. At 153 *rpm* rated speed value, it draws 160 *W* power.

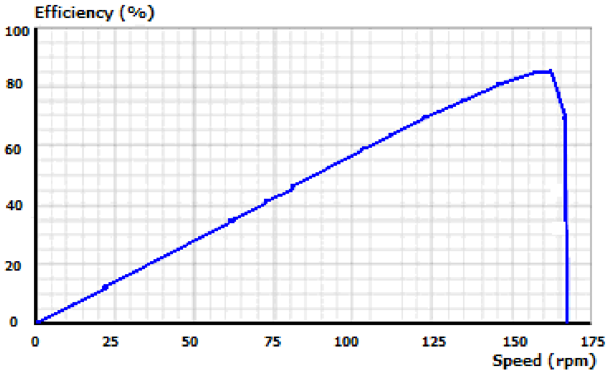


Fig. 13. Efficiency-speed graph of the designed motor

In Fig. 13, efficiency-speed graph of the designed motor is shown. In this graph, the efficiency of the motor at 150-160 *rpm* rated value is 82.54 %.

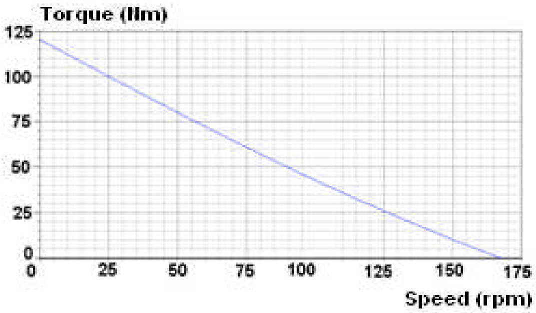
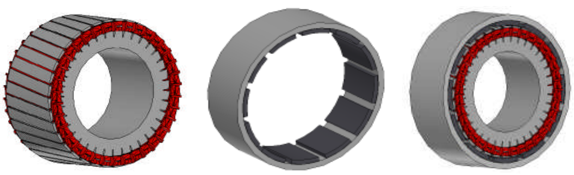


Fig. 14. Torque-speed graph of the designed motor

In Fig. 14, the torque-speed graph of the designed motor is shown. It is seen that the torque-speed graph of the motor is linear. At the start, the maximum torque of the motor is 120 *Nm*. At 153 *rpm* rated speed, the motor produces 10 *Nm.*

Placement of the Designed Motor in the Wheel

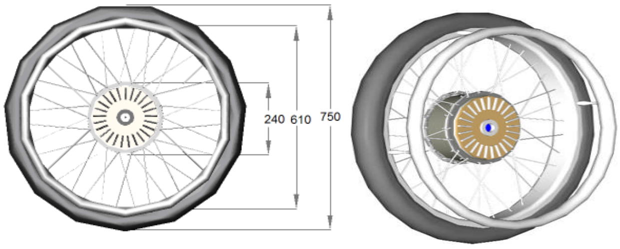
In line with the results obtained from the magnetic analyses, performance curves, geometric form of the motor was drawn. In Fig. 15, design model views of the motor are given.



(a) (b) (c)

Fig. 15. Modeled views of the designed motor. (a – b – c): Stator & rotor coils, stator & rotor poles and 3 – D model views of the motor

In Fig. 15, modeled views of the designed motor; (a) stator and coils on it, (b) rotor and poles mounted on it, (c) 3 D model view of the motor are seen. In Fig. 16, the motor designed in (a) and (b) and mounted in the hub of standard 24 *inch* (610 *mm*) wheel rim and its sizes are shown.



(a) (b)

Fig. 16. Location of the designed motor in the hub (a–b): Front views with measurements and 3 D view of the wheel

In figure 16, location of the designed motor in the hub of the wheel of the wheelchair, (a) front views of the wheel and motor and their sizes, (b) 3 D view of the wheel are seen. This motor has the sizes appropriate to be used in wheels of the wheel chairs with 510, 560 and 610 *mm* diameters. In this study, the motor is fixed on the steel bars of the wheel and the aluminum rims are covered with inflated wheels. The designed power assisted electrical wheelchair is a hybrid system which is a combination of human and electric power. In figure 17, placement of hub wheel into electrical wheelchair and a perspective view belonging to the designed model. In figure 18, rear view of the electrical wheel chair is seen with the measures in millimeters.

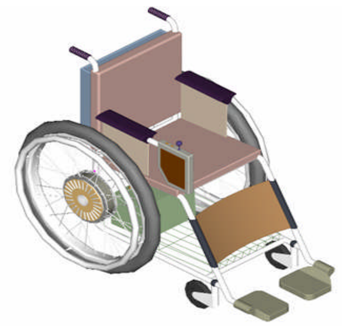


Fig. 17. Perspective views of the integrated design

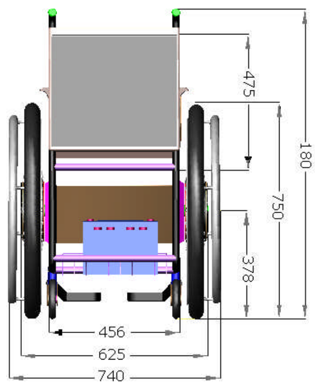


Fig. 18. Rear view of the electrical wheelchair

There are two wheels in the chair where the motor which is designed as hub motor is located. This power assisted electrical wheelchair can be used by the user with the support of hands and arms. By putting the motor out of operation, without using any electrical devices, the chair can be pushed only with arms. When it’s desired to be used with electricity the motors are started with the power key.

Results

In this study, a brushless permanent magnet DC motor that produces high efficiency and high torque at low speed was designed to be used in power assisted electrical wheelchair. It is aimed to directly place this designed motor into the hub of the power-assisted wheelchair without using geared system. The design was developed by using Maxwell 2D magnetic field simulator. In the design, magnetic flux intensity and flux distributions were obtained by using finite element analysis. It was proved that when appropriate rotor magnets, stator slots and stator coils are used in the motor, high power, power intensity and high efficiency are obtained. Moreover, by decreasing the torque, the friction can be reduced to a level negligible. Consequently, the designed brushless DC motor can have higher power intensity and yield efficiency more than traditionally used motors. With the elimination of the geared system, many mechanical problems are avoided.

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The use of the electrical wheelchairs designed for the disabled people should be easy and flexible. A brushless DC motor with a permanent magnet that can operate without gears was designed to be used in an ergonomic electrical power supported wheelchair. This motor will be placed within the hub of rear wheel with standard diameter of the wheelchair and it will have the capacity of producing high torque at low speed. The stator structure of the designed motor, its physical measurements and features, appearance of its iron sheet package, its mesh production, magnetic flux intensity, and flux lines and performance characteristic values were obtained. The results obtained showed that this new design with low speed and high torque can be an alternative in electrically driven devices and systems. Ill.18, bibl. 8 (in English; summaries in English, Russian and Lithuanian).

И. Таример, А. Акпунар, Р. Гурбуз. Проектирование двигателя постоянного тока для эргономических электрических инвалидных кресел // Электроника и электротехника. – Каунас: Технология, 2008. – № 3(83). – С. 75–80.

Использование электрических инвалидных кресел, разработанных для больных людей, должно быть легким и гибким. Был разработан двигатель постоянного тока с постоянным магнитом, который может работать без трансмиссии. Он будет использоватся в эргономическом электрическом инвалидном кресле. Этот двигатель будет помещен между задними колесами стандартного диаметра. Он способен создать высокий вращающий момент в низкой скорости. Предложена новая структура статора разработанного двигателя, расчитаны его физические размеры и форма компонентов, интенсивность магнитного потока и показатели эффективности. Полученные результаты показали, что новый двигатель может быть альтернативой в электрически питаемых устройствах и системах транспорта для больных людей. Ил. 18, библ. 8 (на английском языке; рефераты на английском, русском и литовском яз.).

İ. Tarımer, A. Akpunar, R. Gürbüz. Bepavarinio nuolatinės srovės variklio, skirto elektriniam vežimėliui žmonėms su negalia, projektavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – No. 3(83). – P. 75–80.

Naudotis elektriniais vežimėliais žmonėms su negalia turėtų būti paprasta. Suprojektuotas nuolatinės srovės bepavaris variklis su nuolatiniu magnetu. Jį galima naudoti ergonomiškame elektriniame vežimėlyje. Variklis bus įtaisytas tarp galinių standartinio skersmens ratų. Jis galės sukurti didelį sukimo momentą esant nedideliam greičiui. Aprašyta suprojektuoto variklio statoriaus struktūra, jo matmenys ir savybės, sudarytas konstrukcijos modelis ir baigtinių elementų tinklelis. Apskaičiuotas magnetinio srauto tankis, lauko linijų pasiskirstymas bei darbiniai parametrai. Gauti rezultatai rodo, jog naujasis produktas yra gera alternatyva. Il. 18, bibl. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).