Chapter 18
PMBLDC Motor Design and Analysis for Automotive Applications

R. Ruthra Prakashini, Aneesh Jategaonkar, Kareti Aasritha, and N. C. Lenin

Abstract Modeling of brushless direct current (BLDC) motor for the application of lumbar support, headrest and lift gate is carried out in this paper. Two separate models have been simulated using finite element software packages for the applications. One of the models is based on surface-mounted configuration of the BLDC motor, while the other is based on spoke-type configuration. The surface-type and spoke-type models procure their names based on the mounting of permanent magnets, which are an integral component of any BLDC machine. Extensive comparison has been carried out between the designed models. Critical parameters such as constituent weights, efficiency, output power, torque, speed, etc. are compared. Performances of the designed machines are depicted using graphical portrayal. Parameters such as locked rotor torque, no load speed, maximum efficiency, maximum output power, etc. are also compared.

Keywords Brushless direct current (BLDC) motor · Finite element analysis · Spoke type BLDC motor · Surface mounted BLDC motor

18.1 Introduction

BLDC motor is most preferred as it has the capability to provide large volume of torque for wide range of speeds and compact in size. So, it is most preferred machine for automotive application and has gained more popularity over few decades. Permanent magnet BLDC motors are being extensively used in automotives because of higher efficiency and operation flexible [1]. As the name implies, BLDC motors are electronically commutated and they do not use brushes for commutation. Compared to induction motors and brushed DC motors BLDC motors have many advantages over them. A few advantages of BLDC motors are: high-speed range, noiseless functioning, better speed versus torque characteristics, high efficiency, long running life [2–4]. Furthermore, making it productive the ratio of torque delivered to the size

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V. Kamaraj et al. (eds.), *Emerging Solutions for e-Mobility and Smart Grids*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-981-16-0719-6_18

Fig. 18.1 Lumbar support fixed in back seat [9]

of motor is higher, which helps to reduce the space and weight constraints of the motor.

18.1.1 Lumbar Support Motor

With the increase in number of driver on road comes in the increase complaints about lower back pain problems. As the time spent while driving has been increased, improper posture will cause discomfort to the driver and also increases the lower back pain. Lumbar support helps to sit up straight rather than a slumped position which benefits for proper posture [5]. It has become one of the criteria buyers look up on. BLDC motors are an appealing prospect for lumbar support for its low audible voice and overload protection. Figures 18.1 and 18.2 show the lumbar motor which is used in automobile.

18.1.2 Headrest Adjuster Motor

It is a control system method to adjust the position of headrest of a seat. A headrest has become attached to support rods. The support rods are inserted in the backrest pushed and arranged longitudinally to the backrest. In the seat notice that the height the headrest is not properly adjusted for individual needs, it is difficult to move the headrest from sitting to a new adjust. So, in some countries beginning in the late 1960s, head restraints have prevented or mitigated thousands of serious injuries

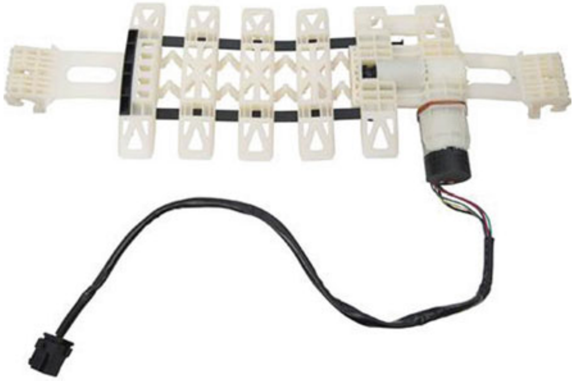


Fig. 18.2 Lumbar support motor [10]

Fig. 18.3 Headrest adjuster [11]

to prevent or mitigate whiplash or injury to the cervical vertebrae [6]. The desired characteristics for BLDC motor for application in headrest are due to its high power and low noise. Figure 18.3 shows the headrest motor system used in application.

18.1.3 Power Lift Gate Motor

Power lift gate is a back-door system. The system is depicted in Fig. 18.4. The user of the vehicle controls the lift gate opening and closing by pressing a key. The keys are located either on the dashboard or handheld remote. Many power lift gate systems require the touch of a button to work, although hands-free options are becoming more available on a range of vehicles [7]. The hands-free power lift gate also offers intelligent anti-trap, height memory function and other functions.

Fig. 18.4 Power lift gate motor [12]

Table 18.1 Specifications of lumbar support motor

Quality	Values
Output power	13.64 W
Voltage	12 V
Speed	4700 rpm
Torque	0.027 N m
Stack length	35.8 mm
Stator outer diameter	65 mm
Stator slot fill factor	45%
Shaft diameter	3.175 mm
Operating Temperature	−40 to 85 °C

18.2 Specification

The motors for the specific applications have been designed for both spoke-type and surface-mounted lumbar support motor with same specifications. Table 18.1 depicts the specifications for lumbar motor which satisfies the constraints of low audible voice and overload protection. BLDC motor is designed with the property of low noise and high powers for headrest adjustment, and its specifications are shown in Table 18.2. Power lift gate specifications are depicted in Table 18.3.

18.3 Design Approach

The BLDC motor for spoke type and surface mounted for the applications lumbar support, headrest adjuster and power lift gate has been designed with steel type of stator and rotor core as M36_29G. Ceramic8D is used as its permanent magnet, and for winding, copper is being used as its material.

Table 18.2 Specifications of headrest adjustment motor

Quality	Values
Output power	5.57 W
Voltage	12 V
Speed	3208 rpm
Torque	0.01669 N m
Stack length	35.8 mm
Stator outer diameter	50 mm
Stator slot fill factor	45%
Shaft diameter	3.175 mm
Operating temperature	−40 to 85 °C

Table 18.3 Specifications of power lift gate motor

Quality	Values
Output Power	46.80 W
Voltage	12 V
Speed	8147 rpm
Torque	54.86 N m
Stack Length	87.3 mm
Stator outer diameter	35.9 mm
Stator slot fill factor	45%
Shaft diameter	3.175 mm
Operating temperature	−40 to 85 °C

18.3.1 Stator Design

The number of slots used for both spoke type and surface mounted varies accordingly to the number of poles in order to achieve the design specification. The slot types used for all the models are same, and it is depicted in Fig. 18.5. "Bs0" is kept twice the diameter of the wire as it would be easier for winding. "Bs1 and "Bs2" help to adjust the width of the slots to make slots the adjacent slot to approximately parallel with it. "Bs0" and "Hs0" size variations play an important role in the core losses. "Hs2" varies the depth the slot. For practical convenience, the slot fill factor is to 45%. The slot configuration for the application lumbar support, headrest adjuster and power lift gate is depicted in Tables 18.4, 18.5 and 18.6, respectively.

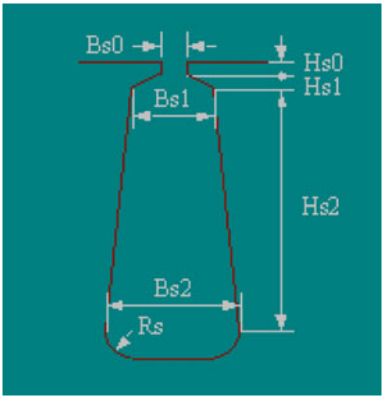


Fig. 18.5 Stator slot model

Table 18.4 Slot configuration of lumbar support motor

Parameters	Surface mounted	Spoke type
Hs0	0.2	0.6
Hs1	0.3	0.3
Hs2	3.5	4.3
Bs0	1.2	1
Bs1	3.5	3.7
Bs2	5	5.5
Rs	1	2

Table 18.5 Slot configuration of headrest adjustment motor

Parameters	Surface mounted	Spoke type
Hs0	0.2	0.3
Hs1	0.2	0.2
Hs2	4	4.9
Bs0	1	1.15
Bs1	3	4.1
Bs2	5	7
Rs	1	2.5

Table 18.6 Slot configuration of power lift gate motor

Parameters	Surface mounted	Spoke type
Hs0	0.2	0.1
Hs1	0.2	0.1
Hs2	3.5	2.5
Bs0	1.6	1.29
Bs1	3	7.8
Bs2	5	10.5
Rs	1	1.8

18.3.2 Rotor Design

Permanent magnet is mounted on the outer surface of the rotor in two arrangements. Those are surface-mounted and spoke-type model. The major weight and cost of the motor are contributed by permanent magnet. Surface-mounted and spoke-type model are depicted in Figs. 18.6 and 18.7, respectively. Material used for permanent magnet is Ceramic8D; it is insusceptible to demagnetization by outer fields. Ceramic8D is stronger and inexpensive than few natural magnets, thus reduces the overall cost of the magnet. The models are designed with minimum of 0.5 mm gap between the outer diameter of rotor and inner diameter of the stator. The magnets are inserted on the rotating shaft, which in turn maximizes the output traits of the air gap flux density

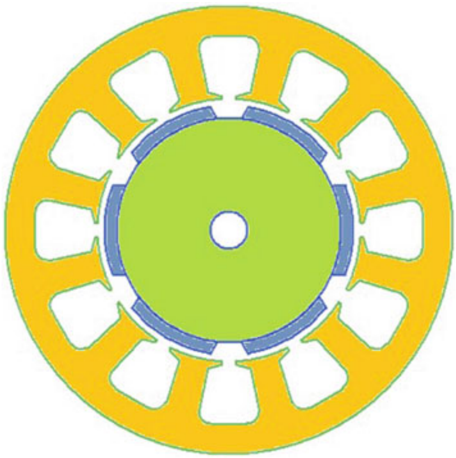


Fig. 18.6 Lumbar support surface-mounted model

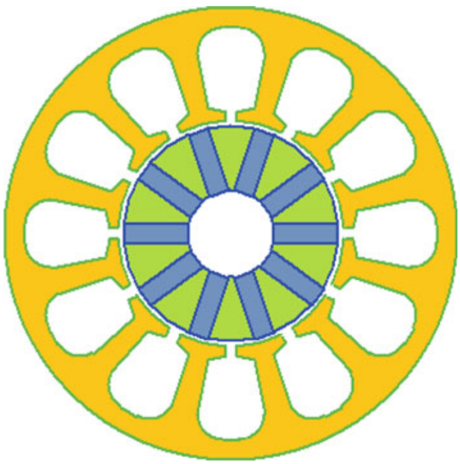


Fig. 18.7 Lumbar support spoke-type model

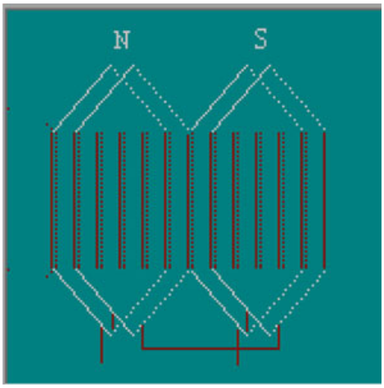


Fig. 18.8 Lap winding

[7]. The magnetic thickness and the magnetic weight have been varied to achieve the output requirements.

18.3.3 Winding Design

The efficiency of whole coiled winding is greater than half-coiled wound motors [8]. To have an efficient motor, the BLDC motors have been designed with whole coiled winding. The winding is depicted in Fig. 18.8. The motors have been designed with two winding layers for all the applications. Lap winding has been used for all the designs. Lap windings are also called as parallel winding. Lap winding has been used for low voltage and also increases the current carrying range.

18.4 Results

Parameters such as output power, input power, efficiency, locked rotor torque, no load speed, maximum efficiency, maximum output power, etc. are compared. The weights of materials used in the rotor and stator like permanent magnet weight, armature copper weight, etc. are also compared to view advantages of motor for different applications.

18.4.1 Lumbar Support

The output results of surface-mounted and spoke-type BLDC lumbar support are shown in Table 18.7; Figs. 18.9, 18.10 and 18.11. The maximum torque in spoke-type model is 0.174 N m which is relatively higher than vividly used lumbar support

Table 18.7 Performance comparison—spoke-type and surface-mounted lumbar support motor

Parameters	Surface mounted	Spoke type
Average input current (A)	1.7009	1.84995
Total loss (W)	6.64658	8.20726
Output power (W)	13.7642	13.9921
Input power (W)	20.4108	22.1994
Efficiency (%)	67.436	63.0293
Rated speed (rpm)	4700	4700
Rated torque (N m)	0.0279657	0.028429
Permanent magnet weight (gm)	12.9651	8.51032
Armature copper weight (gm)	43.5015	76.1842
Armature core steel weight (gm)	181.2	184.347
Rotor core steel weight (gm)	107.509	51.5869
Total net weight (gm)	345.175	320.628

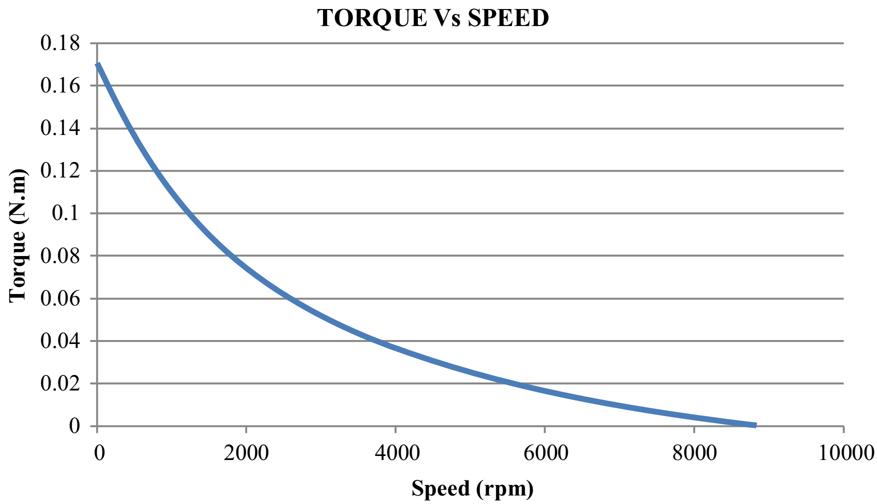


Fig. 18.9 Torque versus speed—lumbar support spoke-type model

motors. In spoke-type model, the maximum efficiency of 75% is obtained at the speed of 6800 rpm. In Figs. 18.12, 18.13 and 18.14, comparison of weight between surface-mounted and spoke-type model is depicted. The permanent magnet weight and overall weight of spoke-type model is comparatively lesser than surface-mounted model. The efficiency obtained by surface-mounted model is 7.4176% greater than spoke-type model.

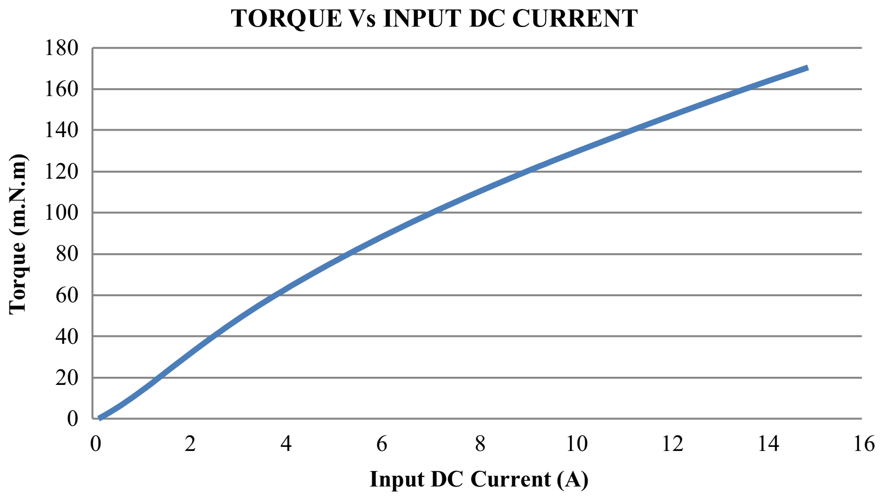


Fig. 18.10 Torque versus input DC current—lumbar support spoke-type model

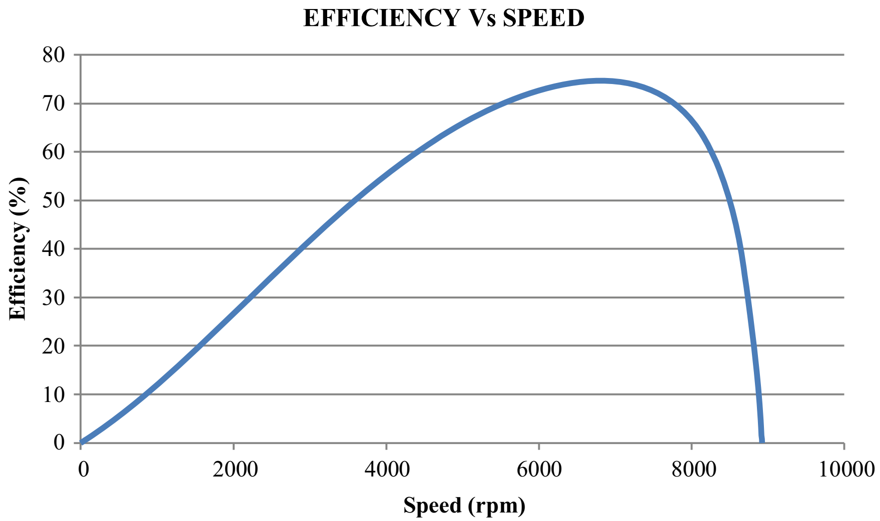


Fig. 18.11 Efficiency versus speed—lumbar support spoke-type model

18.4.2 Headrest Adjuster

The results of headrest adjuster motor are shown in Table 18.8; Figs. 18.15, 18.16, 18.17, 18.18, 18.19, 18.20 and 18.21. In Fig. 18.15, the torque takes up a parabolic gradual decline as the speed increases. The critical point, i.e., 70% efficiency, is

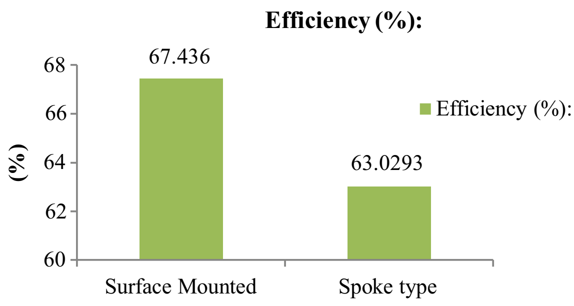


Fig. 18.12 Efficiency comparison—lumbar support spoke-type and surface-mounted model

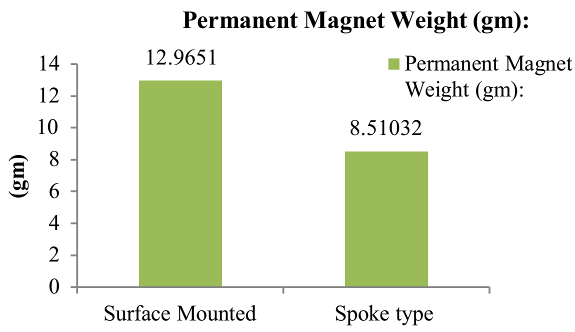


Fig. 18.13 Permanent magnet weight comparison—lumbar support spoke-type and surface-mounted model

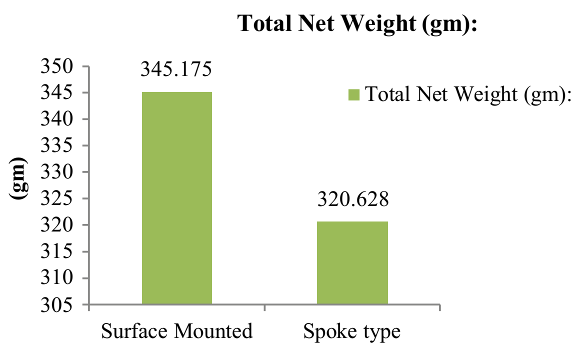


Fig. 18.14 Total net weight comparison—lumbar support spoke-type and surface-mounted model

obtained at the rpm of 4000. The spoke-type model has consumed 3.40826 g permanent magnet lesser than surface mounted, in turn spoke-type model has resulted 17.255 g lesser. The weight achieved in comparably lesser than the motors which are widely used. This helps to cut down the cost of the motor slightly. In Fig. 18.21, the flux distribution of the motor is shown.

Table 18.8 Performance comparison—spoke-type and surface-mounted headrest adjuster motor

Parameters	Surface mounted	Spoke type
Average input current (A)	0.656287	0.754401
Total loss (W)	2.20148	3.2021
Output power (W)	5.67397	5.85071
Input power (W)	7.87544	9.05281
Efficiency (%)	72.0463	64.6287
Rated speed (rpm)	3208	3208
Rated torque (N m)	0.0168898	0.0174159
Permanent magnet weight (gm)	10.2369	6.82864
Armature copper weight (gm)	37.6109	66.2452
Armature core steel weight (gm)	147.598	163.23
Rotor core steel weight (gm)	89.5907	31.4776
Total net weight (gm)	285.037	267.782

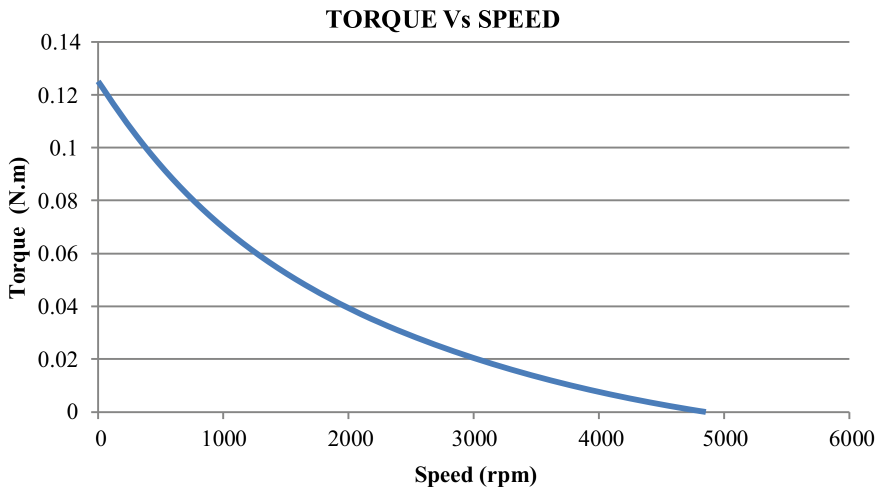


Fig. 18.15 Torque versus speed—headrest adjuster spoke-type model

18.4.3 Power Lift Gate

Table 18.9; Figs. 18.22, 18.23, 18.24, 18.25, 18.26 and 18.27 depict the output results of power lift gate design. In Fig. 18.22, there is a steep fall of torque from 0.55 to 0.1 N m, and then the torque reduces gradually. The maximum efficiency is obtained at the speed 11,260 rpm. The spoke-type model has consumed less permanent magnet

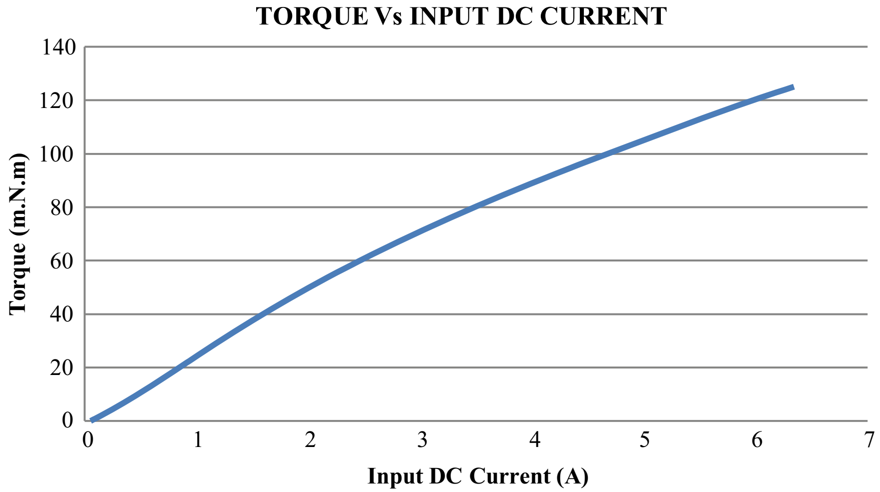


Fig. 18.16 Torque versus input DC current—headrest adjuster spoke-type model

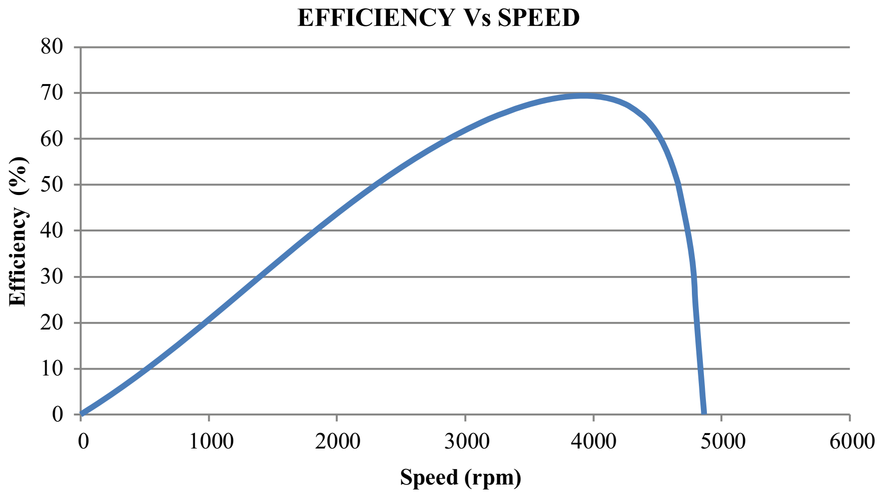


Fig. 18.17 Efficiency versus speed—headrest adjuster spoke-type model

weight with the difference of 11.7531 g, which can effectively reduce the cost of the motor. The efficiency and overall weight of surface-mounted motor are higher.

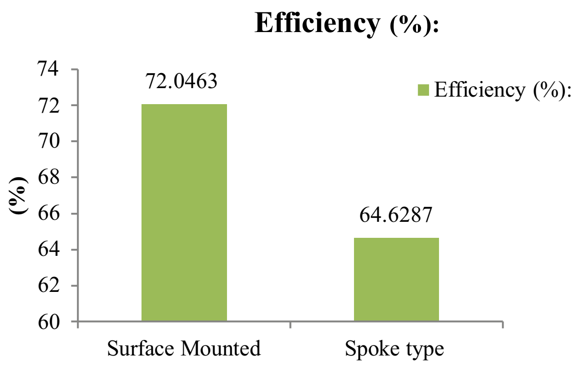


Fig. 18.18 Efficiency comparison—headrest adjuster spoke-type and surface-mounted model

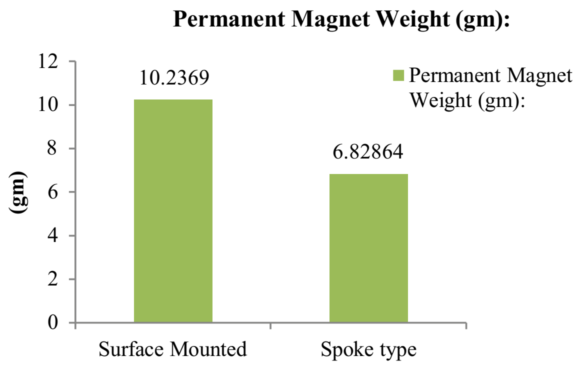


Fig. 18.19 Permanent magnet weight comparison—headrest adjuster spoke-type and surface-mounted model

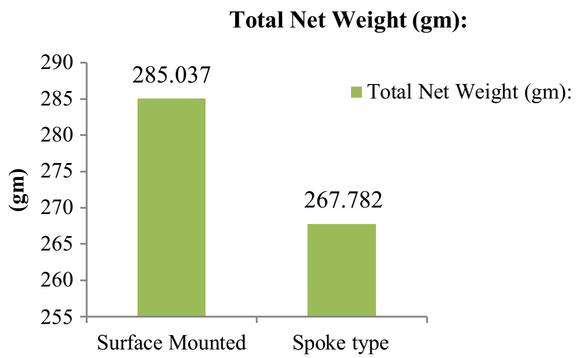


Fig. 18.20 Total net weight comparison—headrest adjuster spoke-type and surface-mounted model

18.5 Conclusion

In this paper, spoke-type and surface-mounted BLDC motor are designed for lumbar support, headrest adjuster and power lift gate application. We can conclude that the

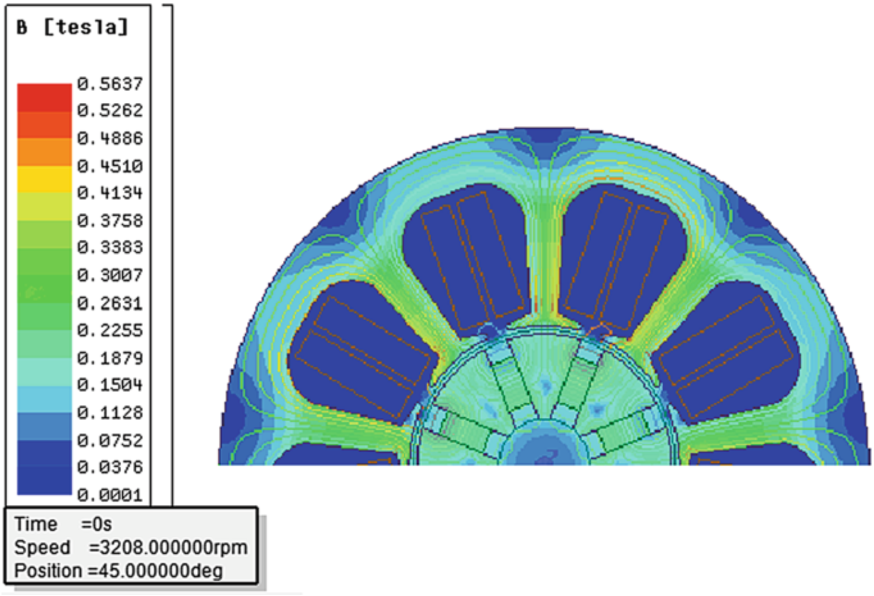


Fig. 18.21 Flux distribution of headrest adjuster spoke-type model

Table 18.9 Performance comparison—spoke-type and surface-mounted power lift gate motor

Parameters	Surface mounted	Spoke type
Average input current (A)	5.3869	6.02014
Total loss (W)	16.2106	25.9777
Output power (W)	48.4322	46.264
Input power (W)	64.6428	72.2417
Efficiency (%)	74.9228	64.0406
Rated speed (rpm)	8147	8147
Rated torque (N m)	0.05677	0.0542272
Permanent magnet weight (gm)	23.4911	11.738
Armature copper weight (gm)	40.485	67.5477
Armature core steel weight (gm)	188.322	327.834
Rotor core steel weight (gm)	69.9239	112.071
Total net weight (gm)	322.222	519.191

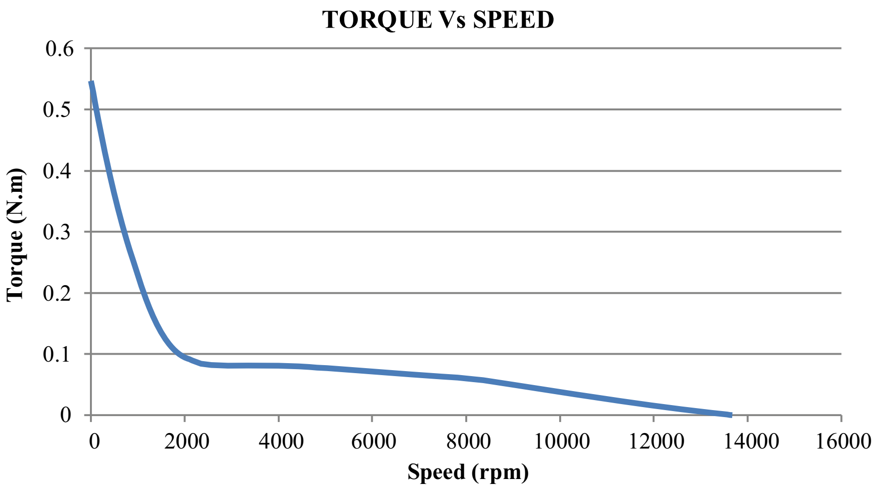


Fig. 18.22 Torque versus speed—power lift gate spoke-type model

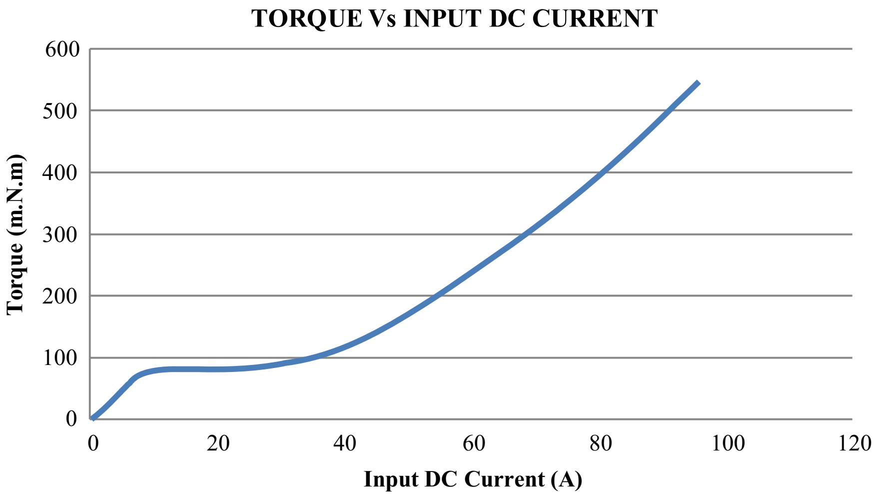


Fig. 18.23 Torque versus input DC current—power lift gate spoke-type model

overall permanent magnet weight of the spoke-type model is lesser than surface-mounted model. Ceramic 8D has been used as permanent magnet material in order to reduce the cost of permanent magnet, the major contributor of the overall cost of the motor. The average input current of spoke-type models is greater than surface-mounted model, and the efficiency of surface-mounted model is greater than spoke-type model for all the applications.

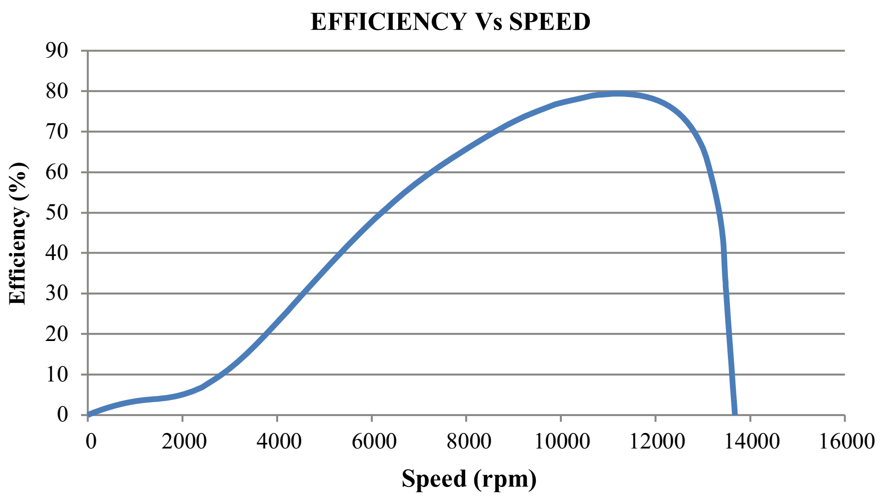


Fig. 18.24 Efficiency versus speed—power lift gate spoke-type model

Fig. 18.25 Efficiency comparison—power lift gate spoke-type and surface-mounted model

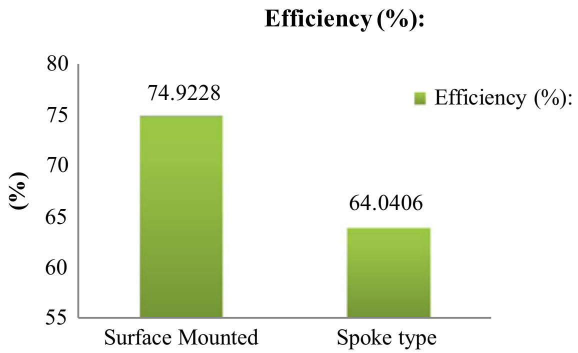
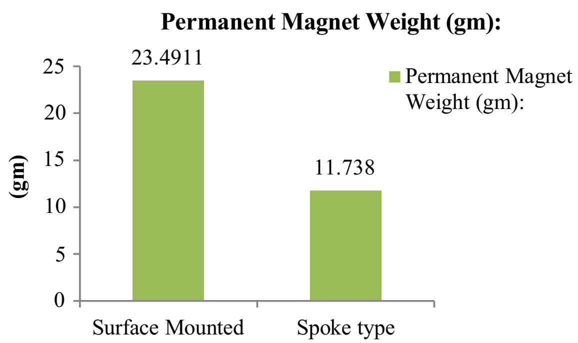


Fig. 18.26 Permanent magnet weight comparison—power lift gate spoke-type and surface-mounted model



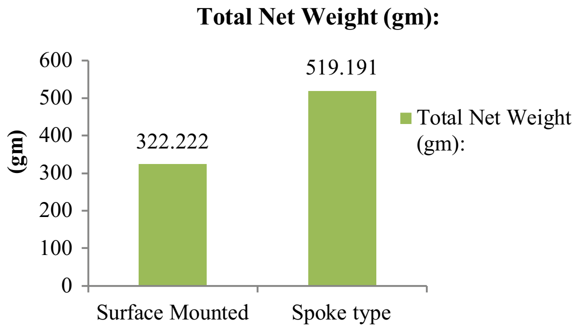


Fig. 18.27 Total net weight comparison—power lift gate spoke-type and surface-mounted model

18.6 Future Works

Future works can be carried out on designing of BLDC motor on other applications like air pump, window lift drive, anti-lock braking system (ABS), seatbelt pre-tensioner, electric parking brake, etc. The designs can be expanded by using different permanent magnet types. Future works can be done on detailed thermal characterises of motor.

References

1. D. Uygun, S. Solmaz, Design and dynamic study of a 6 kW external rotor permanent magnet brushless DC motor for electric drivetrains, in *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives* (2015)
2. L. Chang, J. Muszynski, Design of a 5-phase permanent magnet brushless DC motor for automobiles, in *2003 IEEE 58th Vehicular Technology Conference* (2003)
3. A. Jategaonkar, P. Ramesh, P. Kochgabay, N.C. Lenin, Electromagnetic and thermal analyst is of permanent magnet BLDC wiper motor, in *The Advances in Electrical Control and Signal System, AECSS* (2019)
4. P. Shetty, A.K.N. Subramonium, M.S. Kumar, Mathematical modeling of permanent magnet brushless dc motor for electric scooter, in *2015 Fifth International Conference on Communication Systems and Network Technologies*, Gwalior, pp. 1222–1226 (2015)
5. H. Hasan, H. Ismail, R. Mohamed Firhad, R. Azidin, Preventive methods of low back pain, in *2010. International Conference on Science and Social Research (CSSR 2010)*, Kuala Lumpur, Malaysia (2010), pp. 1278–1282
6. J. Murgoitio, M. Ferros, A. Goti, M. Larburu, T. Rodríguez, Robotiker-Tecnalia, Networking sensors and actuators for a new active headrest, in *Advanced Microsystems f or Automotive Applications*, ed. by J. Valldorf, W. Gessner (VDI-Buch, Springer, Berlin, 2007), pp 3–46
7. A. Müller, K.P. Jankowski, Tailored modeling of a vehicle power liftgate avoiding explicit definition of body-fixed reference frames, in *Volume 6: 11th International Conference on Multibody Systems, Nonlinear Dynamics, and Control* (2015)
8. H.-W. Kim, K.-T. Kim, Y.-S. Jo, J. Hur, Optimization methods of torque density for developing the neodymium free SPOKE-type BLDC motor. IEEE Trans. Magn. **49**(5), 2173–2176 (2013)
9. https://www.toyota-4runner.org/attachments/5th-gen-t4rs/259160d1499577377-lumbar-support-motor-fix-img_3442-jpg?s=42b7d44d8ebf119b292d35969314bca2
10. https://images11.palcdn.com/hlr-system/WebPhotos/87/873/8735/8735771.jpg

11. https://cdn11.bigcommerce.com/s-hkk7s/images/stencil/1600x1600/products/15161/162826/inv_0132343173.1523301139.jpg?c=2&imbypass=on&imbypass=on
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