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PAPERS

Optimal design of brushless DC motor for electromobility propulsion applications using Taguchi method

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This paper presents the optimal design of the permanent magnet brushless DC (BLDC) motor for electromobility propulsion applications. Two BLDC machines were analyzed: (a) – exterior rotor machine, and (b) – interior rotor machines The optimization of both motors structures was executed by the Taguchi method. The device structure was described by three design variables. The functional parameter (efficiency) and the economic parameter (total mass of the permanent magnets) were included in the objective function. The BLDC motors have been modelled using a finite element method (FEM). Finally, the functional parameters for both motor constructions were compared. The selected results of the calculations were presented and discussed.

Keywords: brushless DC motor, Taguchi method, finite element analysis, optimal design

1 Introduction

In real-time industrial application, the faults occurred in machines causes high maintenance charges and unwanted downtime. The prime target of maintenance division is to avoid any failure in the plant, thereby decreasing production loss by keeping all the equipment in well operating condition. The condition-based maintenance planning is being utilized for continuous product development in industries. Condition-based maintenance comprises continuous assessment of the state of a machine and there after effectively identifying faults and their severity before disastrous breakdown occurs. The same problem concerning good reliability and efficiency is important for machines for mass and personal transport [1, 2]. The high cost from downtime of damaged vehicles and maintenance are minimized by companies managing such types of transport devices [3].

Over a decade, the brushless machines cost fallen due to advancements in technology and capital investment in manufacturing. The application of the brushes machine for various high-speed applications such as aerospace and its suitability is given in [4]. The accuracy and smooth running of the motor required for high-performance applications like robotics and space are the ideal and perfect match for harsh kinds of environments like medical, e-vehicles, defence and veterinary devices described in [5].

The BLDC motors are categorized as interior and exterior types. In interior rotor construction, the rotor is located in the centre of the motor and the stator winding are surrounded the rotor whereas in exterior type windings surrounded by a rotor. Interior rotor pole magnets are also known as surface-mounted magnets. Coreless rotor produces high torque to inertia ratio described in [6]. The interior rotor pole types are further classified according to their rotor shape and placement. One of the rotor types called the spoke-type BLDC motor gives the high torque-to-volume ratio with concentrating structure [7]. Different types of rotor poles existing are traditional radial arc magnet, radial arc magnet with parallel sides, solid ring magnet, spoke type and buried magnet type configurations.

Designing electric motors for electric vehicles, the different types of mathematical model can be applied. Some authors use analytical models to modelling phenomena in the designed device [8]. Additionally, the different parameters are taken account in the objective function. The drive systems, including controllers and mechanical systems are optimized [9]. However, there are a lack of research, in which the finite elements models are employed and economic parameters are included objective function. The main aim of this paper is to design the optimal structure of the BLDC motor for electric vehicle applications. The optimization calculations were made for two BLDC motors structures: (a) exterior rotor and (b) interior rotor. Next, the characteristics of two optimal motors were compared.

2 Design constraints

The stator should be picked with the right appraising of the voltage relying upon the power supply capacity.

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Table 1. Slot parameters for interior rotor BLDC

S. No	Parameter	Value (mm)
1	H_{s0}	2.5
2	H_{s2}	4.5
3	B_{s0}	3
4	B_{s1}	8
5	B_{s2}	11
6	H_{s1}	1
7	R_s	0.5

For advanced mechanics, auto and little impelling applications, 48 V or less voltage BLDC motors are preferred. For modern applications and robotization frameworks, 100 V or higher rating machines are utilized. The interior rotor slot dimensions are given in Tab. 1, see Fig. 1. The stator can be slotted or slot-less. In the slotted type case the stator field is changed in the entire air gap and in the magnet region because of the presence of coil slots. The variation in the magnetic field due to slotting is depending on the distance from the slots. The impact of spaces is least at the magnet and rotor iron connection point, while the best impact of openings is competent at the stator surface. Other than this the opening is an element of immersion of the ferromagnetic material utilized in the rotor and stator. A slot-less machine, however, experiences crossing of lower magnetic flux in the air-gap of motor which yields a less power output in the case of slot-less design compared with a slotted design. This reduced magnetic is compensated by utilization of a Halbach magnetized array, which consists of strong and uniform magnetic field [10].

The design process of an interior rotor type BLDC, its performance analysis carried out by varying the parameters such as windings, stator and rotor slots, and maximum input current and circuit type [11]. The modification of the magnet influences the output torque of the motor. Maximum output torque is achieved when both length and width of magnet is largest. The increment of torque will not determine the increases in the motor efficiency as well [12]. The magnetic flux distribution changes with the change of the shape of the permanent magnet.

Further, a change in the magnetic flux distribution due to the shape change of the permanent magnet changes the cogging torque of the BLDC motor [13, 14]. A short air gap length maximizes the flux for a given thickness of magnet. It is the flat portion of the back EMF that actually is responsible for the production of the torque and any imbalances in the three phases and effects of slotting on the back EMF will cause a difference in torque and power production [15, 16].

3 Design of the permanent magnet machine using FEM

The finite element method (FEM) is a tool for processing surmised answers for complex numerical issues. The limited component technique can be adjusted to fluctuating prerequisites for precision and can diminish the requirement for actual models in the plan interaction. ANSYS is a recreation programming item that assists organizations with guaranteeing their models are liberated from bugs before they support them. Engineers can use it to make virtual models of their creations and then subject them to a battery of verification trials. Conducting a design analysis in this way can drastically reduce the amount of physical testing that has to be done before something gets sent to the market. In the FEM models, it is possible to take into account many different phenomena occurring in electrical machines for electromobility applications. In the case of a permanent magnet machine, the electromagnetic field is generated simultaneously by stator winding and permanent magnets placed in the exterior rotor/interior rotor. The set of equations describing the distribution of the electromagnetic field in BLDC motor has the form [17]

$$\mathrm{curl}\Big(\frac{1}{\mu}\mathrm{curl}\boldsymbol{A}\Big)= \boldsymbol{J}_\mathrm{u} + \boldsymbol{J}_\mathrm{M}\,. \tag{1}$$

The magnetizing current density in the regions with permanent magnet is calculated by the use the magnetization vector [26, 27]

$$\boldsymbol{J}_\mathrm{M} = \mathrm{curl}\,\boldsymbol{M}\,, \tag{2}$$

where $\boldsymbol{M}$ is the magnetization vector in the permanent magnet region.

The BLDC motors are supplied by electronic commutator. The motor controller is supplied by DC voltage. Due to non-linearity and back-electromotive force inducted by rotating rotor in the stator winding the value of phase currents are not know in advance. Therefore, the Kirchhoff equations are taken into consideration

$$\frac{\mathrm{d}\Psi}{\mathrm{d}t} + \boldsymbol{R}\boldsymbol{i} = \boldsymbol{u}\,, \tag{3}$$

where, $\boldsymbol{u}$ is the vector of phase supply voltages, Ψ is the matrix of flux linkage, $\boldsymbol{R}$ is the diagonal matrix of winding resistances, $\boldsymbol{i}$ is the vector of phase currents.

4 Permanent magnet brushless DC motor design

The basic design of the motor has been executed in RMxprt of Ansys Maxwell and optimization calculations have been done in Maxwell 2D. The parameters of analysis setup for design are shown in Tab. 2.

Rotor design

The analyzed exterior rotor type BLDC motor design is shown in Fig.1. The structure of the magnetic circuit

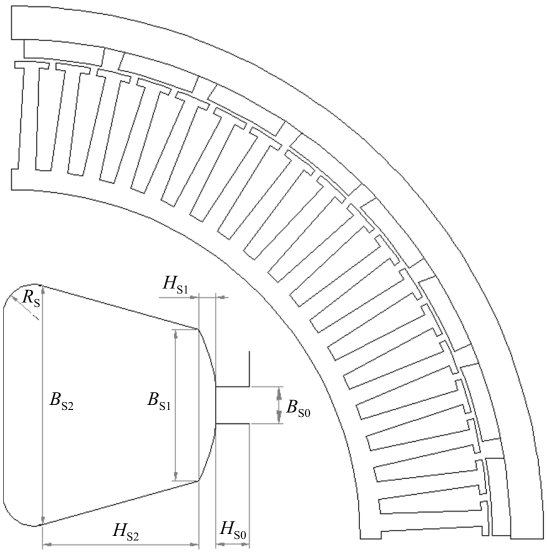

Fig. 1. The 32 pole, 72 slot exterior rotor BLDC

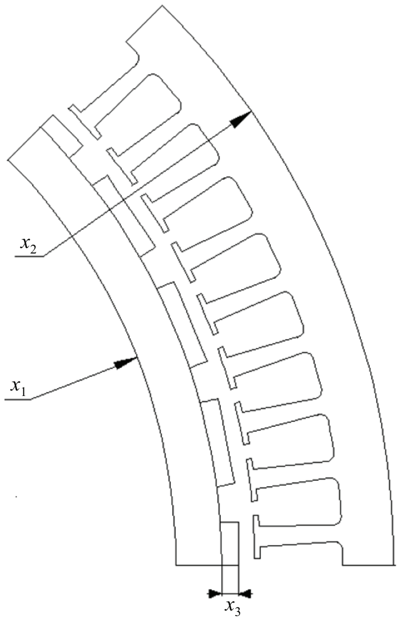

Fig. 2. The magnetic circuit of the inner rotor BLDC motor

of the inner rotor with design variables is presented in Fig. 2.

Table 2. Input functional parameters of designed BLDC motor

S. No	Parameter	Value	Unit
1	Rated power	1500	(W)
2	Rated supply voltage	96	(V)
3	Rated speed	1500	(rpm)
4	Number of pole pairs	32	(-)
5	Frictional loss	10	(W)
6	Windage loss	10	(W)
7	Number of slots	72	(-)
8	Length of stator core	45	(mm)
9	Stacking factor	0.95	(-)
10	Conductor per slot	8	(-)

5 Multi-objective optimization

Both structures of BLDC motors have been described by three design variables. In the case of the exterior BLDC motor the set of design variables is following: $x_1 = r_i$ is the inner rotor diameter, $x_2 = D_o$ is the outer diameter of the stator, $x_3 = h$ is the permanent magnet thickness (see Fig. 2). All design variables form design variables vector $\mathbf{x} = [x_1, x_2, x_3]^\top$. The multi-objective optimization of the BLDC motor consist in maximization of the motor efficiency, while the minimum value of total mass is necessary [28]. The objective function has form

$$f(\mathbf{x}) = \frac{\eta(\mathbf{x})}{\eta_0} + \frac{m_0}{m(\mathbf{x})}, \tag{4}$$

where $\eta(\mathbf{x})$ is the efficiency of the motor, $m(\mathbf{x})$ is the total mass of BLDC motor, η_0 and m_0 are the average values of mass from all experiments.

The Taguchi method has been applied to determination the optimal structure of the motor [29, 30]. The range of design variables is shown in Tab. 3.

Table 3. Design variables range

Design variable	Down (mm)	Up (mm)
x_1	280	295
x_2	268	278
x_3	2.2	2.8

Table 4. The Taguchi levels table for all design variables

Variable	Level 1	Level 2	Level 3	Level 4
x_1	280	285	290	295
x_2	268	270	274	278
x_3	2.2	2.4	2.6	2.8

The range of design variables have been divided into four levels according to ordering principle from 1 to 4. The values assigned to each level are shown in Tab. 4.

In case of traditional single-variable optimization the number of calculations is equal 4^3. According to the principle of the orthogonal table proposed by Taguchi, it is necessary to create an orthogonal table including 16 variation of design variables. The orthogonal table with results of the 2D FEM calculations is presented in Tab. 5.

The best value of the objective function was obtained for the 11th experimental calculation. Next, the optimization calculations were carried out for the inner rotor BLDC motor. The same ranges for the all design variables were adopted. In the case of the interior rotor BLDC, the following optimal values of the design variables were obtained: $x_1 = 268\,\text{mm}$, $x_2 = 290\,\text{mm}$, $x_3 = 2.6\,\text{mm}$.

Table 5. The orthogonal table with results of functional parameters

Exp	x_1 (mm)	x_2 (mm)	x_3 (mm)	$\eta(\mathbf{x})$ (%)	$m(\mathbf{x})$ (kg)	$f(\mathbf{x})$ (-)
1	1	1	1	88.68	8.34	1.93
2	1	2	2	88.45	8.13	1.95
3	1	3	3	88.04	7.95	1.97
4	1	4	4	87.82	7.64	2.01
5	2	1	2	89.78	7.38	2.06
6	2	2	1	88.64	7.14	2.09
7	2	3	4	88.38	6.98	2.11
8	2	4	3	88.26	6.76	2.10
9	3	1	3	90.87	8.46	1.94
10	3	2	4	90.42	7.12	2.13
11	3	3	1	90.56	8.46	1.97
12	3	4	2	90.03	7.69	2.02
13	4	1	4	91.44	8.98	1.89
14	4	2	3	91.56	8.51	1.94
15	4	3	2	90.21	8.16	1.97
16	4	4	1	90.01	7.95	1.99

Table 6. Performance parameters of PMBLDC

Parameter	Unit	Rotor	
		Exteriorr	Interior
Average input current	(A)	16.61	17.28
Root-mean-square	(A)	14.08	14.44
armature current	(A)	14.08	14.44
Frictional and	(W)	83.5	98.40
windage loss	(W)	83.5	98.40
Armature copper loss	(W)	8.15	57.30
Iron-core loss	(W)	9.04	9.5319
Transistor loss	(W)	58.67	60.084
Diode loss	(W)	1.27	0.459
Total loss	(W)	160.62	225.58
Output power	(W)	15.46	1502.63
Input power	(W)	1660.08	1728.42
Efficiency	(%)	90.42	86.94
Rated speed	(rpm)	1558.2	1589.3
Rated torque	(Nm)	9.2	9.03
Motor weight	(kg)	7.93	8.66

6 Comparison of the performance parameters for optimal structures of both BLDC motors

Next, the FEM calculations were made for both optimal structures of BLDC motors. The average torque values for every material have been recorded. Additionally, flux, efficiency and losses were determined for both structures. The selected performance parameters of compared BLDC are given in Tab. 6.

The performance characteristics were determined for both motor structures using FEM. Various parameters such, as speed, phase currents and efficiency for different values of the loading torque were calculated.

6.1 Interior rotor type motor

After simulating the BLDC motor for an interior-type rotor, the results show the efficiency of the BLDC for rated loading torqe is 86. 94 %. The obtained value of rated torque is equal to 9.03 Nm for a rated speed equal to 1589.3 rpm.

Efficiency as a function of the loading torque, velocity as a function of loading torque and for interior BLDC motor are presented in Fig. 3.

It is worth noting, that, the phase current in the no-load operation state is 1.23 A. The results of the calculation of the phase current value for different loading torque show that the current value is proportional to loading torque.

6.2 Exterior rotor type motor

After simulating the BLDC motor for exterior type rotor, the results shown efficiency of the is 90. 42%, rated torque is 9.2 Nm, rated speed is 1558.2 rpm and output mechanical power of is 1499.46 W.

The characteristics $\eta = f(T)$, $I = f(T)$ and $n = f(T)$ for exterior rotor BLDC motor are presented in Fig. 4.

Two structures of BLDC motors can be applied to electrical vehicles. The exterior rotor BLDC motors for the same outer diameter allow obtained a higher efficiency and bigger electromagnetic torque in comparison of interior rotor motors. The mass of the exterior rotor BLDC motor is smaller than mass of the interior rotor BLDC for the same mechanical power. If the designed motor should be characterized by a higher maximum and rated speed, then the BLDC with interior rotor type is preferable.

7 Conclusion

The Taguchi method was applied to the search for optimal structures of BLDC motors for electromobility applications. Two types of motors were optimized: (a) exterior rotor BLDC motor, and (b) interior motor BLDC motor. In electrical vehicles very important are the efficiency and mass of the drive machine.

Both optimal types of analyzed motors have the same value in outer diameter, but the inner rotor diameter and the thickness of the permanent magnet are different. The exterior rotor BLDC motor are characterized by better efficiency and a smaller value of phase current for rated loading torque. It is worth noting, that the exterior rotor BLDC has a smaller value of the no-load phase current. If the applied motor should have a higher maximum and rated speed the interior rotor BLDC should be used.

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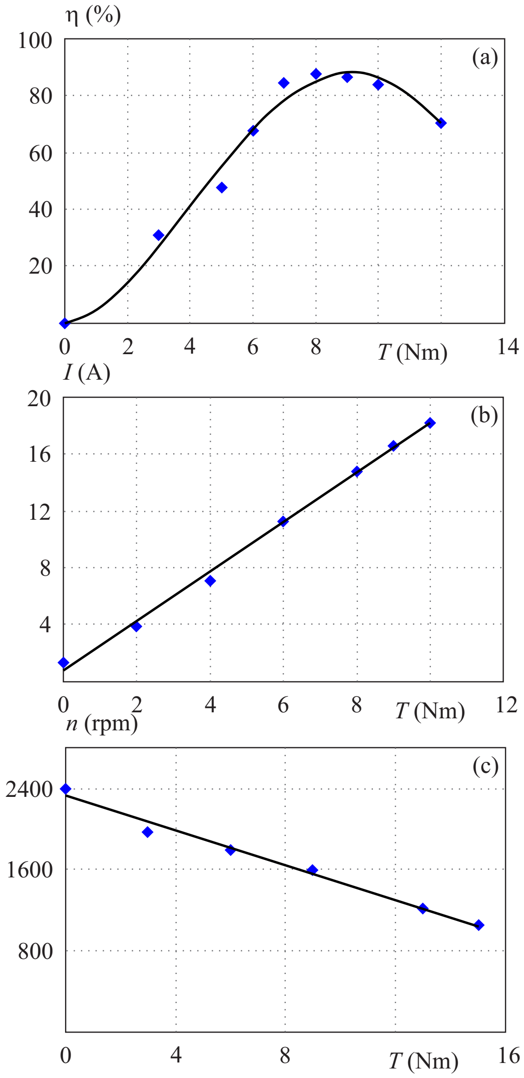

Fig. 3. The performance characteristics for interior rotor BLDC motor: (a) – $\eta = (T)$, (b) – $I = f(T)$, (c) – $n = f(T)$

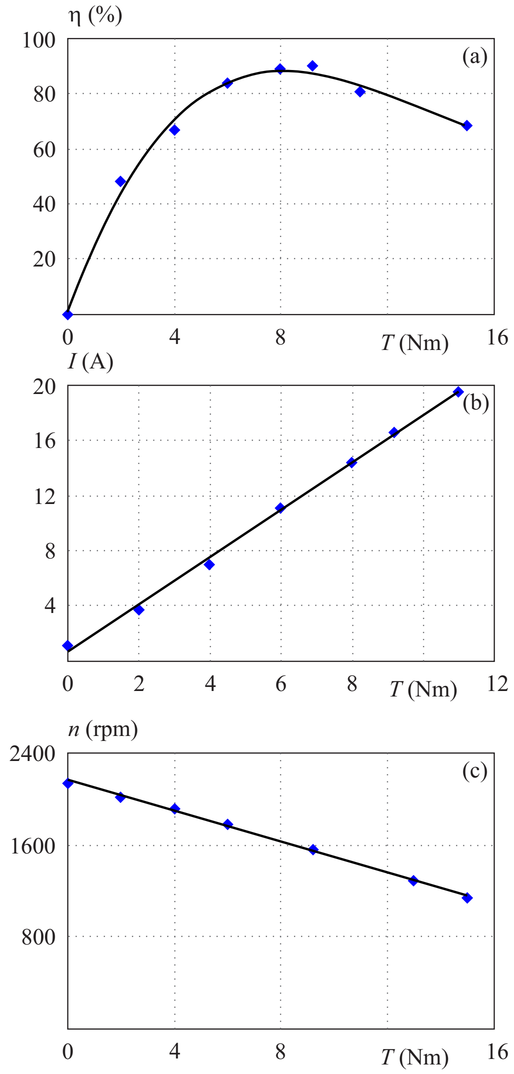

Fig. 4. The performance characteristics for exterior rotor BLDC motor: (a) – $\eta = f(T)$, (b) – $I = f(T)$, (c) – $n = f(T)$

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