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A Novel Semi-inserted Dual-stator Low-speed High-torque Permanent Magnet Drive Motor

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Low-speed high-torque permanent magnet direct drive machine (LSPMDM) overcomes the shortcomings of traditional drive system, but its volume is large. In this paper, the numerical relationship between the motor external diameter and the rated speed is deduced, and improvement of the torque density is qualitatively analyzed for a dual-stator motor. Owing to that semi-inserted magnetic circuit structure and auxiliary slots under the poles can further increase the torque density of the motor, the effect of the shape, number and position of the auxiliary slots on the salient pole rate is also studied through comparative analysis. By incorporating the merits of dual-stator motor and semi-inserted magnetic circuit structure with the auxiliary slots, a novel motor topology is proposed, which is verified by finite element analysis with good performance.

Keywords : low-speed high-torque, torque density, dual-stator motor, semi-inserted magnetic circuit, auxiliary slot, overload capacity

1. Introduction

The application prospect of low-speed high-torque transmission system is extremely wide, in the fields of industrial production, oil field exploitation, wind power generation and ship propulsion. For the traditional drive system of induction motor with mechanical deceleration mechanism, the disadvantage is complicated structure, easy wear of deceleration mechanism, leakage of lubricating oil, poor operation reliability, high maintenance cost, and low overall system efficiency [1]. In order to meet the requirements of energy conservation and environmental protection, there is a broad consensus among scholars all over the world about replacement of direct drive system for traditional drive system.

However, low-speed permanent magnet direct drive machine suffers from large volume and low torque density [2]. In order to solve this problem, scholars spare no effort to innovate the topology and design theory of the motor. Permanent magnet vernier machine based on field modulation principle is applied in wind power generation [3]. The number of poles and slots of the permanent magnet vernier machine become fewer while the torque density is improved [4], but the disadvantage is that the power factor is generally low. The transverse flux motor effectively overcomes the mutual restriction of the stator teeth and the armature windings in space [5]. The number of poles can be greatly increased to achieve low-speed operation of the motor. Increasing the number of poles within a certain range, the torque density of the transverse flux motor improves accordingly [6].

A novel topology of the dual-stator motor for low-speed application was presented in [7], which makes the internal space of the motor fully utilized. The fractional-slot concentrated winding is applied in the outer stator, and the permanent magnet vernier structure is adopted in the inner stator. The incorporation of the two structures reduce the number of slots, which is conducive to the further improvement of torque density.

Research on low-speed high-torque machine has made good progress in wind power generation and automotive drive. The low-speed high-torque motor may be temporarily overloaded for application in such occasions as pumping unit and ball mill, requiring higher overload capacity of the motor. In this paper, it is put forward that the dual-stator motor effectively increases the torque density while enhancing the overload capability. The

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torque density and the overload capability of the motor are further increased by the semi-inserted magnetic circuit structure and auxiliary slots.

2. Dual-stator Structure

2.1. Equation of numerical relationship

With the decrease of the rated speed, the power density of the motor decreases which leads to the increase of the volume. On the premise of keeping the length of iron core constant, the numerical relationship between motor external diameter and rated speed is deduced in this paper. Several of the basic formulas for rotating motor are shown below

$$\begin{cases} E_0 = \sqrt{2}\pi f K_{dp} N \Phi_0 \\ f = \dfrac{pn}{60} \\ \Phi_0 = B_\delta \alpha_i \tau_1 L_{ef} = B_\delta \alpha_i \dfrac{\pi D_{i1}}{2p} L_{ef} \end{cases} \tag{1}$$

The expression of the back EMF is obtained by the integration of the several formulas (1).

$$E_0 = \frac{\sqrt{2}\pi^2 K_{dp}}{120} B_\delta \alpha_i n N D_{i1} L_{ef} \tag{2}$$

where K_{dp} is the winding factor, B_δ is the amplitude of air-gap flux density, α_i is the pole-arc factor, N is the turns-in-series per-phase, n is the rated speed, D_{i1} is the stator internal diameter, L_{ef} is the effective length of the iron core.

According to the above formula (2), the no-load back EMF of motor is proportional to the speed n. The speed of LSPMDM is relatively low, which results in the decrease of the back EMF. Therefore, some parameters of the motor need to be changed to keep the back EMF constant. It is assumed that the winding factor, air-gap flux density and pole-arc factor are constant. For motors with different rated speed, the following equation is approximately held.

$$\frac{E_1}{E_2} = \frac{n_1}{n_2} \frac{D_1}{D_2} \frac{N_1}{N_2} \frac{L_{ef1}}{L_{ef2}} = 1 \tag{3}$$

where D_1 is the stator external diameter.

The bearing sliding and ventilation losses will be reduced as the decrease of the motor rated speed. Increasing the turns-in-series per-phase of the armature winding increases the winding resistance, which in turn increases the stator copper loss. Stator copper loss accounts for a large proportion of the total loss which is the main factor determining motor efficiency. Therefore, in order to maintain the motor performance at different speed, the most critical is that the value of the winding resistance is unchanged.

$$R = \rho \frac{2Nl_o}{Aa_1} \tag{4}$$

$$\frac{R_1}{R_2} = \frac{N_1}{N_2} \frac{A_2}{A_1} \frac{l_{o1}}{l_{o2}} \approx \frac{N_1}{N_2} \frac{D_2^2}{D_1^2} \frac{l_{o1}}{l_{o2}} = 1 \tag{5}$$

where l_o is the average half-turn length of the coil, A is the sectional area of winding wire, a_1 is the number of parallel branches of stator winding.

The equation (6) is obtained through combining equation (3) and equation (5).

$$\frac{E_1}{E_2} = \frac{n_1}{n_2} \frac{D_1^3}{D_2^3} \frac{L_{ef1}/l_{o1}}{L_{ef2}/l_{o2}} = 1 \tag{6}$$

Based on the assumption (7)

$$\frac{L_{ef1}/l_{o1}}{L_{ef2}/l_{o2}} = 1 \tag{7}$$

the equation (6) can be simply expressed as

$$\frac{E_1}{E_2} = \frac{n_1}{n_2} \frac{D_1^3}{D_2^3} = 1 \tag{8}$$

The equation (8) can be expressed as another form

$$\frac{D_1}{D_2} = \sqrt[3]{\frac{n_2}{n_1}} \tag{9}$$

According to the equation (9), it is concluded that the external diameter of motor is large at low speed, especially at ultra-low speed. The large volume of motor increases the difficulty of manufacture and transportation, moreover, the flexibility of application and installation is limited. As a result, the traditional drive system is difficult to be completely replaced by LSPMDM. Increasing the torque density and further reducing the volume are the key to promote the application of LSPMDM.

The rotor internal diameter of LSPMDM is large while the stator external diameter is large. The dual-stator structure can effectively improve the utilization rate of the internal space of the motor, which makes the motor higher torque density while also enhances the efficiency and maximum output power [8]. Two sets of separate armature windings are wound on the inner stator and the outer stator of dual-stator motor, which can run in series or independently. The flexible change of the connection mode of two sets of windings enables the motor to maintain good performance over wider working range.

2.2. Rotor structure

The design of single-layer permanent magnets (as shown in Fig. 1(a)) is in general adopted in the rotor of dual-stator motor, of which the yoke thickness is relatively thin and the structure is simple. This kind of structure is weak in mechanical strength and is not suitable for low-speed high-torque applications. Therefore, the rotor structure with double-layer permanent magnets (as shown in Fig. 1(b)) is adopted in this paper. Compared with the common structures, the PM volume of this structure increased, as a result the augment of magnetic energy product increases the maximum output power and enhances the overload capacity of the motor.

With the parameters of the inner stator and the outer stator mutually restricted, there are two air-gaps in dual-stator motor, making the motor design become difficult. The dual-stator motor usually adopts a design method in which the motor is equivalent to the inner and outer two motors independently designed and then integrates the two of them. However, this design method is inaccurate, due to magnetic coupling between the inner and outer motors.

When the rotor structure with double-layer permanent magnets is adopted and the magnetic flux direction of the opposite inner and outer permanent magnets are the same, the structure (as shown in Fig. 2(a)) is similar to that shown in Fig. 1(a). The magnetic coupling between the inner and outer motors is almost nonexistent, in the circumstances that the magnetic flux direction of the opposite inner and outer permanent magnets are contrary (as shown in Fig. 2(b)). As a result, the dual-stator motor is divided into two parts, and it can be independently designed flexibly and accurately.

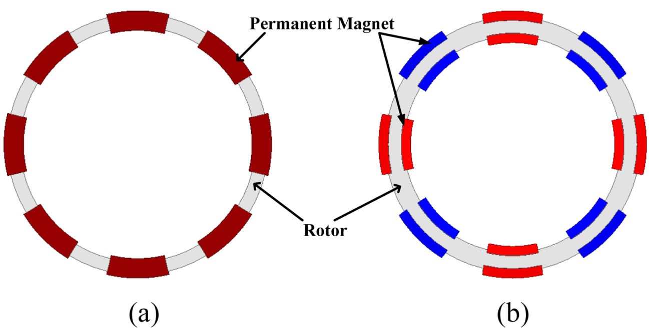


Fig. 1. (Color online) Rotor structure of dual-stator motor. (a) single-layer permanent magnets, (b) double-layer permanent magnets.

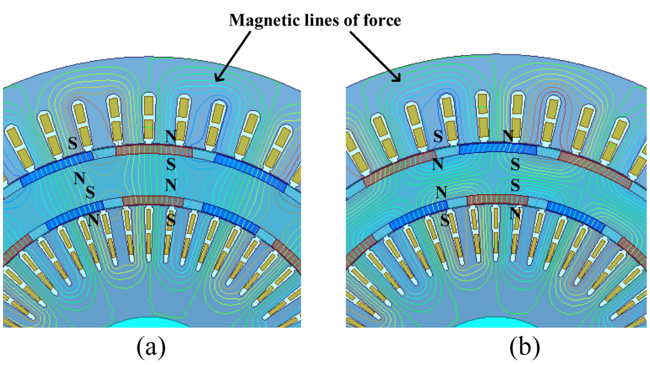


Fig. 2. (Color online) Magnetics lines of force. (a) magnetic coupling, (b) without magnetic coupling.

3. Semi-inserted Magnetic Circuit Structure and Auxiliary Slots

Surface mounted permanent magnet synchronous motor takes the advantages of simple structure and small rotational inertia. However, because of the large electromagnetic torque of LSPMDM, the semi-inserted magnetic circuit structure (as shown in Fig. 3(a), and the 2D simplified model is shown in Fig. 3(b)) is sometimes adopted in consideration of mechanical strength, of which the interpolar fasteners turn surface mounted structure into semi-inserted structure. Fasteners are added between the adjacent permanent magnets to make them more stable. Moreover, compared with surface mounted structure, the quadrature-axis inductance is no longer equal to the direct-axis inductance, and the generated reluctance torque increases the torque density of the motor (as shown in Table 1).

In semi-inserted structure, leakage flux between the adjacent permanent magnets lead to the output capacity of the motor decreasing. The added fasteners make the air-gap flux density waveform distorted, and the harmonic

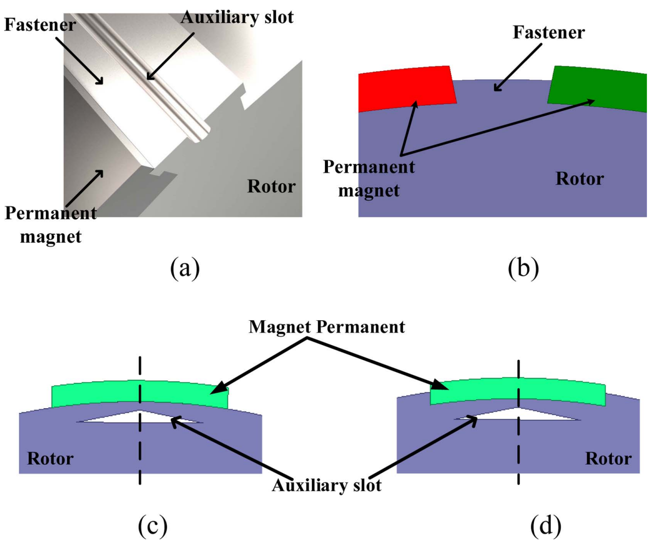


Fig. 3. (Color online) Semi-inserted magnetic circuit structure. (a) 3D model, (b) 2D simplified model, (c) surface mounted with auxiliary slot, (d) semi-inserted with auxiliary slot.

Table 1. Salient pole rate with different magnetic pole structures.

Magnetic pole structure of the rotor	Salient pole rate
Surface mounted structure	1.0001
Semi-inserted structure	1.2396
Surface mounted with auxiliary slot	1.0010
Semi-inserted with auxiliary slot	1.3503

content of the back EMF increases, resulting in amplification of torque ripple and noise of the motor. Opening the auxiliary slots between the poles increases the interpolar magnetic resistance, reducing the leakage flux and the ripple torque effectively. In addition, for the semi-inserted structure, opening the auxiliary slot under the poles (as shown in Fig. 3(d)) significantly increases the salient pole rate, thereby further increasing the reluctance torque. In contrast, the effect on salient pole rate by the auxiliary slot is not obvious in surface mounted structure (as shown in Fig. 3(c)). The optimization and design of the auxiliary slots is important, because it has great influence on the performance of the semi-inserted structure motor.

In this section, the influence of the motor performance which is produced by the several key parameters including the shape, number, and position of the auxiliary slots under magnet permanent is studied.

3.1. Shape of auxiliary slots

Three different shapes of the auxiliary slots are studied, consisting of rectangle, semicircle, and triangle (as shown in Fig. 4). In order to avoid the generation of new harmonics in the motor as much as possible, the auxiliary slots should be symmetrical along the center line of permanent magnet. The area and height of the auxiliary slots are the same, and the distance between the auxiliary slots and the bottom of the permanent magnet is also equal, making the comparative study scientific and rigorous. In this analysis, the salient pole rate is obtained by the magnetostatic field analysis with 2-D finite element method (FEM). From the analytical results in Table 2, the following conclusion can be drawn that triangular slots

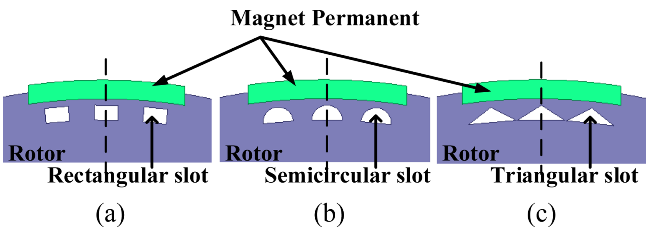


Fig. 4. (Color online) Auxiliary slots of different shapes.

Table 2. Salient pole rate with auxiliary slots of different shapes.

Shape of the auxiliary slot	Salient pole rate
Rectangular slot	1.3102
Semicircular slot	1.3148
Triangular slot	1.3540

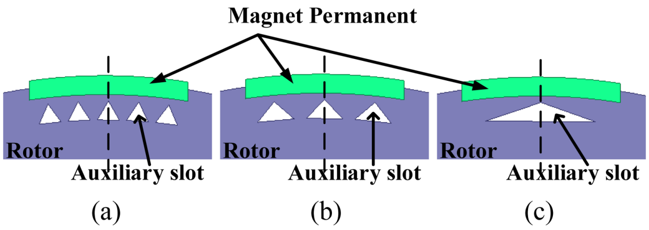


Fig. 5. (Color online) Auxiliary slots of different numbers.

Table 3. Salient pole rate with auxiliary slots of different numbers.

Number of the auxiliary slot	Salient pole rate
5	1.3144
3	1.3150
1	1.3413

are better than rectangular and semicircular slots.

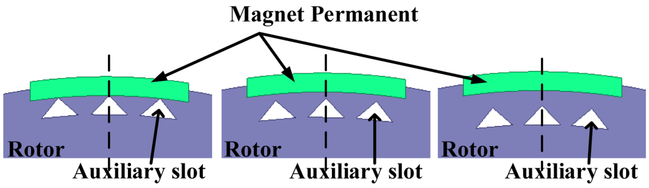
3.2. Number of auxiliary slots

The effect of the number of auxiliary slots on the salient pole rate of the motor was studied (as shown in Fig. 5). The area and height of the auxiliary slots are the same, and the distance between the auxiliary slots and the bottom of the permanent magnet is also equal. It is obviously more advantageous to adopt one auxiliary slot than multiple distributed auxiliary slots from the data shown in Table 3.

3.3. Position of auxiliary slots

Three triangular slots are adopted to investigate the influence of the position of the auxiliary slots on the salient pole rate of the motor (as shown in Fig. 6). Except for the distance between the slot and the bottom of the permanent magnet, the other parameters of the auxiliary slots are exactly the same. The closer the auxiliary slots to the permanent magnet, the greater the salient pole rate of the motor (as shown in Table 4).

The principle of increasing the salient pole rate by auxiliary slots is that the magnetic permeability of air is much lower than that of the silicon steel, and it is equivalent to narrow the magnetic line path under the direct-axis with the auxiliary slots opened, which increases the



(a) (b) (c)

Fig. 6. (Color online) Auxiliary slots of different position.

Table 4. Salient pole rate with auxiliary slots of different position.

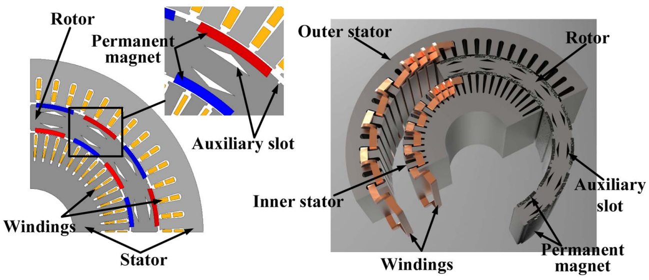
Distance between auxiliary slot and the bottom of PM (mm)	Salient pole rate
0	1.3215
2	1.3150
4	1.2452

reluctance of the direct-axis. Consequently, the unreasonable auxiliary slots result in partial saturation of the magnetic circuit and augment of iron loss.

4. Topology and Results of Finite Element Analysis

Through the analysis above, a novel topology–semi-inserted dual-stator low-speed high-torque permanent magnet drive motor–is proposed (as shown in Fig. 7). A 3 kW 90 r/min LSPMDM with 54/16 slot/pole combination is improved with this novel structure (The important data of three motor projects is shown in Table 5). A 2-D finite element model is built to analyze the influence of the novel structure on the torque density.

The external diameter of the motor is shortened in project 1, under the premise of keeping the two basic performance indexes including efficiency and overload capacity unchanged. According to the calculation result of the data in



(a) (b)

Fig. 7. (Color online) Semi-inserted dual-stator low-speed high-torque permanent magnet drive motor. (a) 2D model, (b) 3D model.

Table 5. Important data for the three of motor projects.

Items	Value		
	Original project	Project 1	Project 2
Rated power (kW)	3	3	3
Rated speed (rpm)	90	90	90
External diameter of outer stator (mm)	400	327	400
Internal diameter of outer stator (mm)	285	245	300
External diameter of rotor (mm)	283.4	243.6	298.4
Internal diameter of rotor (mm)	85	185	230
External diameter of inner stator (mm)	—	184	228.8
Internal diameter of inner stator (mm)	—	85	85
Effective length of the iron core (mm)	160	160	160
Efficiency	85.43 %	85.29 %	89.81 %
Maximum overload ratio	1.93	1.85	2.47
Torque density (kNm/m^3)	30.52	43.78	39.07

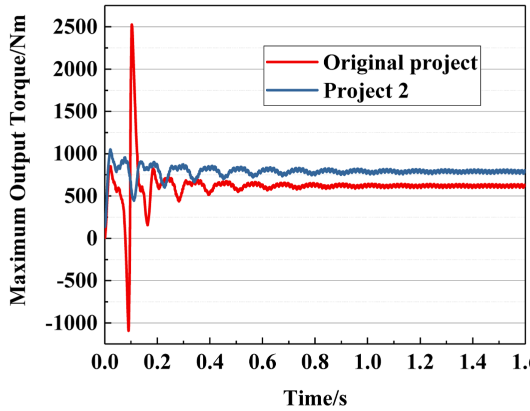


Fig. 8. (Color online) Maximum output torque of motor.

Table 5, the motor volume is reduced by 33 %, in the case of a slight decrease of efficiency and overload capacity. The torque density of the motor is increased by 49.6 % at rated load.

The external diameter, length and volume of project 2 motor are the same as those of original project. The maximum overload capacity of the motor is obtained by the transient field analysis based on the 2-D finite element model. The load continuously increases from the rated load until the motor fails to operate normally, and the load at this moment is the maximum load. Fig. 8. shows the maximum output torque of the original project and project 2, from which there comes a conclusion that the overload capacity of project 2 is 27.6 % higher than the original project. Meanwhile, the efficiency of project 2 is greatly improved, reaching 89.81 %.

The cogging torque of project 2 motor is relatively small, less than 1 % of the rated torque (as shown in Fig. 9), which leads to lower vibration and noise.

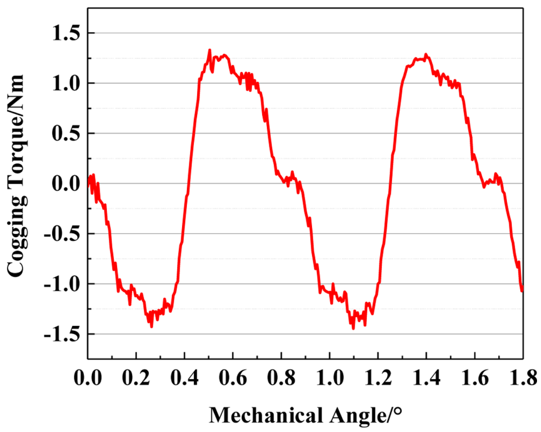


Fig. 9. (Color online) Cogging torque of project 2 motor.

5. Conclusion

The novel semi-inserted dual-stator low-speed high-torque permanent magnet drive motor is designed in this paper. Compared with the original structure, the torque density of the novel motor is greatly improved, exceeding 39 kNm/m^3. As a result, the volume of the novel motor is significantly reduced while keeping the overload capacity constant. The overload capacity of the novel motor is greatly improved, in the case of keeping the volume constant. Furthermore, other performance indexes of the novel motor, such as efficiency and the cogging torque, meet the requirements of practical applications. Therefore, the novel motor can be a good choice to achieve LSPMDM with high overload capability and high torque density.

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References

[1] Y. Gao, R. Qu, D. Li, J. Li, and G. Zhou, IEEE Trans. Appl. Supercond. **26**, 4 (2016).
[2] Q. Wang, S. Niu, and S. Yang, IEEE Trans. Magn. **53**, 6 (2017).
[3] K. Xie, D. Li, R. Qu, and Y. Gao, IEEE Trans. Magn. **53**, 6 (2017).
[4] Y. Zhang, H. Lin, S. Fang, D. Decker, and D. Wang, IEEE Trans. Appl. Supercond. **26**, 3 (2016).
[5] T. Husain, I. Hasan, Y. Sozer, I. Husain, and E. Muljadi, IEEE Trans. Ind. Appl. (2018).
[6] J. R. Anglada and S. M. Sharkh, IEEE Trans. Energy Convers. **33**, 2 (2018).
[7] S. Niu, S. L. Ho, and W. N. Fu, IEEE Trans. Magn. **46**, 6, (2010).
[8] W. Zhao, D. Chen, T. A. Lipo, and B. I. Kwon, IEEE Trans. Ind. Appl. **53**, 4 (2017).