Research on Structure Parameters and Performance of a Dual-Stator Permanent Magnet Motor

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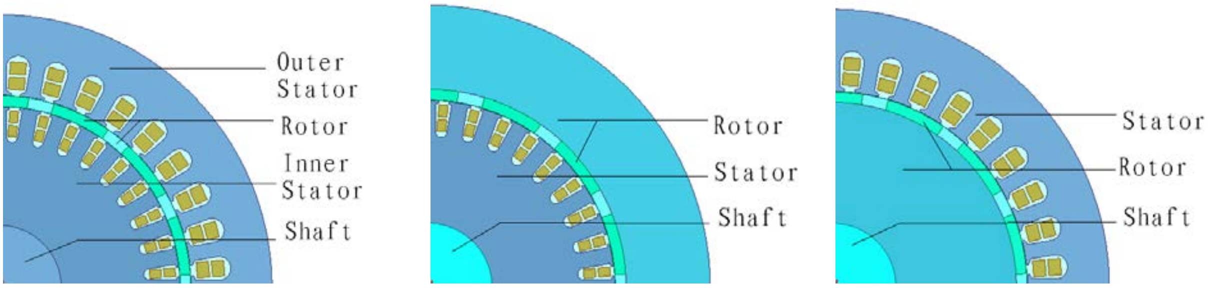
Abstract. Double-stator permanent magnet motor (DSPMM), with special structure characteristics, has many excellent performance features. Firstly, this paper researches the structure parameters of the DSPMM, including the air gap length and pole-arc coefficient. According the research, a DSPMM of the same size with a common single stator permanent magnet motor (SSPMM) is designed. The comparison results of the performance between the two motors show that the DSPMM has faster response speed, higher maximum load torque and efficiency than the SSPMM, which verified the rationality of the structure parameters selection and the performance advantages of the DSPMM.

Introduction

DSPMM is designed with two separated stators, the inner one and the outer one. The winding in the two stators can jointly produce higher electromagnetic torque and power. Without rotor core, the cup-shaped rotor has effectively reduced rotational inertia, and dynamic response time is effectively shortened. In fact, the DSPMM can be regarded as a combination of an inner rotor and an outer rotor permanent magnet motor (PMM), which have the same rotor. Figure 1 shows the three kinds of PMM. By increasing the utilization ratio of motor internal space, power density and torque density will be improved when the DSPMM is used as generator and electromotor [1-6]. The features of the DSPMM mentioned above broaden its prospect of application and enable it to be a research hot spot.



（a）DSPMM （b）Inner Stator Motor (c)Outer Stator Motor

Fig.1. Structure of motor

As a kind of PMM with double air-gap structure, the design parameters of DSPMM are divided into two parts. The one part sharing with traditional SSPMM includes winding distribution, air gap length, permanent magnet thickness and pole-arc coefficient. The other part unique contains split-ratio, power distribution between the inner and outer winding and ratio of the inner and outer air gap length. The impact of inner and outer diameter ratio of outer stator on torque angle characteristics has been studied in [7]. Another paper [8] researches the influence of the inner and outer winding turn ratio on the electromagnetic torque. Paper [9] analyzes how the split-ratio impact on output power.

Using Finite Element Analysis (FEA) tool, the paper researches the influence of some structure parameters, including air gap total length, the ratio of inner and outer air gap length and pole arc coefficient on efficiency, cogging torque and induced voltage. Then a DSPMM is designed referring to an ordinary SSPMM. Also, the dynamic response, maximum load capacity and efficiency of the two motors are compared.

Research on structure parameters

Structure parameters of motors determine performance of motors. As a type of PMM owing new structure, research on special structure parameters of the DSPMM is helpful to improve the performance of the motor.

A. Air gap length

A longer air gap length may cause higher stray losses and lower efficiency while a shorter one may increase vibration and noise. Usually, SSPMMs have only an outer stator and their air gap length is designed according to the empirical equation 1 in the paper [10]:

$$\delta = 4.7 D_{il} / \sqrt{p} \tag{1}$$

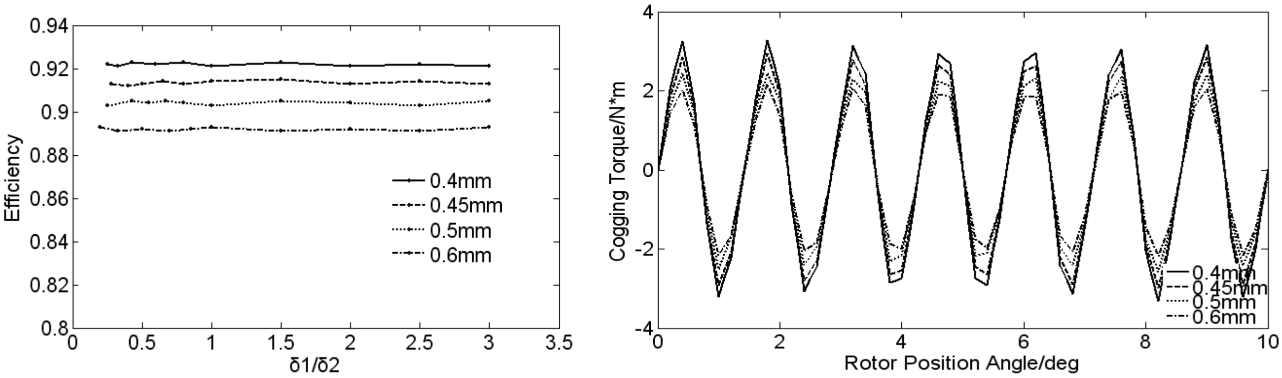
Where δ is the air gap length, D_{il} is the inner diameter of the stator, and p is the pole pair.

The air gap of the DSPMM is divided into the inner part and outer part, which can be expressed as

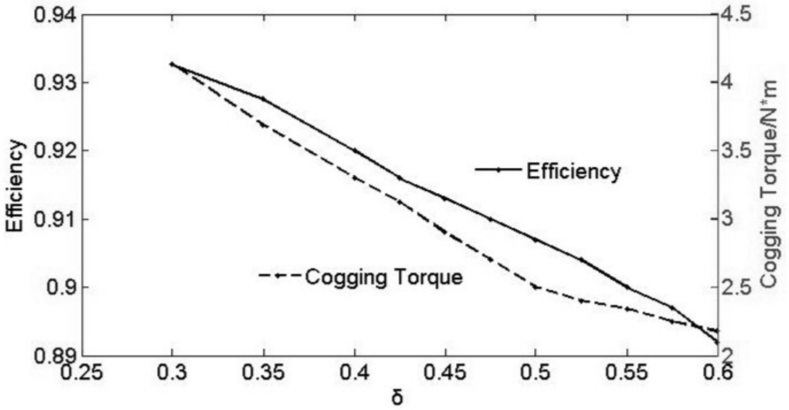
$$\delta = \delta_1 + \delta_2 \tag{2}$$

where δ_1 is the length of outer air gap; δ_2 is the length of outer air gap.

There are no exact equations for the air gap selection. In order to optimize the air gap length, a series of δ values are simulated, including: 0.4mm, 0.45mm, 0.5mm, 0.6mm. Figure 2(a) shows the impact of δ_1 / δ_2 (δ_1 / δ_2 referring to the ratio of inner and outer air gap length) on the efficiency and the cogging torque change under different δ values is shown in figure 2(b). Figure 2(c) presents the variation of the efficiency and cogging torque when the δ changes.



(a) The efficiency of different air gap ratio (b) The cogging torque of different air gap length



(c) The change of efficiency and cogging torque

Fig.2. Research on air gap

For the DSPMM, the ratio of δ_1 and δ_2 do not affect efficiency because whole magnetic circuit must contain total air gap. It is similar to common PMMs that the thinner the air gap length is, the higher the efficiency and cogging torque become, which may cause vibration and noise problems. Considering the analysis above and the fixation of the rotor, the inner and outer air gap lengths are set as 0.25mm.

B. Pole arc coefficient

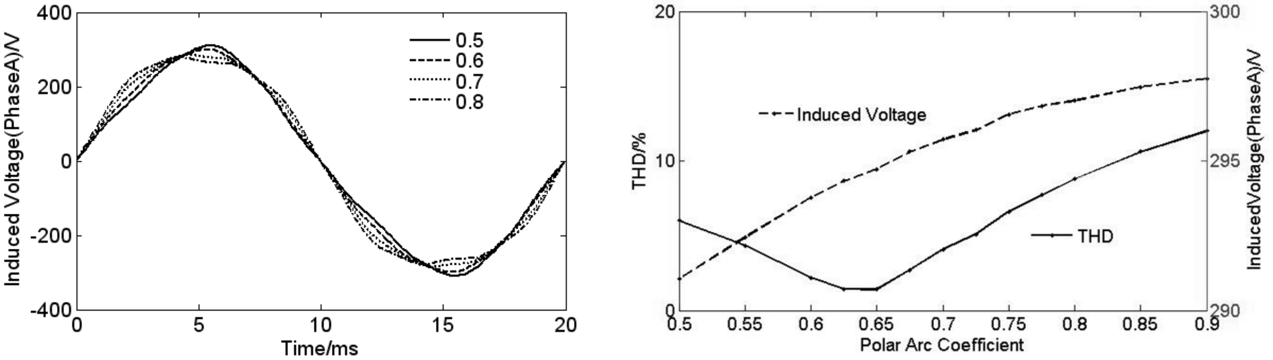
The permanent magnetic pole design relates to two main factors: one is the induced voltage in windings which impact on speed control, the other is the dosage of the permanent magnet material. The pole-arc coefficient is an important index of the design process. According to the research method of SSPMMs, pole-arc coefficient is defined as

$$a_p = \frac{\frac{1}{\tau}\int_{-\tau/2}^{\tau/2} B(x)dx}{B_\delta} = \frac{B_{\delta av}}{B_\delta} \tag{3}$$

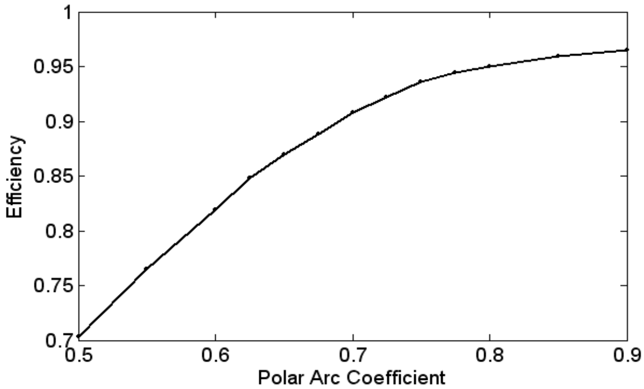
where $B(x)$ is the air gap flux density along the air gap circle, $B_{\delta av}$ and B_δ are the average and maximum value of the air gap flux density, and τ is the pole pitch. Suppose that air-gap flux of each pole distributes evenly in b_p, which is distance of pole arc, then the pole-arc coefficient can be expressed approximately as

$$a_p = b_p / \tau \tag{4}$$

A series of a_p (from 0.5mm to 0.8mm) are simulated with other structure parameters unchanged. Figure 3(a) shows the winding induced voltage of different a_p. The fundamental amplitude and total harmonic distortion (THD) of the induced voltage have been analyzed by Fast Fourier Transform (FFT), and the results are presented in figure 3(b). The Figure 3(c) shows the influence of a_p on the efficiency.



(a) The winding induced voltage of different a_p (b) The induced voltage of different a_p



(c) The efficiency of different a_p

Fig.3. Research on polar arc coefficient

With the increase of pole arc coefficient, induced voltage waveform changes from approximate sine wave into rectangular wave. FFT analysis results show that its amplitude increases, while the minimum THD appears at a_p=0.65. The motor efficiency increases gradually but the growth rate decreases. Considering above points, selecting of arc coefficient from 0.65mm to

0.7mm is quite reasonable.

Performance analysis

Through the study of motor parameters above, a DSPMM was designed referring to a SSPMM. The two motors' main size data are listed in Table 1.

TABLE 1

MAIN SPECIFICATIONS OF THE TWO MOTORS

	SSPMM	DSPMM
Outer diameter of outer stator/mm	210	210
Outer diameter of inner stator/mm	148	148
Inner diameter of outer stator/mm	/	139
Inner diameter of inner stator/mm	/	48
Length of core/mm	240	240
Length of outer air-gap/mm	0.25	0.25
Length of inner air-gap/mm	/	0.25
Thickness of the permanent magnet/mm	6	4
Pole arc coefficients of permanent magnet	0.7	0.7
Dosage of permanent magnet/kg	4.8	3.2
Number of poles	14	14
Number of slots	36	36
Conductors per slot of outer stator	40	28
Conductors per slot of inner stator	/	12

DSPMM has been known for low moment of inertia and high output torque. The rotor of the DSPMM is composed of permanent magnet and stent, which shapes cup structure instead of traditional iron core structure, so rotor's weight decreases greatly. Moment of inertia has been given by [11]

$$J = \sum M_i R_i^2 \tag{5}$$

where M_i is mass of infinitesimal volume; R_i is volume infinitesimal vertical distance to the axis of rotation; J is moment of inertia.

Calculation results show that the DSPMM rotor's moment of inertia is 0.012 kg•m^2, far lower than 0.031 kg•m^2 of the SSPMM. Thus, the response speed of DSPMM should be faster.

Traditional SSPMM maximum electromagnetic torque can be expressed as [10]

$$T_{\max} = \frac{\sqrt{2}\pi}{4} B_{\delta 1} L_{ef} D_{il}^{\ 2} A \tag{6}$$

$$A = \frac{mNIk_w}{2p\tau_1} \tag{7}$$

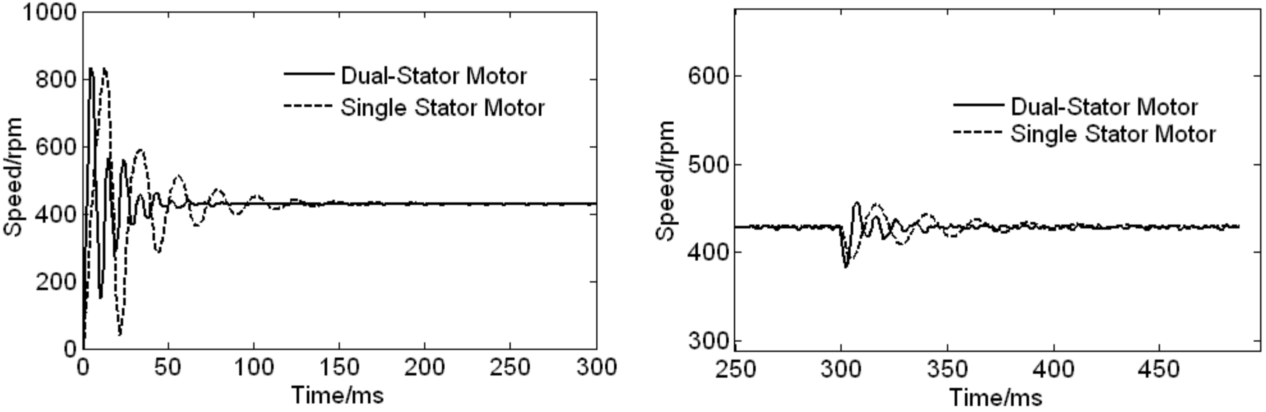
where $T_{\max}$ is maximum electromagnetic torque, $B_{\delta 1}$ is air gap base amplitude value, L_{ef} is calculation length of armature, D_{il} is inner diameter of stator, A is electric load of stator, N is winding coil number per phase, I is winding current, τ_1 is pole pitch of stator, k_w is winding coefficient.

Maximum electromagnetic torque of permanent magnet motor is determined by electromagnetic load and dimension. On the one hand, while the current is the same, the coil number of turns of the DSPMM, with two stators placed coil in, is more than the SSPMM. On the other hand, while the coil number of turns is same, two stators that containing coil of more coarse wire with larger slot area can reduce resistance and increase current. Thus, the maximum load torque of the DSPMM should be bigger than single stator motor, which means higher load capacity.

To validate its superior performance, the two motors' finite element models are built and simulated by using the finite element analysis (FEA) software Ansoft.

A.Dynamic response time

In order to compare dynamic response performance more directly, same AC voltage source is imposed to the two motors. The speed changing over time is shown in Figure 4 (a) for starting under no-load and Figure 4 (b) for increasing load torque to 40N•m.



（a）Starting with no load （b）Changing load from 0N•m to 40N•m

Fig.4. Comparison of response time

Assuming that motor runs in a stable state if the speed fluctuates around the rating in less than 10N•m. It takes the DSPMM 70ms when it starts without load and 50ms when the load is changed to 40N•m to enter a stable state. But for the SSPMM, the time is respectively 150ms and 100ms. According to this result of simulation, dynamic response performance of the DSPMM is superior to the SSPMM.

B.Load capacity and efficiency

Increasing load torque of the two motors gradually under same rated voltage, simulation results show that the maximum load of the DSPMM is 320N•m while the SSPMM is 115N•m. Figure 5 shows the efficiency of the two motors changing with the load torque.

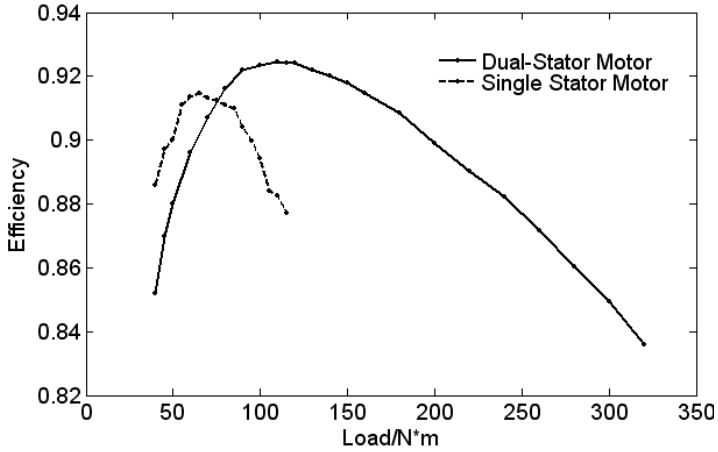


Fig.5. Efficiency under different load torque

With low load, the efficiency of the DSPMM is slightly less than the SSPMM. But when load is high, the former exceeds the latter and maintains more than 85% during a large range even reach 92.5% at 100N•m. Therefore, the DSPMM owns greater load capacity, meets the requirements of motor efficiency, and can be used in those situations calling for high torque.

Conclusion

Analysis about structure parameters of the DSPMM indicates that, at same total length, different ratios of the inner and outer air gap length do not affect the motor performance, and that reducing the total length of air gap can increase efficiency and magnify cogging torque. Moreover, with the arc coefficient increasing, induced voltage waveform changes and its THD gets minimum under a certain value, efficiency gains improvement but its growth rate declines. Simulation results confirmed that performance of the DSPMM in dynamic response, maximum load capacity and efficiency is superior to that of the SSPMM.

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