Electromagnetic Design and Experiment of Halbach Array Based Permanent Magnet Fault-Tolerant Motors

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Abstract—In order to meet high reliability application requirements of modern electric drive system, a kind of Halbach array based permanent magnet fault-tolerant motors (PMFTM) is studied in this paper. Firstly, the structure, characteristics and fault-tolerant working principle of PMFTM are analyzed. Secondly, according to the electromagnetism theorem and Maxwell's equation, the electromagnetic parameters calculation equations are derived, and then the key parameters of 1KW four-phase six-pole Halbach array based PMFTM are worked out. Thirdly, a PMFTM prototype is built and tested, and the experiment on this researched motor has proved that the rationality and accuracy of this motor.

Key words-permanent magnet fault-tolerant motors; Halbach array; motor design; electromagnetic analysis

I. INTRODUCTION

With the rapid development of rare earth permanent magnetic materials, permanent magnet motor is getting more and more widely utilization in the electric drive system with its advantages like high efficiency, high torque inertia ratio, high energy density and so on. In some high reliability of electric drive application demand situations, we often use the backup redundancy technology, which connects lots of independent motor systems together in the way of series or parallel, and through switching the working way of hot and cold standby to improve the ability of continuous work of whole machine when machine is at the state of mechanical or electrical parts fault[1,2]. This fault-tolerant method has clear principle and simple control, but it still has some weaknesses, like large volume, a lot of parts and low utilization rate. In order to overcome these shortcomings, based on the mind of backup fault-tolerant technology, researching on the permanent magnet motor with high reliability is gradually becoming a hot issue in the study of modern electric drive system[3,4].

Permanent magnet fault-tolerant motor (PMFTM) is a new type of permanent magnet brushless motor which developed in recent years, this kind of motor can also use the phase segregation and redundant capacity method to make the rest of fault phase continue running after one phase or number phases of motor having a failure occurs, in addition to the general advantages of traditional permanent magnet motor. At present, the research of permanent magnet motor on the aspects of motor structure, fault-tolerant control strategy are still in the initial stage. Literature[5,6] respectively used the permanent magnet fault-tolerant motor as the drive motor in electric fuel pump system of electric or overall-electrical plane, and designed them as the electric actuator of electric steering gear system to make the plane has stronger reliability and security. Literature[7] applied permanent magnet fault-tolerant motor into driving system of electric vehicle, and took it as execution motor of wire control steering device to further improve the car driving safety performance. Literature[8] studied the direct torque control and the optimal current control strategy of multiphase permanent magnet fault-tolerant motor. Literature[9] proposed the fault tolerant control strategy with single-phase open circuit which is based on two driving topological structure of H-bridge and star type.

In this paper, a four-phase six-pole permanent magnet fault-tolerant motor is our research target. This motor has combined with the advantages of Halbach permanent magnet array structure in the aspect of sinusoidal in unilateral magnetic field and the aspect of magnetic shielding. According to the analysis of working principle of the motor, we determined the phase number, poles number, and the shape of stator slot and rotor magnet steel. Based on the arrangements of rotor magnet steel and the arrangements of winding, and the parameters calculation of magnetic circuit, we obtained the structure parameters of motor with Halbach array, which can make the motor has a small torque ripple and the no-load counter electromotive force has a high sine degree.

II. STRUCTURE PARAMETERS DESIGN OF PERMANENT MAGNET FAULT-TOLERANT MOTOR

Because of the different structure, compared permanent magnet fault-tolerant motor with the traditional permanent magnet synchronous motor, there are many differences in terms of parameter design. In this section, we use a four-phase six-pole permanent magnet fault-tolerant motor as an example, and research the design of motor structure and electromagnetic parameters. The main performance parameters of this motor are as follows: rated power P_N=1*KW*, rated voltage U_N=36*V*, rated speed n_N=1200*rpm*, number of the stator N_s=8, rotor pole pairs *p*=3, number of phase *m*=4, rated efficiency η_N=90%, the rated power factor $cos\psi_N$=0.8.

A. Design of stator inner diameter and core length

The main dimensions of the permanent magnet fault-tolerant motor are specified the inside diameter and the effective axial length of stator core which can be determined according to the need of maximum torque and dynamic response indication[10]. When the biggest electromagnetic torque of motor is $T_{em\max}(N{\cdot}m)$, then the relationship between main dimensions and electromagnetic loads is:

$$T_{em_{\max}} = \frac{\sqrt{2}\pi}{4} B_{\delta 1} L_{ef} D_{i1}^2 A \times 10^{-4} \tag{1}$$

where $B_{\delta 1}$ is the flux density of fundamental amplitude (*T*), *A* is the stator electric load valid value (*A/CM*).

Obtained the relationship between the main dimensions of motor and the electromagnetic loads according to formula (1):

$$D_{i1}^2 L_{ef} = \frac{2\sqrt{2} T_{em_{\max}} \times 10^4}{\pi B_{\delta 1} A} \tag{2}$$

$$A = \frac{mNI_1 K_{dp}}{p\tau} \tag{3}$$

where *m* is the motor phase, *N* is the winding turns, I_1 is the stator current, *p* is the rotor pole pairs, K_{dp} is the winding factor, τ is the motor pole pitch. Here we take power load *A*=150*A/cm*, the flux density of fundamental amplitude $B_{\delta 1}$=0.8*T*.

Because the dynamic response performance index of a permanent magnet fault-tolerant motor mainly refers to the motor that under the effect of maximum electromagnetic torque T_{emmax} can accelerate linearly from rest to turning speed ω_b during time of t_b , that is:

$$T_{em_{\max}} = \frac{J\Delta\omega}{p\Delta t} = \frac{J\omega_b}{pt_b} \tag{4}$$

where *J* is the rotor and load inertia ($kg{\cdot}m^2$).

Therefore, according to formula (4) we can obtain the ratio of maximum electromagnetic torque to the moment of inertia is:

$$\frac{T_{em_{\max}}}{J} = \frac{\omega_b}{pt_b} \tag{5}$$

The moment of inertia of the motor rotor can approach to:

$$J = \frac{\pi}{2} \rho_{Fe} L_{ef} \left(\frac{D_{i1}}{2}\right)^4 \times 10^{-7} \tag{6}$$

where ρ_{Fe} is the mass density of the rotor material iron (g/cm^3).

We take formula (1) and formula (6) into equation (5), can obtain the stator inner diameter D_{i1}(*cm*) is:

$$D_{i1} = \sqrt{\frac{8\sqrt{2} pt_b B_{\delta 1} A}{\omega_b \rho_{Fe} \times 10^{-3}}} \tag{7}$$

Then according to equation (2), we can obtain the effective axial length of the stator core L_{ef}(*cm*) is:

$$L_{ef} = \frac{2\sqrt{2} T_{em_{\max}} \times 10^4}{D_{i1}^2 \pi B_{\delta 1} A} = \frac{10 T_{em_{\max}} \omega_b \rho_{Fe}}{4\pi p t_b B_{\delta 1}^2 A^2} \tag{8}$$

B. Design of groove parameters

Fig .1 shows the block diagram of stator slots of permanent magnet fault-tolerant motor after straightening. From Fig .1, we can know that the parameters which need be calculated include: notch thickness H_{s0}, slot width B_{s0}, stator tooth width B_t and stator tooth height H_{s2}.

Firstly, according to the magnetic saturation constraint conditions of the stator teeth, we obtained the tooth height and the tooth width. Secondly, according to the design requirements of slot leakage inductance, we derived the notch height and width. Finally, in accordance with the requirements of internal winding current density of stator slot, we calculated the other parameters, like the width of the groove bottom B_{s2} and the width of the groove top B_{s1}.

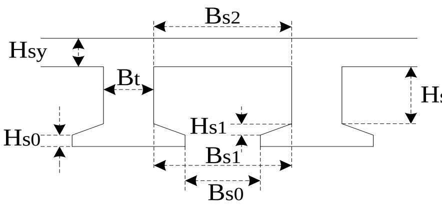


Figure 1. An alveolar structure of stator

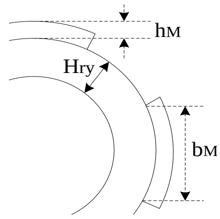


Figure 2. The rotor yoke structure

1) Parameter calculation of stator teeth

Assuming all of the air-gap magnetic flux through the main stator teeth, so the stator tooth width is obtained as follows:

$$B_t = \frac{B_\delta \cdot \alpha_i \tau}{b_{t_{\max}}} \quad (9)$$

where B_δ is magnetic load, α_i is calculated pole arc coefficient.

Because when ferromagnetic material under normal circumstances, the maximum magnetic flux density of the stator teeth b_{tmax} equal to 1.4~1.6*T*, therefore, this article selected b_{tmax}=1.5*T*, and according to formula (9) can derive the stator tooth width B_t.

Generally, the height and width ratio of the stator teeth is between 1.5 and 3. Because, if the ratio is small, the stator slot is very shallow, this may cause very high current density that through the inner winding. But if the ratio is large, then the stator slot is very deep, the stator yoke is easy to reach saturation, and the electromagnetic torque may reduce. So in this paper, we take the value of 2, and the stator tooth height is:

$$H_{s2} = 2B_t \quad (10)$$

2) Calculation of notch parameter

In order to reduce the saturation degree of the stator tooth tip maximum extent, at the same time to improve the slot leakage inductance $L_{s0\sigma}$, the notch thickness H_{s0} generally taken to be (0.35~0.5)B_t, this article is taken as 0.4 times, that is:

$$H_{s0} = 0.4B_t \quad (11)$$

Slot leakage inductance $L_{s0\sigma}$ is:

$$L_{s0\sigma} = \frac{2\mu_0 N^2 (H_{s0} + B_{s0})(L_{ef} + B_{s0})}{B_{s0}} \quad (12)$$

Because the notch width B_{s0} is much smaller than the effective axial length of stator core L_{ef}, therefore, formula (12) can be simplified as:

$$L_{s0\sigma} \approx \frac{2\mu_0 N^2 (H_{s0} + B_{s0}) L_{ef}}{B_{s0}} \quad (13)$$

Rearranging slot width B_{s0} is:

$$B_{s0} = \frac{2\mu_0 N^2 H_{s0} L_{ef}}{L_{s0\sigma} - 2\mu_0 N^2 L_{ef}} \quad (14)$$

where the slot leakage inductance $L_{s0\delta}$ taken as 0.33 times of the coil inductance L_s, and has the following formulas:

$$L_s = \frac{E_0}{\omega_e I_s} = \frac{E_0}{2\pi f_e I_e} \quad (15)$$

$$I_e = \frac{P_N}{mU_N \eta_N \cos\varphi_N} \quad (16)$$

where E_0 is the motor back electromotive force (*V*), ω_e is the electrical angular frequency (*rad/s*), I_s is the steady-state short-circuit current (*A*), I_e is the motor rated current (*A*), f_e is the rated synchronization frequency (*Hz*).

3) Calculation of armature winding turns and coil diameter

The definition of motor no-load back electromotive force(EMF) is:

$$E_0 = 4.44 f_e N k_{w1} \Phi_0 \quad (17)$$

where f_e is the rated synchronization frequency(*Hz*), k_{w1} is the winding factor, Φ_0 is the fundamental magnetic flux air gap(*Wb*), and has the following formulas:

$$\Phi_0 = \frac{2}{\pi} \cdot \left(\frac{4}{\pi} \sin\frac{\alpha_i \pi}{2} B_\delta\right) \cdot \tau L_{ef} \quad (18)$$

So the number of turns of the armature winding *N* is:

$$N = \frac{0.18 E_0 p}{f_e k_{w1} B_\delta D_{i1} L_{ef} \sin(\alpha_i \pi / 2)} \quad (19)$$

According to the dimensions of slot form, we can get the area of stator slots A_s is:

$$A_s = \frac{(B_{s1} + B_{s2}) H_{s2} \sin\theta}{2} \quad (20)$$

where θ is the mechanical angle that relative to the centerline of the pole (*rad*), and:

Width of the top slot is:

$$B_{s1} = \frac{\pi (D_{i1} + 2H_{s0})}{Q} - B_t \quad (21)$$

Width of the bottom slot is:

$$B_{s2} = \frac{\pi\left[D_{i1} + 2(H_{s0} + H_{s1} + H_{s2})\right]}{Q} - B_t \quad (22)$$

where *Q* is the number of stator slots, in order to reduce the degree of magnetic saturation of tooth boots, H_{s1} generally taken as 0.5~1*mm*.

4) Calculation of stator and rotor yoke portion thickness

The thickness of the yoke of stator and rotor needs to meet the constraints of magnetic saturation, for the four-phase six-pole permanent magnet fault-tolerant motor in this article, the maximum value of yoke flux density is 1.6~1.8*T*, which is slightly larger than the maximum limit value of flux density in tooth portion, in this paper the value is 1.6*T*. Then the thickness of the stator yoke portion H_{sy} is:

$$H_{sy} = \frac{1}{2} \frac{b_{\delta m} \alpha_i \tau}{b_{sy}} \quad (23)$$

The thickness of the rotor yoke is:

$$H_{ry} = \frac{1}{2} \frac{B_\delta \alpha_p \tau}{b_{ry}} \quad (24)$$

where b_{sy} is the flux density of stator yoke portion (*T*), b_{ry} is the flux density of rotor yoke portion (*T*).

C. Magnetic circuit design

Magnetic circuit design includes the determination of overall structure, the determination of sizing and the selection of material, which focuses on the work of choosing permanent magnetic materials and designing the operating point.

1) Permanent magnet material selection

In this paper, we chose NdFeB *N38H* as the permanent magnet material, the remanence density B_{r20} is 1.23*T*, the temperature coefficient α_{Br} is 0.12 %/℃, the irreversible demagnetization loss *IL* is 0.7%, the calculated coercive force of permanent magnet H_{c20} is 899*kA/m*.

We can obtain following results according to the selection of NdFeB *N38H*:

(1)Remanent flux density during the operating temperature:

$$B_r = [1+(t-20)\alpha_{Br}/100]\times[1+IL/100]B_{r20} = 1.18T$$

(2)Calculated coercive force during the operating temperature:

$$H_c = [1+(t-20)\alpha_{Br}/100]\times[1+IL/100]H_{c20} = 833.7kA/m$$

(3)Relative permeability of the permanent magnet:

$$\mu_r = \frac{B_{r20}}{\mu_0 H_{c20}\times 1000} = 1.089$$

where μ_0 is vacuum permeability, $\mu_0=4\pi\times10^{-7}H/m$.

2) Determine the shape of permanent magnet

Surface magnetic pole structure can improve the ability of isolation between the windings, in this article we use the surface-type tile-shaped magnetic poles in the permanent magnet fault tolerant motor, shown in Fig .3. The structure of permanent magnet contacting the air gap directly is easy processing and installation. And uses a concentric tile-shaped magnetic poles, i.e., the outer diameter and the inter diameter of the permanent magnets have a common center, it shown as in the Fig .4.

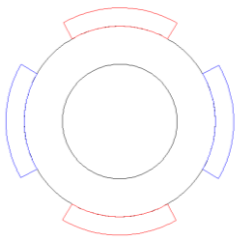


Figure 3. Surface tiles pole

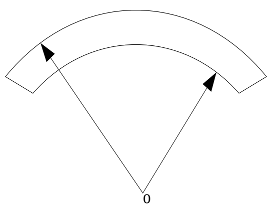


Figure 4. Concentric magnetic tiles

3) Calculate the size of permanent magnet

The main size parameters of permanent magnet part include the thickness and the width of permanent magnet, and can be determined by the following formula:

The thickness of permanent magnet h_M is:

$$h_M = \frac{\mu_r}{\frac{B_r}{B_\delta}-1}\delta_i \quad (25)$$

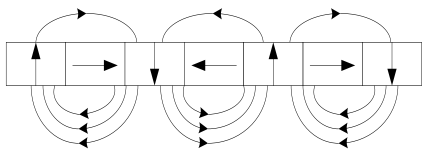
The width of permanent magnet b_M is:

$$b_M = \alpha_p \tau \quad (26)$$

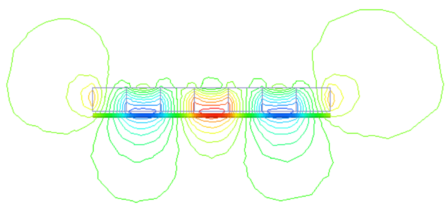
where μ_r is the relative permeability of ferromagnetic material; δ_i is *the* calculating air gap length of motor(*cm*); B_r is the residual magnetic induction intensity of permanent magnet (*T*); B_δ is the magnetic load (*T*); α_p is the percentage of pole embrace. Generally B_r/B_δ equal to 1.1~1.35.

4) Permanent magnet magnetization way of design

In this paper, the arrangement of permanent magnet is in the way of Halbach array[11], this kind of arrangement can not only enhance the air gap flux of motor, but also can weaken the magnetic flux of rotor yoke, which is particularly suitable for the rotor structure of using surface-mounted permanent magnet. Halbach array is a novel magnetic structure array that combines radial array with tangential array, as Fig .5(a) shows, so that we can make the magnetic field in one side of permanent magnet strengthening and the other side weakening. The rational design of Halbach array can make the air-gap flux density and the no-load back electromotive force having good sinusoidal.



(a) Halbach array structure diagram



(b) The distribution of magnetic force lines

Figure 5. Magnetic field distribution of Halbach array structure

Fig .5 (b) shows the distribution of magnetic equipotential line of the permanent magnet motor with Halbach array which is calculated by the ANOSOFT which is one of the finite element analysis software. As we can see, after using Halbach array, the magnetic flux of rotor yoke significantly reduced, while the magnetic flux that across air gap into the stator significantly increased, which increases the magnetic load of permanent magnet motor and the density of force and energy, so Halbach array is very suitable for the ideal for the permanent magnet fault-tolerant motor with the inter rotor structure of permanent magnet posted outside.

TABLE Ⅰ. PARAMETERS OF 1KW FOUR-PHASE SIX-POLE PERMANENT MAGNET FAULT-TOLERANT MOTOR

Rated voltage/*V*	36	Rated speed/r.min^{-1}	1200
Magnet Material	NdFe N38H	Stator and rotor material	DW310-35
Outside stator diameter/*mm*	131.2	Inside stator diameter/*mm*	65.6
Stator tooth width/*mm*	11.4	Stator yoke thick/*mm*	5.4
Inside rotor diameter/*mm*	64	Rotor yoke thick/*mm*	11.5
Magnet thickness/*mm*	8.7	Stator core length/*mm*	139.3
Notch thickness/*mm*	4.6	Percentage of pole embrace	0.64
Gap length/*mm*	0.8	Winding turns of per phase	36

Through the simulation of ANSOFT software, we determined to use the Halbach array with two pieces of permanent magnet per pole, and the radian numbers of these two pieces of permanent magnet are 35° and 25°. Because we can get the highest sinusoidal waveform of no-load back electromotive force with this radian. According to the design results of this motor, we got the parameters of this 1*KW* four-phase six-pole structure permanent magnet fault-tolerant motor that listed in Table 1.

III. EXPERIMENTAL TESTING OF THIS MOTOR

Based on the permanents of motor size that designed before, We manufactured a 1*KW* experimental prototype of this four-phase six-pole permanent magnet fault-tolerant motor. The external appearance is shown in Fig .6.

(a) External appearance of motor

(b) Rotor of motor

Figure 6. A 1KW four-phase six-pole permanent magnet fault-tolerant motor

Fig .7 is an actual measured waveform of one phase no-load back electromotive force. From this figure, we can know that the sinusoidal of this waveform displayed very well, so the motor design is reasonably and accurate which laid a good foundation for the control research of fault-tolerant motor.

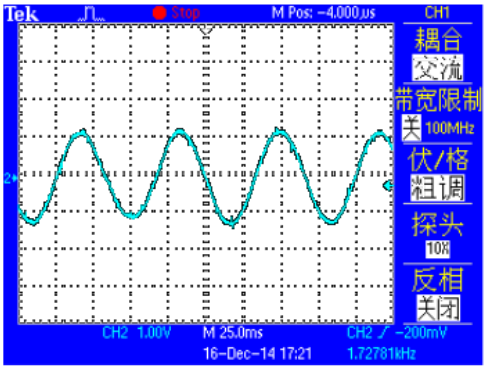


Figure 7. One phase no-load back electromotive force waveform

IV. CONCLUSION

In this paper, for the requirement of power-driven applications with high-reliability, we have researched and designed one kind of permanent magnet motor of four-phase six-pole structure with Halbach array. Based on the characteristics of the motor structure and the analysis of fault-tolerant mechanism, and combined with the principles of electromagnetism and design method of Halbach array, we calculated the main dimensions and the electromagnetic parameters of the 1*KW* permanent magnet fault-tolerant motor. And through the experimental testing of this motor, we also verified the correctness and rationality of this motor design process.

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