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Field Circuit Coupling Optimization Design of the Main Electromagnetic Parameters of Permanent Magnet Synchronous Motor

Guang-Xu Zhou*,, Ren-Yuan Tang**, Dong-Hee Lee* and Jin-Woo Ahn†**

Abstract – The electromagnetic parameters of a permanent magnet synchronous motor (PMSM) such as the open load permanent magnet flux, d axis reactance X_d, and q axis reactance X_q , are most essential to the performance analysis and optimization design of the motor. Based on the numerical analysis of the 3D electromagnetic field, the three electromagnetic parameters of permanent magnet synchronous motors with U form interior rotor structures are calculated by FEA. The rules of the leakage coefficient and reactance parameters changing with the air gap length, permanent magnet magnetism length, and isolation magnetic bridge dimensions in the rotor are given. The calculated values agree well with the measured values. The FEA results are integrated with the self compiled electromagnetic design program to optimize the prototype motor. The tested performances of the prototype motor prove that the method is suitable for the optimization of motor structure.

Keywords: Field circuit couplingm, Optimization design, Main electromagnetic parameter, Permanent magnet synchronous motor(PMSM), Pump system.

1. Introduction

PMSMs possess many merits such as high efficiency, long life, compact size, light-weight, and simple structure [1]. They also have some beneficial characteristics such as high precision and high ratio of speed adjustment precision. As such they are used in more and more factory fields. The capability of output torque, power factor, and efficiency is the important performance of the adjustable speed PMSM. When the applied condition is confirmed, three main electromagnetic parameters [2-3], the open load permanent magnet flux, d axis reactance X_d, and q axis reactance X_q are highly influential on the motor operation performance.

The electromagnetic power formula of interior adjustable speed PMSM is as follows:

$$T_{em} = p\{\psi_f i_q + (L_d - L_q) i_d i_q\} \tag{1}$$

From (1), we can see that three main electromagnetic parameters have obvious influence on the system performance. As for speed adjustment of the PMSM, the exact calculated reactance parameter is very important for realizing the control algorithm and is necessary to predict steady state and transient characteristics of the PMSM. When the stator structure is invariable, heightening the ratio of X_{aq} and X_{ad} by changing rotor structure can improve the system power factor and efficiency. Rational parameter design is the core of the successful design of the PMSM.

For the medium capacity variable speed high efficiency permanent magnet synchronous motor (PMSM) such as 200kW or 300kW, to obtain a good cooling effect, there are radius channels and axis holes inside the motors. At present, the influences of radius channels and core length on no-load leakage coefficients are difficult to obtain with existing calculation methods. This has resulted in the blind choice of no-load leakage coefficient while designing the motors, thereby prolonging the course of research and development (R&D), increasing the cost of R&D, and proving a lack of scientific basis in design optimization and performance simulation. All of this has influence on the application of the PMSM. So as for the medium capacity, the exact no-load leakage coefficient of the PMSM is more essential to the optimal design of the motor than the size of the motor.

Due to the effect of permanent magnet material, the reactance parameters calculating method is different from other AC machines. For the PMSM there are no open circuit and short circuit states like the electrical excited motor. The excitation of permanent magnet material is effected at all times. At the same time, different magnetic motive force and field saturation of the reactance parameters are different. The parameter calculating method must take the influence of PM material into account.

Based on the above reasons, the traditional circuit calculating method is not fit for the PMSM. So the finite element method is applied to calculate the parameters σ_0, X_{ad} and X_{aq}. σ_0 is the no-load leakage flux coefficient.

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In this paper the 3D electromagnetic field is used to obtain the exact parameters of the U form medium capacity PMSM[4-6]. Through analyzing the electromagnetic parameter changing with the structure, the detailed experience data and curve can be obtained. Finally, rules of the three main electromagnetic parameters are integrated with the self compiled electromagnetic design program to optimize the prototype motor, providing a good foundation for designing and applying of the PMSM.

2. No load leakage flux coefficient

In this part, Ansoft is used to calculate the no-load leakage coefficient of U form interior PMSM. On the basis of the calculations of many PMSM's, the change law and influence factor of the no-load leakage coefficient with motor structure parameters are analyzed, and the curve of a different structure dimension is given.

Fig. 1 is the Cross section of Multi-segment U form rotor structure. Fig. 2 is the U form magnetic circuit structure separate magnetic bridge diagram. Fig. 3 is the solved magnetic density of the PMSM.

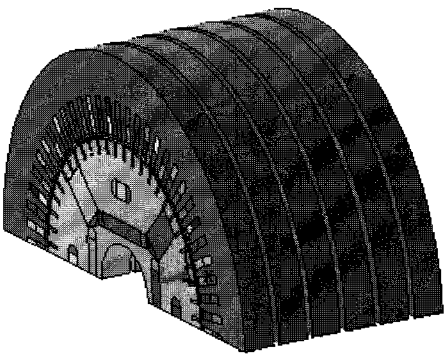

Fig. 1. Cross section of Multi-segment U form rotor structure

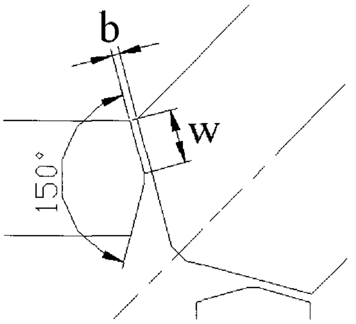

Fig. 2. U form circuit structure separate magnetic bridge diagram

2.1 Motor modeling

During the calculating process of the electromagnetic parameter that is solely based on the exact analysis model of a motor analysis model, we can obtain a valid simulation result. Therefore, a 3D FEA model is established as follows:

1) *According to the motor structure dimensions, the motor simulation model is established.*
2) Confirm the material attribute;
3) Ensure the boundary condition and outside source parameter;
4) Mesh;
5) Setting the resolve parameter, calculate.

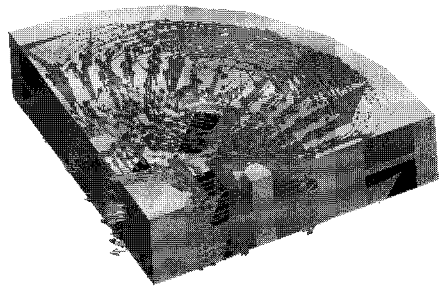

Fig. 3. Solved magnetic flux density of PMSM

2.2 FEM analysis results of leakage flux coefficient

Fig. 4 is the σ_0=f (δ, h_m) curve. δ is the air gap length, and h_m is the length of the permanent magnet material. Fig. 5 is the no-load leakage coefficient change with magnetic bridge length w of the proposed U form motor. Fig. 6 is the no-load leakage coefficient change with magnetic bridge width b.

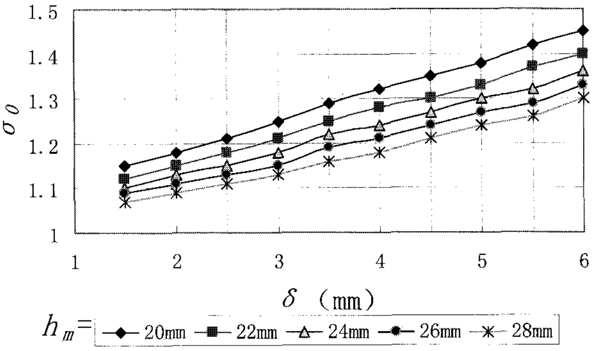

Fig. 4. U form σ_0=f(δ, h_m) curve

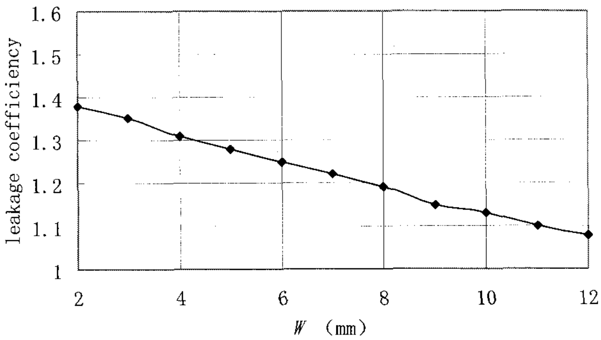

Fig. 5. σ_0 change with magnetic bridge length w

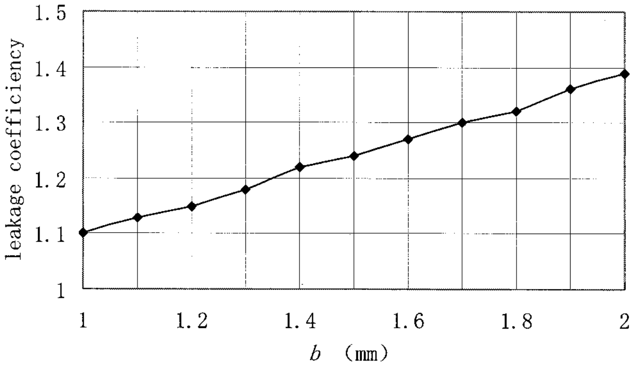

Fig. 6. σ_0 change with magnetic bridge width b

3. Influence of Structure Dimension on Reactance Parameters

As for the X_{ad}, the air gap fundamental flux ϕ_{10} and the effective air gap fundamental flux can be attained when the direct axis armature current is equal to the I_d.

$$X_{ad}=\frac{4.44fK_{dp}N|\phi_{10}-\phi_{1N}|}{I_d} \tag{2}$$

As for the reactance X_{aq}, directly give the winding current I_q, and resolve the air gap flux ϕ_{aq}.

$$X_{aq}=\frac{4.44fK_{dp}N\phi_{aq}}{I_q} \tag{3}$$

Where K_{dp} is the waveform coefficient of flux. From the above 3D FEA results, the *d-q* axes reactance parameters are calculated by a self compiled program in matlab software.

3.1 Influence of air gap length and the magnetism length on reactance

This section presents the *d-q* axes reactance X_{ad} , X_{aq} curves variation with air gap length and permanent magnet magnetism length.

Fig. 7 and Fig. 8 are the curve of *d-q* axes reactance parameter X_{ad}, X_{aq} variation with the air gap length δ and the permanent magnet magnetism length of U form rotor. From Fig. 7 we can see with the increase of h_m, X_{ad} becomes increasingly smaller; with the increase of h_m and the influence of δ on X_{ad} it becomes increasingly weaker. The reason for this is that *d* axis armature reaction flux passes through the PM material. The magnetism permeability of the *d* axis is reduced with the increase of the h_m, and then the X_{ad} is decreased. Generally, with the increase of δ, the X_{ad} becomes lower, but with the increase of h_m, it becomes more effective on X_{ad} than air gap δ. The influence of h_m and δ on X_{aq} has some slight difference compared with the X_{ad}. This is because of a small amount of flux passing through the PM. The influence of air gap length on X_{aq} is higher than X_{aq}. As for the *q* axis reactance X_{aq}, it is mainly influenced by the air gap.

Fig. 7 and Fig. 8 indicate that with the increase of δ, the reduction in X_{aq} and X_{ad} are very obvious. It shows that rational selection δ is very important.

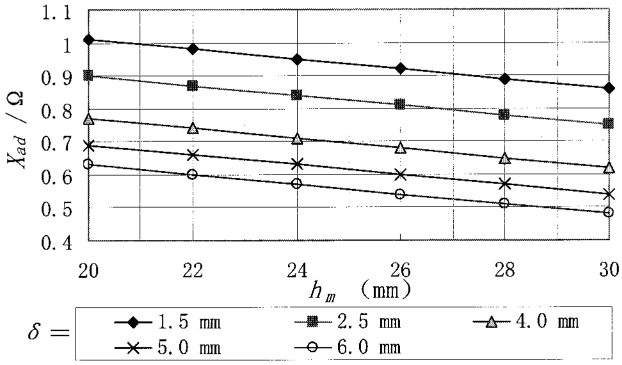

Fig. 7. $X_{ad}=f(h_m,\ \delta)$ curve

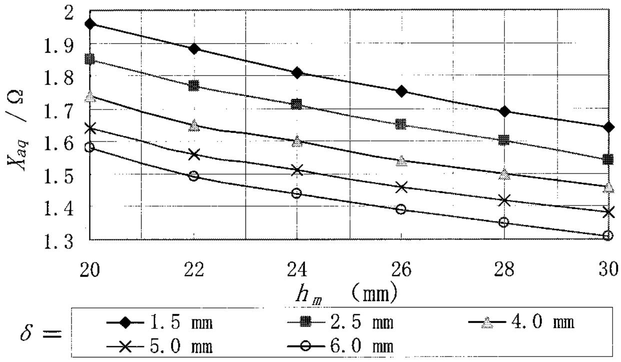

Fig. 8. $X_{aq}=f(h_m,\ \delta)$ curve

3.2 Influence of magnetic bridge on reactance

Fig. 9 shows reactance parameters X_{ad} and X_{aq} and their variation with the separate magnetic bridge dimension in the proposed U form rotor structure.

From the above figures we can see that the X_{ad} of U form is decreased by 5.8% when the bridge length changes from 2 mm to 12mm. X_{aq} of U form is decreased by about 2.8% when the bridge length changes from 2 mm to 12mm. The influence of bridge length on the reactance parameter is achieved.

At the same time when the bridge width b changes from 1mm to 2mm, the X_{ad} of U form is increased 6.1%. The X_{aq} of U form changes 8.3%.

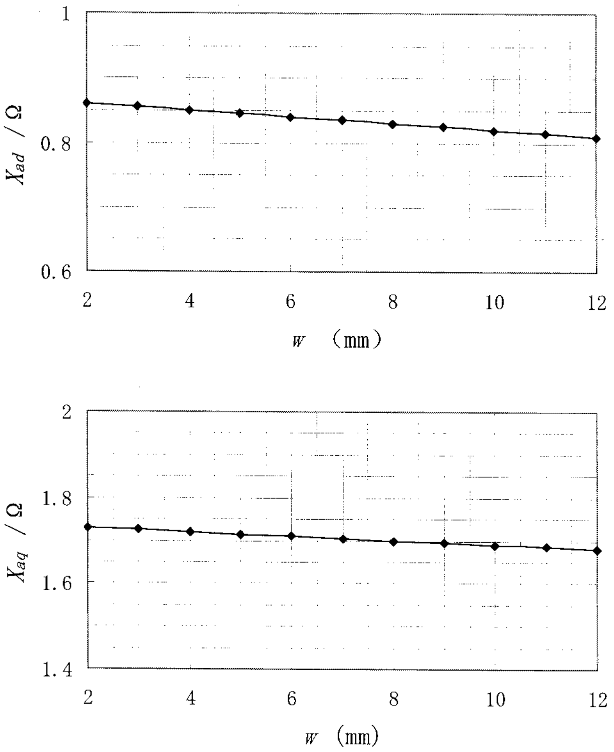

Fig. 9. X_{ad} and X_{aq} variation with magnetic bridge length w

3.3 Comparison between simulation and measured of reactance

For validating the veracity of the FEA results, the voltage integral method [7-9] is adopted to measure the reactance parameters of different types of PMSMs. From the compared results in Table I between FEA and measured data of different types of PMSMs, it can be seen that the calculated values agree with the measured values very well. It is proved that the proposed method is feasible.

Table 1. Comparison of different rotor structure

Motor	Rotor structure	Calculated		Measured		Error /%	
		X_{ad}/Ω	X_{aq}/Ω	X_{ad}/Ω	X_{aq}/Ω	X_{ad}	X_{aq}
120-6	radial	38.58	101.15	36.85	98.52	4.69	2.67
180-4	tangential	28.74	55.17	29.75	57.62	-3.39	-4.25
180-6	tangential	29.36	69.18	29.52	69.32	-0.54	-0.20
370-6	tangential	14.81	39.23	15.45	38.54	-4.14	1.79
2500-6	W shape	14.02	14.29	13.52	14.57	3.69	-1.92
135000-4	U shape	0.79	1.37	0.82	1.39	-3.66	-1.44
200000-4	U shape	1.51	2.54	1.47	2.50	2.72	1.60
300000-4	U shape	0.88	1.68	0.84	1.71	4.76	-1.75
300000-4	W shape	0.82	1.49	0.78	1.46	5.12	2.05

4. Field circuit coupling optimization design and prototype motor manufacture

Through the 3D electromagnetic field analysis of U form rotor magnetic circuit structure, the no-load leakage coefficient and d-q axes reactance variation rules with rotor dimensions are obtained.

Several kinds of electromagnetic design strategies are presented. When designing isolation magnetic bridges and reactance parameters, based on the influence of parameter change on motor performance, the following rules will be used for instructing the proper selection of rotor structure: 1) reduce the leakage flux coefficient as low as possible, such as by adopting the stainless sheet at the terminal of the rotor. 2) Rationally design the no-load EMF to enhance the stall torque and overload ability, and let the motor have high power factor. 3) Increase the ratio of X_{aq}/X_{ad} (salient ratio) to make the best use of reluctance to enhance the power factor. 4) In view of the manufacturer's craftwork and mechanism strength of the rotor silicon steel sheeting, the dimensions of the rotor bridge should be in accordance with the following value: the width b=1.15~1.75mm, the length w≥5mm.

The key stone of the field circuit coupling method is calculated by the torque-speed curve at pump load. First, the change rule of three electromagnetic parameters is obtained by the 3D FEM, and then other operation characteristics are calculated by the self compiled electromagnetic program. Fig. 10 is the flow chart of field circuit coupling optimization design. Fig. 11 is the 300kW motor stator. Fig. 12 is the 300kW motor rotor. Fig. 13 is the tested results of efficiency and power factor at pump load.

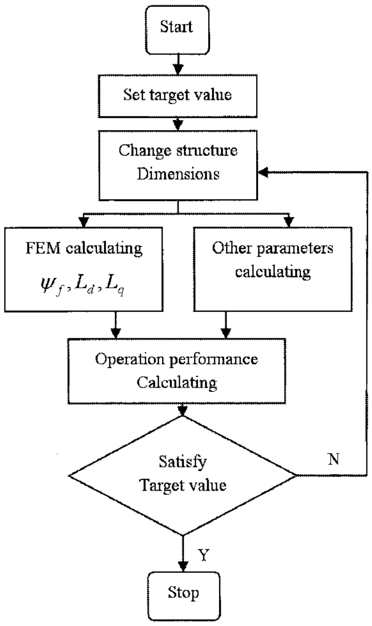

Fig. 10. Flow chart of field circuit coupling optimization design

From Fig. 13 we can see that the 300kW prototype motor efficiency is higher than 88.6%, and power factor is higher than 0.96 under the pump application in the entire running scope.

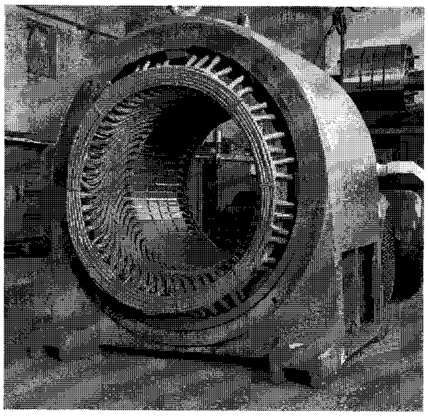

Fig. 11. Prototype of 300kW motor (stator)

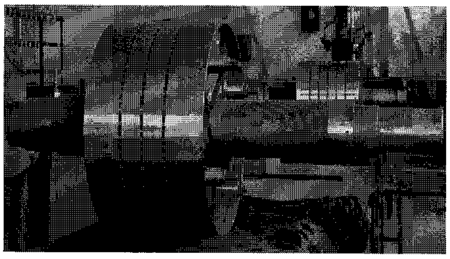

Fig. 12. Prototype of 300kW motor (rotor)

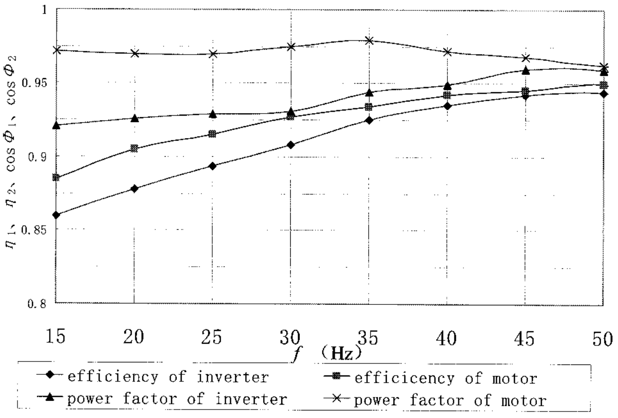

Fig. 13. Efficiency and power factor with pump load

5. Conclusion

In this paper three electromagnetic parameters of the U form interior PMSM are calculated by the Ansoft software. On the basis of the calculations of PMSM no-load leakage coefficient, the change law and influence factor of the no-load leakage coefficient with motor structure parameters are analyzed. Then the reactance parameters of the U form interior PMSM are calculated by the Ansoft software. The calculated result is in good accord with the tested result. This proves the method can be used to instruct the selection of rotor structure. Based on the above analysis, the rule of the reactance parameters changing with the gap length and permanent magnet magnetism length of the permanent magnet synchronous motors is given. At last, a variable speed high efficiency prototype PMSM is designed and manufactured. Experimental results of the whole system including the PMSM and general inverter prove the field circuit coupling method is effective.

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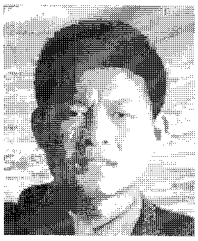

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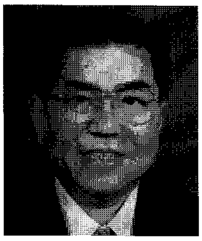

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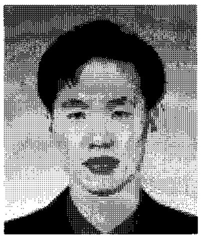

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