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Calculation of Iron Loss of Medium-sized High Voltage Motor which Have Axial Ventilation Holes in Rotor

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Abstract. When optimizing the ventilation and cooling system of medium-sized high power density asynchronous motor, it is found that the temperature rise of the motor can be greatly reduced after punching the axial ventilation holes in the rotor yoke, but the traditional method based on the magnetic circuit method cannot accurately calculate the motor iron loss of this new structure. In this paper combined with the finite element field-circuit-motion coupled analysis method, taking YXKK355-4, 355kW and YKK400-4, 400kW medium-sized high voltage asynchronous motor for example, a two-dimensional geometric model and mathematical model of the motor are established, then the iron loss calculation method is improved. Using this method not only the iron loss value of the whole motor can be obtained, but also the specific distribution of iron loss in different areas of the motor can be known, and the correctness of the simulation results is proved by experiments.

1. Introduction

With the increasing capacity of motor, the optimization of ventilation system becomes more and more important. It is the first choice for the air cooling motor with high power and heavy load to adopt the hybrid structure because of better cooling effect. At present most of research only focus on the cooling effect of the ventilation structure of motor, according to the literature[1-2], it is pointed out that the axial ventilation holes in the rotor yoke can effectively limit the temperature rise of high power density motors and improve the reliability of motor operation. We have a try on YXKK355-4, 355kW and YKK400-4, 400kW two kinds of motors in the rotor yoke opening axial ventilation holes. Through the experimental findings, the temperature of the stator winding of the motor is decreased by about 8 degrees after opening holes, and the temperature of the rotor bar is decreased by about 11 degrees. But there are few papers on how to calculate the iron loss of the hybrid ventilation structure, especially for the axial opening holes in the rotor yoke.

The traditional method for calculating iron loss assumes that the magnetic flux density even distribution in each section within the equivalent magnetic circuit, only the magnetic density of a certain segment in the stator and rotor of the tooth and the yoke is used. This method is used to calculate the whole machine iron loss. However, the internal magnetic field distribution is very complex. The traditional method is only suitable for the estimation of the motor iron loss with only the radial ventilation ducts. This method is no longer for motors with radial ventilation channel coupled rotor axial ventilation holes, nether are more detailed iron loss in each region of the motor. A more accurate calculation of iron loss and specific distribution at the stage of motor design, it is of great significance to the arrangement of the axial vent holes in the rotor yoke and improve the ventilation hole structure to reduce the loss.

2. Motor model

To express simplicity, in this paper the motor with only radial ventilation duct structure is named radial ventilation structure of motor. The motor with radial ventilation channel coupled rotor axial ventilation holes is named hybrid ventilation structure motor. Its structure is shown in Figure 1.

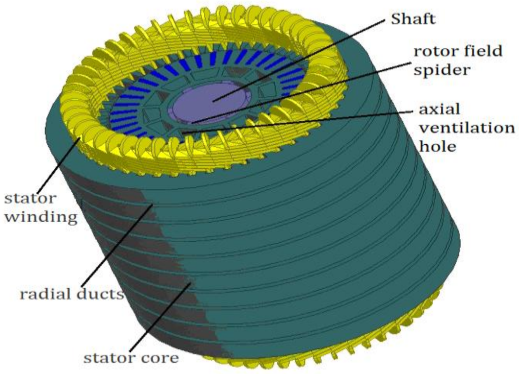

Figure1. Physical model of hybrid ventilation structure

In this paper, the number of radial ventilation ducts is 11, width of 10mm. All the radial ventilations of stator and rotor iron core are aligned, and the rotor bracket and the opening holes of the rotor yoke form a double shaft ventilation duct of the motor.

2.1. Computational model

Obtaining the motor data of hybrid ventilation structure from an enterprise, the main dimensions of the motor, such as: motor axial length is 550mm; the inner and outer diameters of the stator are 380mm, 620mm; the single side air gap length is 1.6mm; rotor inner diameter is 160 mm; the number of stator and rotor slots are 48 and 38. The shape of the vent hole is shown in Figure 2. The quantity is 12. All of axial ventilation holes are equally distributed along the circumferential direction in the rotor yoke. The distance between W2 and the center of shaft is 93mm. Specific dimensions are as follows: W1 is 52mm; W2 is 22mm; H1 is 32mm; R0 is 2.5mm.

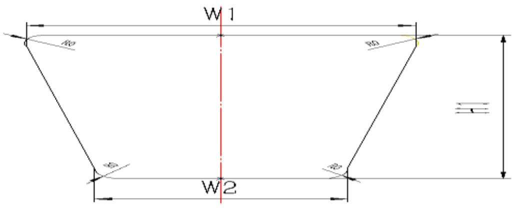

Figure2. Axial vent hole size marking

In this paper, the influence of axial ventilation holes on the iron loss of the motor is mainly studied, so the influence of the end is ignored to simplify the calculation. The motor is divided into finite elements, each of which is triangular, as shown in Figure 3.

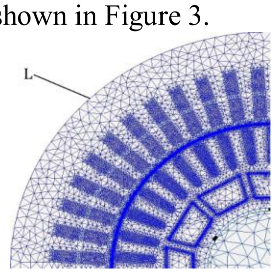

Figure3. 1/4 of motor model finite element meshing mesh

In the two-dimensional field, the vector magnetic potential only have axial component. The boundary of the model is the circumference of the stator. The mathematical model of the two-dimensional transient field and the boundary condition for the motor are as follows:

$$\begin{cases} \frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{y}\right)=-J_s+\gamma\frac{\partial A_z}{\partial t} \\ A_z\big|_{\Gamma_L}=0 \end{cases} \quad (1)$$

In this formula: axial component of magnetic vector is A_z; electrical conductivity is γ; source current density is J_s; magnetic conductivity is μ.

3. Calculation of iron loss

The calculation model of iron loss has been explored since 1890s. The hysteresis loss model was first proposed by Steinmetz in 1892. In 1924, Jordan further divided ferromagnetic materials into hysteresis and eddy current loss. Until now this conclusion has been widely recognized in the academic circles, and a large number of the calculation methods about iron loss are based on the above theory. There are many methods for calculating iron loss, but they can be classified in two main categories: algorithm based on magnetic circuit and algorithm based on finite element.

When the ferromagnetic material is subjected to an alternating magnetic field, hysteresis and eddy current loss occur in the iron core of the motor. And the variation of the magnetic flux density B and the magnetic field intensity H is shown in Figure 4 (a) in curve O→P→Q→R→S→T→O. When H increases (decreases), B does not decrease (increase), and the energy loss caused by this process is called hysteresis loss. Eddy current loss is due to the electrical conductivity of the ferromagnet[3]. When it is in an alternating magnetic field, the material will be induced eddy current, resulting in the Joule heat consumption of energy, as shown in Figure 4(b).

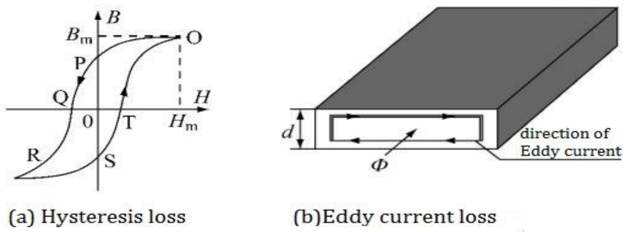

Figure4 . Hysteresis and eddy current loss mechanism

3.1. Algorithm based on magnetic circuit

For the yoke iron loss:

$$P_{Fej}=k_{aj}\times p_{10/50}\left(\frac{f}{50}\right)^{1.3}B_j^2G_{Fej} \quad (2)$$

In this formula: G_{Fej} is weight of yoke; kg, B_j is the value of maximum magnetic flux density; T, $p_{10/50}$ indicates loss of unit weight in silicon steel when $f=50Hz$ and $B=1T$; the value can be found in the manual according to the specific model of silicon steel sheet, k_{aj} representation of empirical coefficients; in this paper $k_{aj}=1.3$.

For the tooth of iron loss:

$$P_{Fei}=k_{ai}\times p_{10/50}\left(\frac{f}{50}\right)^{1.3}B_i^2G_{Fei} \quad (3)$$

In this formula: G_{Fei} is weight of tooth; kg, B_i represents the average value of the magnetic flux in the magnetic circuit of the tooth; T, the meaning of $p_{10/50}$ is consistent with the above, k_{ai} representation of empirical coefficients; in this paper k_{ai} is 1.8.

The traditional algorithm is used to calculate the iron loss of the high voltage motor YXKK355-4, 355kW and YKK400-4, 400kW of hybrid ventilation structure, and compared with the experimental value, as shown in Table 1.

Table1. Comparison of calculated values of iron loss with experimental values

Rated power	Iron loss（W）		Deviation
	calculated value	trial value	
355kW	7613.63	9230.25	17.5%
400kW	6988.15	8030.11	13.0%

It is obvious that the traditional algorithm based on magnetic circuit is no longer suitable for the motor with axial ventilation holes. Based on the finite element analysis method, we cannot only consider the influence of the saturation of the core, harmonic and other factors on the internal magnetic field of the motor, but also can analyze and calculate the specific structure in detail.

3.2. Algorithm based on finite element

In 1988, *Bertotti* put forward the constant coefficient three term calculation model, which is widely used at present[4]. In this paper, based on the finite element model of iron loss calculation is made on the basis of combining with the actual improvement. The iron loss calculation model proposed by Professor *Bertotti* is as follows:

$$P_{Fe} = k_h B^{\alpha} f + k_e (Bf)^2 + k_a (Bf)^{1.5} \qquad (4)$$

In this formula: k_h is hysteresis loss coefficient; k_e is eddy current loss coefficient; k_a is the abnormal loss coefficient; α is called the *Steimmetz* coefficient, with the method of Epstein frame and ring samples can be measured and its value; the values of k_h and k_a are fitted by measured data of silicon steel sheet; $k_e = \pi^2 \gamma d^2 (6\rho)^{-1}$, ρ is the density of silicon steel sheet, kg/m^3; d is the thickness of silicon steel sheet, m; γ is the electrical conductivity of silicon steel sheet, s/m.

This model cannot be used to analyze the influence of axial ventilation holes on the iron loss of the whole machine, and it also doesn't put up a clear theory of how to deal with the non- sinusoidal and rotational magnetization of magnetic flux[5].

Combined with the finite element analysis method, this paper presents the application of the model to each mesh unit. So we cannot only find out the total core loss, but also analyze the position specific analysis. By using the transient field, we can obtain the magnetic flux density at any time of each mesh unit. The Fourier Function is used to decompose it into a fundamental wave and a series of harmonics[6-7]. The maximum value of magnetic density is $B_{\max}$ and the minimum value is $B_{\min}$. Calculation of hysteresis loss caused by rotating magnetization by introducing a coefficient k_x, $k_x = 1 + |B_{\max}| / |B_{\min}|$. Abnormal loss value is very small. Each mesh unit is smaller after split. In order to prevent the accumulation of errors in computation, the overall solution is used to solve the abnormal loss.

Taking the stator core as an example, we suppose that the stator core has a total of n mesh units, sum of all units. The calculation formula of core loss is obtained.

$$P_{Fe}=\left\{k_e\sum_{i=1}^{n}\sum_{j=1}^{v}kf_j^2\Delta_i\left[\left(\left(B_r^i\right)_j\right)_i^2+\left(\left(B_\theta^i\right)_j\right)_i^2\right]+k_h\sum_{i=1}^{n}\sum_{j=1}^{v}kf_j\Delta_i k_x\left[\left(\left(B_r^i\right)_j\right)_i^\alpha+\left(\left(B_\theta^i\right)_j\right)_i^\alpha\right]+k_a\left(\sum_{1}^{v}f_jB_{\max}\right)^{1.5}\right\}l\rho \quad (5)$$

In this formula: v indicates the number of harmonics; f_j is the corresponding frequency of high order harmonic; B_r^i , B_θ^i are the amplitudes of the normal and tangential components of the corresponding i mesh elements; l and ρ are the axial length of iron core and the density of silicon steel; Δ_i is area of the corresponding i mesh elements; $B_{\max}$ is the maximum value of the magnetic density. k is the correction factor when considering the machining process and the non-sinusoidal magnetic density. By using the formula (5), we can get the value of iron loss in different position of the motor. The results are shown in Table 2 and Table 3.

Table2. YXKK355 kW Calculation value of iron loss of hybrid ventilation structure (W)

Stator yoke		Stator tooth		Rotor yoke		Stator tooth		Stator abnormal loss	Rotor abnormal loss
Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss		
4062.65	1087.21	2147.06	635.99	247.97	72.22	619.48	195.89	17.36	7.16

Table3. YKK400 kW Calculation value of iron loss of hybrid ventilation structure (W)

Stator yoke		Stator tooth		Rotor yoke		Stator tooth		Stator abnormal loss	Rotor abnormal loss
Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss	Hysteresis loss	Eddy current loss		
3576.71	941.82	1916.98	630.24	132.41	44.83	475.63	165.52	21.52	11.23

The distribution of iron loss in the whole motor is shown in Figure 5. The results show that the maximum value of YXKK355kW iron loss per unit area in Stator tooth; the value is $8.22W/kg$. The rotor iron loss of this motor mainly concentrated in the tooth, ventilation holes near the iron loss is small. The iron loss of the rotor tooth is 815.37W, which accounts for 71.8% of the rotor iron loss. The iron loss near the ventilation hole is 110.31W, which accounts for 9.7% of the rotor iron loss; the rotor iron loss accounts for about 8.97% of the total iron consumption of the analyzed motor.

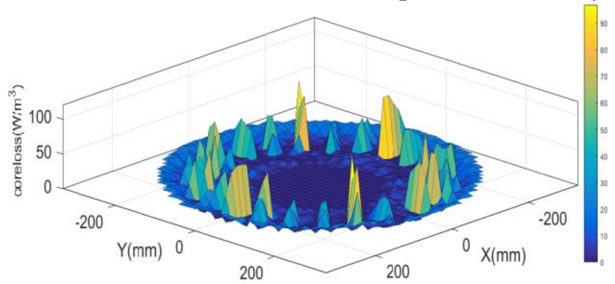

Figure5. YXKK355kW Global distribution of iron loss of hybrid ventilation structure

3.3. Comparison between simulation results and experimental values

In order to explore the rationality of numerical calculation, YXKK355-4, 355kW and YKK400-4, 400kW motor were tested. The measured data of multiple groups were obtained, and the average value was taken as the experimental result.

Table4. Comparison of simulation results and experimental values

Motor	Core loss（W）	Deviation

		calculated value	trial value	
355kW	radial ventilation structure	8557.34	8689.57	1.52%
	hybrid ventilation structure	9092.99	9230.25	1.49%
400kW	radial ventilation structure	7414.46	7552.67	1.83%
	hybrid ventilation structure	7916.89	8030.11	1.14%

The calculated value and trial value in Table 4 are the iron loss of the whole machine. The comparison of the data shows that the proposed method is accurate and meets the requirement of engineering calculation.

4. Conclusion

Through the simulation analysis, the distribution of motor iron loss which have axial ventilation holes in rotor is obtained. The iron loss in different areas of the motor is sorted from large to small: stator yoke, stator tooth, rotor tooth, ventilation hole and near shaft end. The unit area iron loss in different regions is from large to small: stator tooth, rotor tooth, stator yoke, ventilation holes and near shaft end. The rotor iron loss is greatly affected by harmonics, which is mainly concentrated in the rotor tooth.

The opening holes of the rotor yoke increases the amplitude of the harmonic wave and the magnetic flux leakage. However, traditional algorithms have some defects in dealing with these problems. This is the main reason that traditional algorithms cannot be accurately calculated[8-9].

5. Appendices

Calculation of iron loss based on the magnetic circuit method comes from this paper the first author, Professor Meng Da-wei who is the chief editor of the large and medium-sized three phase induction motor electromagnetic performance calculation software. The iron loss algorithm based on finite element. First of all, the magnetic flux density is extracted by MAXWELL simulation software produced by ANSYS company. Then MATLAB is used to process data.

Acknowledgments

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