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Fan characteristics of the self-support components of rotor ends and its performance matching ☆

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ABSTRACT

In order to perform a comprehensive study on the ventilation characteristics of an induction motor rotor end's self-support components, and specify the relationship among its size, structure, motor loss and cooling performance, in this paper a 3D physical model of the rotor, stator and motor shell was established according to the characteristics of the total enclosed fan-cooled (TEFC) induction motor. Then the fluid field and temperature field of the TEFC induction motor was solved by combining finite volume method (FVM) and the basic principles of electric machine. By taking the rotor air friction loss and stator end windings temperature rise into consideration and comparing various solutions, the optimum solution to the length of the self-support components was determined, which provided a reference for the optimization of the motor rotor physical construction.

1. Introduction

As the major driving force machinery in industrial production, the TEFC induction motor is used widely due to its favorable features, such as its simple structure and safe operation. However, the power consumption of the TEFC induction motor accounts for nearly 60% in the whole industrial production. If the efficiency of all the running induction motors can be improved by 1%, billions of kW h will be saved each year. Therefore, decreasing the loss of each part of the motor and improving its efficiency are very important. The machine loss mainly includes bearing friction loss and air friction loss of rotor, which account for 10–50% of the motor total losses. In addition, the larger the motor capacity and ventilation are, the greater the air friction loss becomes. Therefore, accurate calculation of air friction loss is the main consideration for motor optimization. As the dynamic balancing structure of motor, the rotor end's self-support blade has a cooling effect on the stator end windings, at the same time it also increases the air friction loss and overall machine loss, resulting in economic losses. Using the computation fluid dynamics (CFD) to solve stator end windings temperature rise and air friction loss of the self-support components, in this paper the optimum matching length of the components is obtained, and the feasibility and accuracy of the method are verified.

CFD is a common method to analyze the temperature rise in the motor. The wind friction loss was calculated through analytical method [1–4] or experimental method [5,6]. The 3D flow field was less presented about TEFC induction motor internal windless friction than in the analysis of motor internal temperature rise [7–13]. Wang et al. [14] used the analytical method to create a permanent magnet rotor and stator for an ultra-high speed magnet motor in the optimized design. It was shown that the air friction loss had a great effect on the optimized design of the ultra-high speed permanent motor, which decreased the counting loss by 63% compared to the designs which did not consider the air friction loss. Due to the complex model structure, it is difficult to accurately compute the air friction loss by applying the analytical method, possibly even leads to incorrect conclusions, Cox and Krahn [15] took a turbine generators an example, but the deviation was great, which mainly resulted from the computation of air friction loss through comparative analysis. A series of tests on fluid and heat transfer were designed for a high-speed pulse generator rotor by Werst et al. [16] to verify the existence of wind friction loss and whether it spins and then spreads outward in the form of heat. The tests provided future reference for the design of high-speed pulse motor. With the development of computer technology, new breakthroughs have also been made in computational methods, and many new ways to compute air friction loss have been derived by means of finite-element software tools. Zhang et al. [17] took a high-speed claw pole motor as an example, and

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used CFD and heat conduction theory to study air friction loss by applying the change of total internal air energy. The relationships between the rotor and its air friction loss at different speeds and degrees of roughness were also obtained. Through finite element method and coupling of stator and rotor loss, the internal air-gap temperature distribution, transient temperature rise of stator and rotor and the instantaneous wind friction loss curve are figured out for a set of high-speed motor by Liu et al. [18]. Compared with the results through traditional method, it is more accurate by using finite element method.

In summary, the analytical method and the energy difference of input and output are two current methods to study air friction loss; however, these methods cannot be applied to full-closed motors. Additionally, a simple ultra-high speed or high speed motor takes on the role of carrier to study air friction loss, most of which involve ventilation at different speeds or different degrees of roughness. The studies for TEFC induction motor are scarce due to its complex structure and rotor with self-support fan.

In this paper, taking a TEFC induction motor as the research object, a three-dimensional physical model and mathematical model were established. Using the FVM combined with the basic principles of motors, the relationship of self-support fans in terms of the length and air friction loss, and the influence of stator end windings on temperature rise were analyzed respectively. Finally, the self-support fan length of the optimum matching scheme was also given.

2. Mathematical model establishing

2.1. Fluid governing equation and three-dimensional heat conduction equation

Based on the fluid characteristics inside motor, the general governing equation under rectangular coordinate system is as follows [19]:

$$\mathrm{div}(\rho \boldsymbol{u}\varphi) = \mathrm{div}(\Gamma \mathrm{grad}\ \varphi) + S \tag{1}$$

where $\boldsymbol{u}$ is the velocity vector, and it can be described as velocity u, velocity v and velocity w along x, y and z direction, respectively; φ is the universal variables; ρ is the fluid density; Γ is the spreading coefficient; and S is the source item.

The expanded form of the formula (1) is:

$$\frac{\partial(\rho u\varphi)}{\partial x} + \frac{\partial(\rho v\varphi)}{\partial y} + \frac{\partial(\rho w\varphi)}{\partial z} = \frac{\partial}{\partial x}\left(\Gamma\frac{\partial\varphi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma\frac{\partial\varphi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma\frac{\partial\varphi}{\partial z}\right) + S \tag{2}$$

The numerical study of the steady state temperature field of motor is the study of the stationary model without the temporal aspect, which simplifies the solution of the equation. The 3D stationary heat source and heat conduction governing equation in the anisotropic media are used in Cartesian coordinates, it can be expressed as formula (3) [20]:

$$\begin{cases} \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) = -q_v \\ \frac{\partial T}{\partial n}\Big|_{S_j} = 0 \\ -\lambda\frac{\partial T}{\partial n}\Big|_{S_d} = \alpha(T - xT_f) \end{cases} \tag{3}$$

where T is the temperature of the solid; λ_x, λ_y and λ_z are the thermal conductivity coefficient along the x, y and z directions, respectively; q_v is the sum of the density of the heat source in the solving region; α is the convection coefficient of the heat dissipation surface; T_f is the temperature of the fluid; S_j is the dissipating surface; and S_d is the insulated surface.

2.2. Air friction loss equation

According to the principles of electric machine, during the process of steady state operation, the rotor is acted upon by electromagnetic torque, friction torque and load torque. Assuming that the rotor rotates counterclockwise at the rated speed ω and ignores the bearing friction, it will be affected by the electromagnetic torque of counterclockwise rotation T_e, as well as the clockwise air friction torque T_{air} and load torque T_L. When the motor is in steady state operation, the balance equation between the three torques is as shown in Formula (4):

$$T_e = T_{air} + T_L \tag{4}$$

When both ends of Formula (4) are multiplied by the angular velocity, we can obtain Formula (5), which is the power balance equation:

$$T_e\omega = T_{air}\omega + T_L\omega \tag{5}$$

Therefore, the rotor air friction loss formula can be obtained when the motor is running at the rated speed.

$$P_f = T_{air}\omega \tag{6}$$

The air friction torque in Formula (6) can be obtained by the following formula [21]:

$$T_{air} = \int_A \tau dA \cdot r \tag{7}$$

where τ is the rotor surface shear stress, r is the radius of rotation, and dA is the rotor surface micro element.

According to the numerical calculation for the rotor surface shear stress τ, and coupling with the above formulas, the air friction loss P_f can be calculated on the surface of the rotor.

3. Establishment of physical model

To analyze the fan characteristics of an induction motor rotor end's self-support components (including calculation of the ventilation effect and air friction loss of the end components) and the heat transfer performance inside of the motor, and confirm the best matching scheme of self-support fan further, a unified solution of the model need to be established.

3.1. Basic data of the TEFC motor

The details of the TEFC motor used in this paper are shown in Table 1.

The illustrations of mesh details are: the mesh type is hexahedron structured grid, and the whole grid number of the solution domain is 2,239,875.

According to the parameters of the TEFC motor, loss distribution of main parts of the TEFC motor can be calculated by finite element method, and the loss distribution of the motor is shown in Table 2.

3.2. Basic assumptions of the model

In order to study the fan characteristics of the self-support components of rotor and further study the matching characteristics, some basic assumptions are given as follows [22]:

(1) The windings end takes straight alignment as the equivalent.
(2) The rotor and its self-support fan components have smooth surfaces.
(3) The Reynolds number of fluid is large in the internal motor, and a turbulence model is adopted to solve the flow field in the internal motor.