NUMERICAL SIMULATION OF HEAT DISSIPATION OF SURFACE MOUNTED PERMANENT MAGNET SYNCHRONOUS HUB MOTOR

by

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Due to the insulation aging, demagnetization and other problems of the permanent magnet and insulating material in the permanent magnet synchronous hub motor under high temperature, the numerical simulation of the heat dissipation of surface mounted permanent magnet synchronous hub motor is proposed. According to the heat transfer of hub motor, the effect degree of heat conduction, heat convection and heat radiation is obtained, the heat transfer coefficient of each part is calculated, and the influence of motor insulation material on temperature rise is analyzed. The experimental results show that the heat dissipation of hub motor under natural cooling condition is poor, and the internal oil cooling method can effectively improve the heat dissipation of hub motor and reduce the temperature difference. When operating at high speed, this reduces the potential safety hazard.

Key words*: hub motor, heat dissipation, numerical simulation, permanent magnet*

Introduction

According to the statistics of China Automobile Industry Association, 78499 new energy vehicles were produced and 74763 were sold in 2014. Among them, the production and sales of pure electric vehicles are 48605 and 45048, respectively, while the production and sales of plug-in hybrid vehicles are 29894 and 29715, respectively. It can be said that 2014 is the first year of the industrialization of new energy vehicles. In 2015, the new energy vehicle industry witnessed explosive growth. In the first half of 2015, the annual production and sales volume of last year were completed, reaching 76223 and 72711, respectively, up 2.5 and 2.4 times year-on-year, respectively. The state has put forward the goal of reaching two million new energy vehicles by 2020. The huge market prospect provides great opportunities for related new energy vehicle enterprises, but at the same time, it also puts forward more stringent requirements for the design and production of complete vehicles and main parts. As one of the three core components of new energy vehicle, motor is the most important power source. The permanent magnet synchronous motor has a high power density, which accounts for more than 90% of the new energy vehicle motor market share. Compared with the drive

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motor types of new energy vehicles sold in 2014 worldwide, except Tesla, all other new energy vehicles chose permanent magnet synchronous motor [1].

The temperature rise of the internal parts of the motor directly affects the life and reliability of the motor. At the same time, another way to effectively improve the power density and torque density of the permanent magnet synchronous motor is to improve the heat dissipation of the motor. The design of high-efficiency heat dissipation structure is inseparable from the accurate calculation of temperature rise inside the motor. Therefore, the calculation of motor temperature rise is also the current research hotspot. At present, the main calculation methods are: simplified formula method, equivalent heat path method, finite element method, finite difference method, equivalent heat network method, *etc*. Mellor *et al*. [1] put forward the equivalent parameter thermal network model of forced air-cooled induction motor earlier. The components with the same thermodynamic characteristics of the motor are divided into a series of concentric cylinders for analysis, and the axial and radial flow of heat flow in the motor is considered at the same time. This method has good accuracy, which provides a good foundation for the development of equivalent thermal network later. On the basis of Mellor's research, Wrobel *et al*. [2] analyzed the influence of winding dissipation and insulation materials on the overall thermodynamic parameters of winding, and proposed the correction method based on experiment, which further improved the accuracy and convenience of the centralized parameter thermal network method. Simpson *et al*. [3] analyzed the thermodynamic characteristics of the tile like structure, established its T-type equivalent thermal resistance network, and deduced the thermal resistance calculation formula. Finally, the accuracy of the network model was verified by experiments. In view of the problem that Mellor model is not conducive to the calculation of thermal resistance of motor components with complex geometry, Boglietti *et al*. [4] proposed a simplified thermal network model which can be simplified as a series thermal resistance model. Shafaie *et al*. [5] used the equivalent thermal resistance network method to analyze the temperature field dissipation of the 10 MW wind turbine running at different speeds, and verified it with 3-D finite element method. Dong *et al*. [6] first used computational fluid dynamics to calculate the cooling fluid parameters of the motor, and then analyzed the temperature field dissipation of a high-speed air-cooled permanent magnet synchronous motor with Gramme ring type winding by using the centralized parameter thermal network method. On the basis of the aforementioned research results, numerical simulation of heat dissipation of surface mounted permanent magnet synchronous hub motor was carried out [3-5].

Materials and methods

Because of its high control accuracy, high power density, high torque density and low vibration and noise, permanent magnet synchronous hub motor is more and more popular in the automotive industry at home and abroad. Hub motor is mainly divided into outer rotor and inner rotor hub motor. The hub motors with the inner and outer rotor have their own advantages and disadvantages. The main purpose of this paper is to study the hub motor with the outer rotor, which is to install the motor inside the wheel and connect the rotor directly with the hub. This eliminates the transmission system between the traditional motor and the wheel, making the system compact, low transmission noise and high transmission efficiency. It is precisely because of such a compact mechanism and poor working environment that the heat generated by motor operation cannot be discharged smoothly, resulting in high temperature rise of motor. Therefore, in order to improve the power density of the motor, reducing the temperature rise of the motor has become the top priority.

Heat transfer performance of hub motor

Heat transfer occurs between the same or different objects in contact with each other. From the microscopic point of view, it is the heat transfer generated by the thermal movement of high-energy micro particles in the object, which includes the heat transfer from the high temperature part to the low temperature part in the same object, as well as the transfer from the high temperature object to the relatively low temperature object among different kinds of objects. Fourier heat conduction law is often used to describe heat transfer. The following formula is the general formula of Fourier heat conduction law:

$$\mu = -\varpi M \frac{\alpha t}{\alpha e} \tag{1}$$

where μ is the thermal conductivity of one side, M – the area of the thermal conductivity surface, ϖ – the thermal conductivity of the cross-section material, and $\alpha t/\alpha e$ – the temperature change rate of the object along the vertical cross-section direction.

In many mathematical models describing heat conduction problems, they are all composed of heat conduction differential equations and corresponding boundary conditions. Therefore, the process of solving heat conduction differential equation is the process of solving heat conduction problem. In order to establish the mathematical model of the temperature field of the heat conducting objects, it is necessary to accurately establish the heat conducting differential equation that can meet the temperature change. In order to solve the specific problem, we need to find out the definite solution conditions, and finally get the calculation results. According to the analysis of heat conduction equilibrium model of micro element, the following formula is obtained:

$$\rho z = \frac{\alpha t}{\alpha \tau} = \frac{\alpha}{\alpha e}\left(\varpi \frac{\alpha t}{\alpha e}\right) + \frac{\alpha}{\alpha r}\left(e\frac{\alpha t}{\alpha r}\right) + \frac{\alpha}{\alpha z}\left(e\frac{\alpha t}{\alpha u}\right) + \dot{\Phi} \tag{2}$$

where ρ, $\dot{\Phi}$, ϖ, z, τ are the density of the microelements, the heat generation, thermal conductivity, specific heat capacity, and time of the object heat source in unit volume and unit time, respectively.

For the thermal model of the motor, the final state to be achieved is steady-state, that is, the heat generated is equal to the amount of the heat dissipation, the temperature will not increase any more, and it will reach the balance state. Therefore, eq. (2) can be rewritten:

$$\vec{j} = -\vec{\varpi} gradt = -\vec{\varpi}\frac{\alpha t}{\alpha e}\vec{n} \tag{3}$$

where $\vec{j}$ is the heat flux density vector, $\vec{n}$ – the normal unit vector on the isotherm of the corresponding point, and *gradt* – the temperature gradient of the corresponding point in space. The size of thermal conductivity ϖ is related to the ambient temperature of the object and the type of substance itself. In engineering calculation, the thermal conductivity values of various substances are mostly determined by special experiments.

Heat transfer coefficient

As for the motor winding, the insulation materials of the stator winding in the hub motor with the outer rotor are mainly used for slot insulation, interlayer insulation, interphase insulation, slot wedge, *etc*. Under the action of the internal temperature rise of the motor, the performance of the insulating materials of the stator slot and winding will gradually deteriorate. When the temperature exceeds the limit that the insulating material can bear, its characteristics will change fundamentally, and the insulating ability will be lost seriously [7]. The temperature rise limit of the winding is basically determined by the maximum allowable temperature of the insulating material of the insulating structure and the temperature of the cooling medium [8, 9]. Starting from the selection of motor materials, the selection of high insulation and high temperature resistant insulation materials is one of the most effective methods to improve the efficiency of the motor's heat dissipation. The biggest standard for selecting this kind of material is its thermal conductivity. The calculation formula of thermal conductivity is [10]:

$$R = \frac{h}{\varpi M} \tag{4}$$

where R is the thermal conductivity of the material, which is used to characterize the resistance of the material to heat flow and h – the thickness of the insulating material.

It can be seen from the previous formula that improving the thermal conductivity of the insulation structure is one of the important measures to improve the temperature field dissipation of the main insulation of the motor [11]. There are mainly two ways: one is to directly select insulating materials with high thermal conductivity, or to fill the insulating materials with better thermal conductivity. The other is to control the insulation treatment process, try to eliminate the gaps in the insulation layer, and improve the compactness of the insulation layer [12]. On the basis of the above calculation results, the numerical simulation experiments are designed as follows [13].

Demonstration of numerical simulation experiment

Internal oil cooling and natural cooling

On the one hand, the cooling oil acts as the heat transfer medium (thermal conductivity 0.149) when the internal oil cooling method is used for heat dissipation. Compared with the air thermal conductivity of 0.023, its thermal conductivity is better, which can better transfer the heat in the stator core and winding of the main heat source inside the motor to the rotor and the shell, so that the temperature distribution of the motor is relatively uniform and the temperature difference is relatively low. On the other hand, because of the other physical properties of cooling oil compared with air, at the same speed, the Reynolds coefficient, which is the parameter to characterize its fluid properties, is much larger than the characteristic value of air [14]. The fluid between the stator and the rotor can be regarded as forced flow because of the tangential motion of the rotor. According to the similar conditions of convective heat transfer, the criterion equation of fluid flow is [15]:

$$\mathrm{Nu} = K_b \,\mathrm{Re}_1^a \,\mathrm{Pr}^b \tag{5}$$

where Nu is Nusselt coefficient, Re – the Reynolds coefficient, and Pr – the Prandtl coefficient. It can be seen from the equation that as long as the velocity is known and the coefficient K_b = 4 and the correlation indexes a, b are determined, the Nusselt coefficient can be calculated.

According to the previous formula, the convective heat dissipation coefficient of the cooling oil is also much larger than that of the air, which further enhances the heat exchange capacity between the stator and rotor. Therefore, the temperature difference between stator and rotor is significantly reduced, the temperature rise of stator core and winding is greatly reduced, and the highest temperature rise point is also reduced. Thus, it is beneficial to the overall heat dissipation of the motor and avoids the adverse consequences caused by the local overheating of the motor.

Effect of rotating speed on heat dissipation

In the heat source of the motor, the iron loss is exponentially related to the frequency of the motor current, while the speed of the permanent magnet motor is directly proportional to the frequency of the current, which is 60 F/P, where F is the frequency and P is the order logarithm, generally 2). Therefore, the iron consumption and speed also show an exponential relationship. Since the rotor can be regarded as a rotating cylinder when the motor is running, it can be calculated according to the calculation method of the surface heat dissipation coefficient of the rotating cylinder. When there is no flow in the axial direction, it can be calculated according to the relative motion of the flow over the large plane wall [16]. Due to the air winding near the outer surface of the motor rotor yoke, it can be calculated according to:

$$\beta_k = 7.68\partial_{x2}^{0.78} \tag{6}$$

where ∂_{x2} indicates that the air velocity near the rotor can be taken as 75% of the rotor speed.

From the simulation results, it can be seen that under the condition of internal oil cooling and heat dissipation, the temperature of each part of the motor increases with the increase of rotating speed, which is within the safe operation range, and can ensure the stable operation of the motor. However, the stable temperature of all parts above the rated speed increased significantly, mainly because the iron consumption is proportional to the power of frequency, and the larger the speed is, the greater the iron consumption is [17]. Therefore, long-term high-speed operation should be avoided.

Influence of overload operation on motor temperature distribution

In case of overload, the change of heat source has obvious influence on the temperature rise of motor, which cannot be ignored. Therefore, it is necessary to carry out temperature simulation analysis in the case of overload. Under the condition of overload operation, the stator current of the motor increases, resulting in a sharp rise in copper consumption, so that the motor winding heats up rapidly in a short time. In general, the motor used in electric vehicles is required to be able to ensure the safe operation of the motor for three minutes under the condition of two times overload. Therefore, the temperature change of the motor is simulated and analyzed when it runs for four minutes under the condition of two times overload. The simulation results are shown in fig. 1 when the overload operation is changed from stable temperature for four minutes.

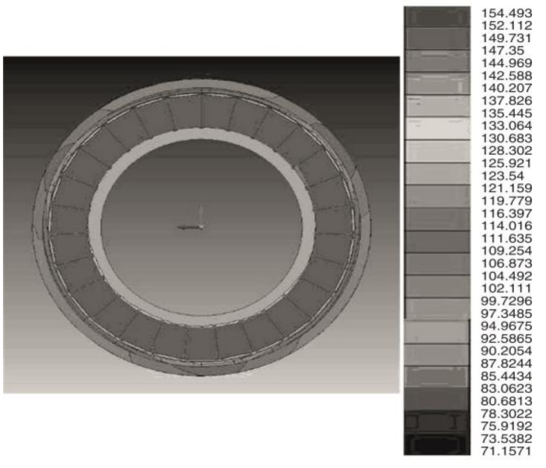

Figure 1. Temperature distribution of 240 seconds operation with two times overload current and overload

In order to better detect the heat dissipation capacity of the internal oil cooling motor, let the motor run normally and then suddenly switch to two times of overload current and operate for a period of time (four minutes), and then return to the normal rated speed. According to the simulation, the temperature changes of each part inside the motor are recorded. According to the previous set of relevant heat dissipation parameters unchanged, according to the operation of the motor real-time change of motor current size for simulation. After simulation, the temperature changes of each part of the motor are shown in fig. 2.

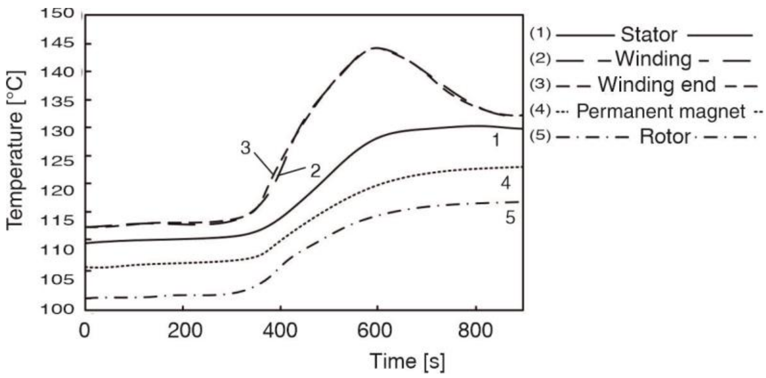

Figure 2. Temperature change curve of various parts of motor under two times of overload current

It can be seen from fig. 2 that switching from rated operation to overload operation will cause the overall temperature of the motor to rise rapidly, especially the winding and its end can reach 147 °C in a short time. This is mainly due to the rapid increase of copper consumption caused by the overload current during the operation of two times overload, which makes the temperature of winding and its end rise rapidly in a short time. While the temperature rise of other parts rises slowly due to the phenomenon of heat conduction. After returning to normal operation, the winding temperature of the motor will decrease rapidly, and then slowly until the stable operation temperature. The rapid reduction is due to the high temperature and large temperature difference in various parts of the motor, the fast heat transfer speed of the cooling oil and the heat stored by the cooling oil itself. When the heat transfer reaches a new balance, the temperature will return to a stable state. Therefore, although the internal oil cooling method can ensure the overload operation of the motor in a short time without damaging the insulation performance of the motor from the simulation results, it is necessary to pay attention to the flash point of the cooling oil in the actual operation process. Otherwise, there will be some hidden danger when the local temperature of the motor exceeds the flash point of the cooling oil.

To sum up, long-term overload operation on the one hand will exceed the motor's heat dissipation capacity, resulting in motor burnout. On the other hand, it will exceed the flash point of cooling oil, which may cause danger. Therefore, when choosing cooling oil, not only its insulation ability and thermal conductivity should be considered, but also its flash point should be fully considered. In addition, the motor should not run for too long under overload condition, otherwise it will cause adverse consequences.

Discussion

Comparing the two methods of calculating the eddy current loss of permanent magnet in different permanent magnet arrangements, the method can be effectively concluded as a set of high-efficiency calculation method of eddy current loss of permanent magnet in the whole working area of motor which is suitable for different permanent magnet arrangements and the winding current is not pure sine wave. Therefore, the analysis of the similarities and differences between the two is also an important research content, which will provide a strong support for the establishment of a unified and universal computing method. The previous research shows that when the magnetic field of the motor core enters into the nonlinear region, the proposed calculation method will have some errors, so it is necessary to study the calculation error correction method of the nonlinear region. This paper studies the mechanism of the influence of various physical parameters such as current, temperature and frequency on the eddy current loss of permanent magnet when the magnetic field is saturated, establishes the accurate analytical relationship, and finally introduces the correction equation with the above physical parameters as variables. An accurate and efficient calculation method of eddy current loss of permanent magnet in the whole working area of motor is obtained, which is suitable for different permanent magnet layout, segmented structure of permanent magnet block and different control modes, and has the ability of temperature self-adaptive and error correction in the nonlinear region of magnetic field.

Conclusion

The research aims at the numerical simulation of the surface mounted permanent magnet synchronous hub motor. Hub motor is widely used in the interior of electric vehicles as an important part of its drive system. Through its unique application and design idea, the power transmission part and brake device are integrated in the hub. The influencing factors of motor temperature rise are analyzed. Through the comparison of oil cooling and air cooling, the simulation analysis of the factors that affect the temperature rise of the motor under different rotating speeds. Due to the limitation of the author's knowledge and time, the analysis and research of the automotive heat dissipation of hub motor using the oil cooling method is not comprehensive and in-depth, which needs to be further improved in some places.

- First of all, the optimization of the motor body is not limited to the improvement of the casing. The influence of the optimization of other parts of the motor body on the temperature can be discussed in detail in the later research.
- Secondly, the analysis of oil cooling and heat dissipation does not fully consider the actual environmental impact on the driving process of electric vehicles, and only discusses the no-load or rated load test of the motor under laboratory conditions. The environmental change factors of electric vehicles in the actual driving process can be studied and analyzed in depth.
- Thirdly, in the process of internal oil cooling analysis, the influence of the selection of cooling medium can be further discussed.
- Finally, in the process of oil quantity selection, only two factors, cooling effect and weight, have not been studied deeply for oil friction loss and some other factors. It can be used as a variable to deduce a more reasonable optimization algorithm to get a more appropriate oil quantity.

At present, the research of eddy current loss measurement of permanent magnet is still difficult. In this study, the experimental method of eddy current loss of permanent magnet is further studied in combination with the back EMF descent method proposed in the earlier stage, and the accuracy of the above-mentioned efficient calculation method is verified by experiments.

References

[1] Mellor, P. H., *et al.,* Lamped Parameter Thermal Model for Electrical Machines of TEFC Design. *Electric Power Applications, IEE Proceedings B, 138* (1991), 5, pp. 205-218

[2] Wrobel, R., *et al.*, Contribution of End-Winding Proximity Losses to Temperature Variation in Electromagnetic Devices. *IEEE Transactions on Industrial Electronics, 59* (2012), 2, pp. 848-857
[3] Simpson, N., *et al.*, Estimation of Equivalent Thermal Parameters of Impregnated Electrical Windings. *IEEE Transactions on Industry Applications, 49* (2013), 6, pp. 2505-2515
[4] Boglietti, A., *et al.*, Determination of Critical Parameters in Electrical Machine Thermal Models. *IEEE Transactions on Industry Applications, 44* (2008), 4, pp. 1150-1159
[5] Shafaie, R., *et al.,* Thermal Analysis of 10-MW-Class Wind Turbine HTS Synchronous Generator, *IEEE Transactions on Applied Superconductivity, 24* (2014), 2, pp. 90-98
[6] Dong, L., *et al.,* Fuzzy Control of Chaos in Permanent Magnet Synchronous Motor With Parameter Uncertainties, *Acta Physica Sinica, 58* (2009), 3, pp. 1432-1440
[7] Zhao, Z., *et al.*, Dynamic Modeling of Brake in Power-Split DHT and Pressure Tracking Control With Sliding Mode Variable Structure Method, *Int. J. of Automotive Technology, 20* (2019), 3, pp. 521-530
[8] Wang, Q., *et al.*, Review of Sensorless Control Techniques for PMSM Drives, *IEEJ Transactions on Electrical and Electronic Engineering, 14* (2019), 10, pp. 1543-1552
[9] Parafes' S. G., *et al.*, On One Approach to Design of the Rudder-Drive System Taking into Account the Aeroelastic Stability Requirements, *Russian Aeronautics, 63* (2020), 2, pp. 75-82
[10] Yang, M., Gao, Y., Advanced Model Predictive Current Control for Induction Motor Drive System Fed by Indirect Matrix Converter, *Journal of Power Electronics, 20* (2020), 2, pp. 466-478
[11] Zhou, Y., *et al.*, Model-free Deadbeat Predictive Current Control of A Surface-Mounted Permanent Magnet Synchronous Motor Drive System, *Journal of Power Electronics, 18* (2018), 1, pp. 103-115
[12] Wang, S., *et al.,* Flow Resistance Modeling for Coolant Dissipation within Canned Motor Cooling Loops, *Chinese Journal of Mechanical Engineering, 33* (2020), 1, pp. 210-220
[13] Devaki, P., *et al.*, Wall Properties and Slip Consequences on Peristaltic Transport of a Casson Liquid in a Flexible Channel with Heat Transfer, *Applied Mathematics and Nonlinear Sciences*, *3* (2018), 1, pp. 277-290
[14] Jung, K. T., *et al.,* Characteristics of Linear Actuator Type Vehicle Horn Considering Magnetic Saturation and Eddy Current Loss, *Journal of Magnetics, 23* (2018), 4, pp. 665-668
[15] Ruzhansky, M. V., *et al.,* On a Very Weak Solution of the Wave Equation for a Hamiltonian in a Singular Electromagnetic Field, *Mathematical Notes, 103* (2018), 5-6, pp. 856-858
[16] Yamac, K., *et al.*, A Numerical Scheme for Semilinear Singularly Perturbed Reaction-Diffusion Problems, *Applied Mathematics and Nonlinear Sciences*, *5* (2020), 1, pp. 405-412
[17] Makarov, D. N., Quantum Entanglement of a Harmonic Oscillator with an Electromagnetic Field, *Scientific Reports, 8* (2018), 50, pp. 84-87

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