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Permanent Magnet Motors in Energy Storage Flywheels

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Abstract: Flywheel energy storage system stores energy in the form of mechanical energy and can convert mechanical energy into electrical energy. Flywheel energy storage is a mechanical energy storage system. Due to its high energy storage density, high power, high efficiency, long life, no pollution and other characteristics, it has a broad application prospect in the field of aerospace, power peaking, UPS, electric vehicles, high-power electromagnetic guns and so on. With the continuous development of magnetic levitation, composite materials, vacuum and other technologies, the current flywheel energy storage technology is mainly through the increase in the speed of the flywheel rotor to achieve energy storage, the continuous development of various technologies, so that the research of flywheel energy storage technology has stepped into the "high-speed" development period, and has been widely used in many fields. Application, and gradually become the focus of research in various countries.

Keywords: Energy Storage Flywheel, Permanent Magnet Motor, High Speed Motor.

1. Introduction

At present, this new type of energy storage technology has been widely used in electric vehicles, space stations, satellites and other major equipment UPS power supply, power station grid stabilization, transient high-power power source and other fields. Developed countries such as the United States, Japan, Germany, the United Kingdom, Britain, Italy, Canada and other countries have invested in flywheel energy storage technology, from the initial experimental research development to commercialization, and achieved significant results.

With the improvement of flywheel energy storage capacity, the development of a new type of flywheel energy storage motor with high rotational speed, high efficiency and small size is the key to the development of flywheel energy storage technology. In addition, the use of a high-speed PMSM as a flywheel drive generates a series of technical difficulties that involve the intersection of multiple disciplines.[1] The design and testing of key technologies for high-speed motors used for flywheel energy storage have been analyzed and summarized for more than 20 years. This project intends to take the high-speed permanent magnet motor as the research object and discuss several key problems from its design perspective. Secondly, the basic topology of the current high-speed motors used for flywheels is summarized, and the characteristics of the motors are analyzed from the perspective of the construction of the motors; the third part of the project is the design of the strength of the rotor, as well as the stability of the rotor; and the fourth part of the project is the design of the support system, especially the magnetic support, and the support technology of the unsupported support. The fifth part is the loss calculation of high-speed permanent magnets, temperature rise calculation, and the technology of heat radiation.

2. High-speed Permanent Magnet Motor Applications

2.1. Design features of permanent magnet synchronous motors

The basic method of electromagnetic design of permanent magnet synchronous motor is as follows: firstly, according to the technical requirements of motor design, the rotor structure and material properties of permanent magnets are determined; secondly, by estimating the electromagnetic load (A,B_δ), the main dimensions (stator inner diameter Di1, motor length Lef) and other motor dimensional parameters are determined.[2] If the calculation results do not differ much from the original design assumptions, subsequent calculations can be carried out. Otherwise, the electromagnetic load is reselected.The electromagnetic design flow of PMSM is shown in Fig. 1.The design idea of this method is clear, and it can be easily realized by computer programming for parameter adjustment and scheme adjustment.

2.2. Design of permanent magnet synchronous motors

The stator of a high-speed permanent magnet motor (PMSM) is similar to an ordinary AC motor, but its characteristics are mainly expressed in the rotor. In the design of PMSM, the selection of rotor magnetic circuit structure is a key issue. In a high-speed permanent magnet motor, the built-in rotor magnetic circuit should be selected. There are various types of built-in rotor magnetic circuits, which have their own advantages and shortcomings, and the appropriate configuration must be selected first in the design. The design of rotor magnetic circuit configuration follows the following principles:

2.2.1. Achieve the performance indexes of the electric motor

In order to ensure the working performance of the motor, a large air gap magnetic density is required. The size of the air gap magnetic density is related to the thickness of the permanent magnets per pole, and as the air gap magnetic density increases, the air gap magnetic density also increases.

However, with the increase of air gap magnetic density, the magnetic density between the stator tooth surface and yoke surface will be strengthened, the iron loss will increase, and the local magnetic density of the rotor will become high.

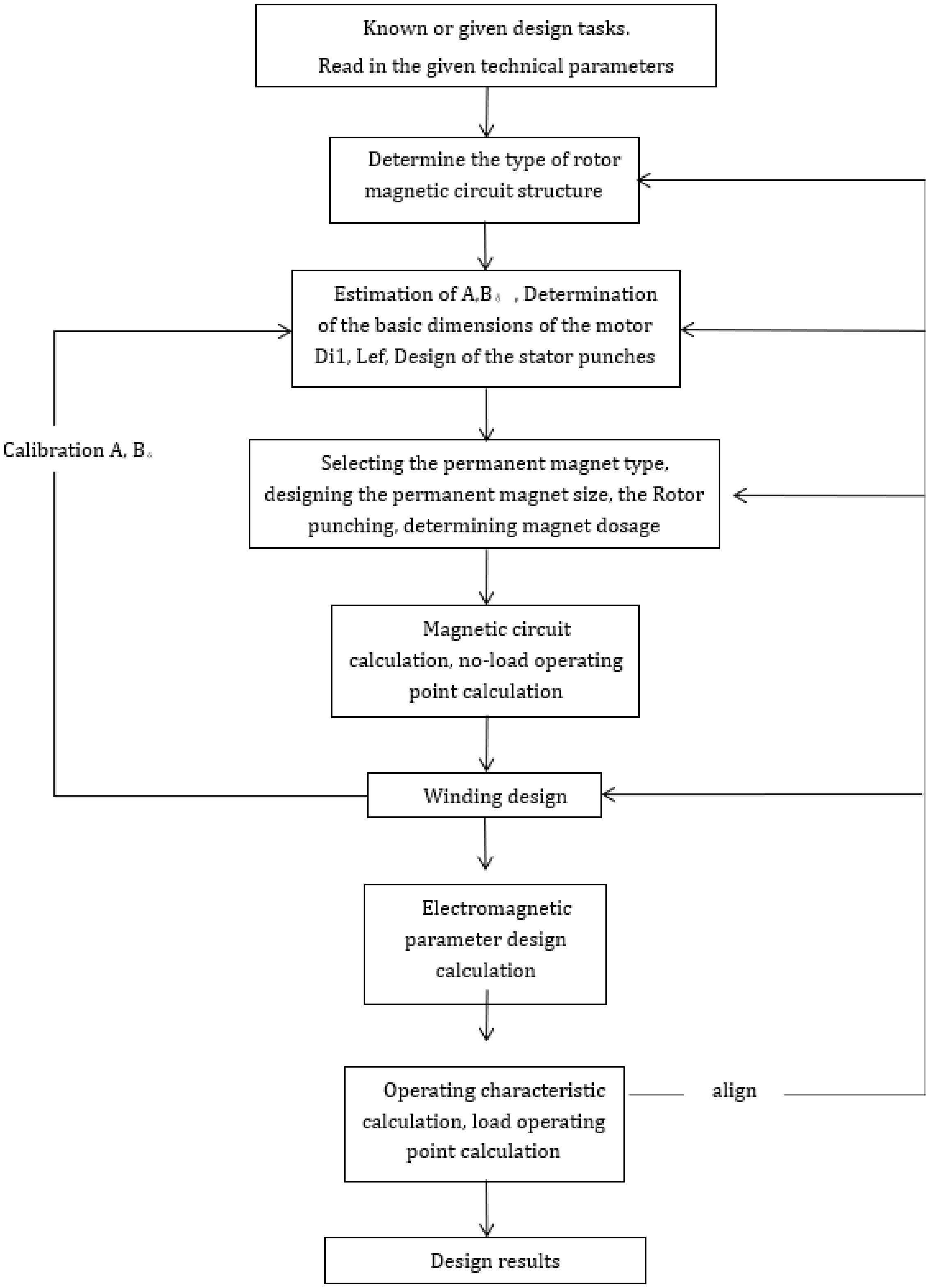

Figure 1. Flow chart of electromagnetic design of permanent magnet high-speed motor

2.2.2. Reliable magnetic isolation

The embedded rotor magnet is located in the iron core, its leakage flux is large, the magnet utilization is not high, and isolation magnetism should be used to reduce its loss. However, the presence of electromagnetic isolation measures will reduce the mechanical strength of the motor, therefore, the design of the motor should consider both the electromagnetic isolation effect and the mechanical strength of the motor. The two commonly used isolation methods are: magnetic isolation bridge and non-conducting shaft.[3] However, whichever method is used, an isolated magnetic bridge is necessary. In the case of tangential types, it is also necessary to use a shaft with a non-conducting magnet. Isolated magnetic bridges have a larger length, lower magnetic field strength, lower magnetic density, and lower leakage flux. As the width of the bridge becomes narrower, its magnetizing effect becomes more significant, but its mechanical properties become lower. In order to reduce the leakage flux of permanent magnets, the width of the spacer bridge is generally about 1-1.5 mm.[4] For high-speed motors, on the other hand, the isolation measures should be based on the primary condition of ensuring sufficient mechanical strength of the rotor structure. In order to achieve this, it is often necessary to increase the width of the isolating magnetic bridge. In that case, a balance has to be struck between mechanical strength and magnetic properties[5].

2.2.3. To have sufficient mechanical strength

The rotor structure of the built-in permanent magnet motor is more complex and its mechanical strength is poor, so both its electromagnetic performance and its mechanical strength must be considered in the electromagnetic design. In the design of high-speed motors, this is usually a necessary consideration.

2.2.4. Alternating and direct axis synchronizing reactances and their ratio X_q/X_d should be appropriate

Synchronous motors are mostly of convex pole structure, and by adjusting the parameters such as the length of the polarization direction of the permanent magnets and the pole arc coefficient, a larger AC reactance (X_q/X_d, or L_q/L_d) can be obtained, which in turn improves the overload and torque densities of the motors, and enhances the performance of the weak magnetic spreading speed. However, if the ratio of X_q to X_d is too large, the power angle of the motor will be large at rated operation, which leads to poorer stability of the motor and increased noise and vibration.

The design of the rotor magnetic circuit takes into account the mechanical strength of the motor, the need for constant power operation, and the cost of production[6]. Regardless of the pole configuration of the rotor, there must be enough magnetic steel to fit. Under the premise of meeting the space requirement for magnetic steel placement, a pole structure with good magnetic isolation properties and good mechanical properties and simple structure should be selected.

2.3. Requirements for technical indicators

The PMSM designed in this thesis needs to match the flywheel energy storage principle prototype and meet the following requirements:

1) The power of charging and discharging is more than 20kW, the energy storage is more than 2kWh, and the design cycle of charging and discharging is more than 100,000 times;

2)The speed of 0-6000 r/min is the constant torque area, and the speed of 6000-12000 rpm is the constant power area;

3) the mechanical power output should exceed 21kW during charging and 22kW during discharging;

4) the motor is operated in a vacuum environment (vacuum less than 0.0133 Pa) and the motor has the ability to run at 13,000 rpm and 10.6 N • m.

2.4. Electromagnetic Design Solutions

On this basis, a new design method is proposed based on the calculation of the magnetic circuit, combined with the numerical analysis of the electromagnetic field. Through several debugging, the electromagnetic design of the whole system is finally completed. The rotor slot dimensions are shown in Fig. 2 (the position of the permanent magnet and other relevant dimensions are also given in the figure). Rotor permanent magnet data: permanent magnet height magnetization direction length) h_m = 6mm; permanent magnet total width b_m = 47.2mm, each permanent magnet is divided into two pieces, b_m is the total width of the two pieces, i.e., the width of each piece of permanent magnet $b_m/2$ = 23.3mm; the overall axial length of the permanent magnet L_m = 150mm; the material of the permanent magnet is Cu-CoR2Co17; in the absence of load, the leakage magnetization of the permanent magnet is about 0.5mm. The leakage coefficient of the permanent magnet is 1.924; the no-load operating point of the permanent magnet is 0.878; the nominal value of the permanent magnet is 0.812; the unloaded air-gap flux is 0.00363Wb; the nominal gap flux is 0.00431Wb; the fundamental frequency magnetic density is 0.4236T without loading; the no-load phase electromotive force is 163.23V (nominal value is 0.742); the permanent magnet flux is 0.1468Wb.

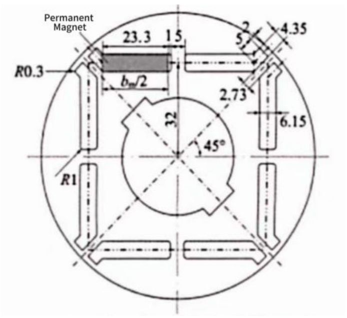

Figure 2. Rotor slot shape and permanent magnet dimensions

3. Permanent Magnet Synchronous Motor Prototype Trial Production and Testing

3.1. Rotor specimens and their mechanical strength tests

According to the requirements of the technical specifications, a specimen of a rotor is fabricated[7]. The rotor specimen designed in this paper is a kind of bionic rotor with smaller axial dimensions, adopting a 20mm axial length, using silicon steel exactly the same as the real rotor, whose structure and dimensions are the same as those of the real rotor's axial length, and replacing the permanent magnet with an iron block. In addition, argon arc welding technology is used on the outer circumference of the rotor, which makes the rotor core a solid whole and thus enhances its mechanical properties.

High-speed running experiments were conducted on the specimens in a special test chamber. After testing, the rotor in the 12000rpm high speed, after a long period of rotation, its overall and part of the deformation and damage did not occur, proving that the selected silicon steel material and the design of the rotor structure is correct[8].

3.2. Type test results

In accordance with the electromagnetic design scheme and the above manufacturing technical requirements, a prototype was machined and fabricated (shown in Fig. 3).

Figure 3. High-speed permanent magnet motor prototype

Afterwards, the prototype was subjected to the necessary type tests in accordance with the relevant standards.

The type test data are shown in Table 1. Where the PTC resistance value is the resistance value of the PTC resistor arranged at the end of the stator winding, which is a lower value due to the lower temperature of the motor.

Table 1. Prototype type test data

Measured Parameter	Cold State	Thermal State			
U-phase DC resistance R_U/Ω	0.038	0.047			
V-phase DC resistance R_V/Ω	0.036	0.043			
W-phase DC resistance R_M/Ω	0.038	0.045			
Insulation resistance to ground/MΩ	500	—			
Phase-to-phase insulation resistance/MΩ	500	—			
Turn-to-turn withstand voltage/V	2000	2000			
PTC resistance value/Ω	86.53	73.23			
Bearing front temperature/°C	18℃	**Electric Motor**	37	**Alternators**	37
Bearing rear temperature/°C	18℃		48		42
Maximum temperature of seat surface/°C	18℃	60			

The results of the power generation no-load and short-circuit tests performed on the prototype are shown in Tables 2 and 3, respectively.

Table 2. No-load test data of prototype power generation

Generator speed/(r·min^{-1})	Engine open circuit voltage/v		
	U-V	V-W	U-W
12000	345	345	345
9000	270	270	270
6000	170	170	170
3000	97	97	97
1500	46.2	46.2	46.2
900	31	31	31
600	23	23	23

Table 3. Short-circuit test data of prototype power generation

Generator speed/(r·min^{-1})	Engine open circuit voltage/A		
	U	V	W
500	42	42	42
600	43.7	43.7	43.7
750	45.3	45.3	45.3
1000	46.1	46.1	46.1
1500	46.5	46.5	46.5
2000	46.5	46.5	46.5

In addition, a prototype electric no-load test was conducted using a power converter to drive the designed and manufactured motor. Table 4 shows the data measured after a hour of operation. The displayed voltage is the terminal voltage value displayed by the power converter, and the measured voltage is the terminal voltage value measured by a pointer-type voltmeter.

Table 4. Electric no-load test data of the prototype

Displayed/measured voltage/V	No-load speed/(r·min)	Input frequency/Hz	No-load current /A
380/365	12000	400	2.2
355/345	8400	280	19.1
317/310	7500	250	20
254/260	6000	200	19.7
190/183	4500	150	20.4
127/130	3000	100	20.7
95/105	2250	75	21
64/65	1500	50	21.8
45/49	1050	35	21.3
39/44	900	30	21.6
33/38	750	25	22
27/32	600	20	22.8
20/28	450	15	20.6

Based on the electric no-load test data of the prototype, the average value of the magnetic chain of the permanent magnet is calculated to be 0.1556Wb.

4. Conclusion

This project takes the rotor pole structure of the built-in permanent magnet synchronous motor (PMSM) as the research object, and through the numerical simulation of the electromagnetic field of its rotor poles, combined with the practical application requirements of the developed flywheel energy storage device, studies the electromagnetic design principles and methods of the three-phase embedded PMSM, and realizes the electromagnetic design of the three-phase embedded PMSM with a maximum speed of 12,000r/min for 22kW.

On this basis, the fabrication process and experimental contents of the prototype are specified with reference to the relevant specifications about AC motors. Many experiments have been done on the prototyped samples. The experiments proved that the no-load and short-circuit performance of the system is good, the voltage and current waveforms are basically in accordance with the sinusoidal waveform, and the magnetic chain of the permanent magnets is also in accordance with the design requirements. From the above results, it can be seen that the design and trial production of the prototype is successful.

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