Electromagnetic design of high-speed permanent magnet synchronous motor for flywheel energy storage system

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Abstract. Flywheel energy storage system (FESS) has significant advantages such as high power density, high efficiency, short charging time, fast response speed, long service life, maintenance free, and no geographical environment restrictions. Motor is the energy conversion core of FESS and plays a significant role on system performance. In this paper, the design features of the motor for FESS are analyzed first. Then, a permanent magnet synchronous motor (PMSM) with a rated speed of 12000 rpm and a rated power of 250 kW is designed. Thirdly, aiming at the key problem of difficult heat dissipation of rotor, an improved rotor structure with “1” rotor permanent magnets layered and divided where placed in tangential and radial directions is proposed, which can reduce eddy current loss by 22.8%. Finally, based on Ansys FEM software, electromagnetic characteristics of the designed motor at no-load and full-load conditions are simulated and analyzed. The results show that the designed electromagnetic scheme meets the expected performance requirements and has guiding significance for prototype.

1. Introduction

Energy storage is not only an important means to use energy effectively, but also an important way to realize energy efficient use. Flywheel energy storage system (FESS) is a kind of mechanical energy storage device, which has high energy storage density, high efficiency, short charging time, fast response speed, long service life, maintenance free, almost without being limited by the geographical environment and other significant advantages, having good development prospects [1]. FESS has been used in transportation, power grid frequency modulation, new energy power generation, aerospace and uninterrupted power supply, and other fields. Since the 1990s, FESS began to develop to high speed with major breakthroughs made in flywheel rotor materials, bearing and power conversion devices.

FESS relies on a motor coaxially connected to the flywheel to drive the flywheel to rotate, thus storing energy in the form of kinetic energy. High-speed permanent magnet synchronous motor (PMSM) has been widely used in FESS due to its advantages such as high efficiency, high power density, suitable for high speed operation, good control characteristics and high efficiency operation within a wide speed range.

FESS puts forward some special demands for the motor. Combining these demands with the design method of high-speed PMSM, this paper designs a 12000 rpm, 250 kW PMSM, summarizes its design characteristics, and provides reference for the design of high-speed PMSM for FESS. Aiming at the
key problem of difficult heat dissipation of rotor, an improved rotor structure is proposed in this paper to alleviate the problem by reducing heat source. Finally, the rationality of the design scheme is verified by finite element simulation analysis, and it is ready for the development of prototype.

2. Design features of motor for FESS

2.1. FESS

FESS is also called flywheel battery. It is composed of flywheel, bearing, motor/generator, power electronic control device and vacuum chamber. FESS has two structures: one is parallel structure of motor and flywheel; The other is the concentric structure of the motor and flywheel [2]. Figure 1 shows the structural diagram of the two FESS structures.

![Figure 1. The structural diagram of the two FESS structures](image)

FESS uses high-speed rotating flywheel to store energy in the form of kinetic energy, it works in the following three working modes periodically and alternately:

1. Charging mode: The motor absorbs electric energy to operate as the motor and drives the flywheel to rotate. The electric energy is stored in the form of kinetic energy of the flywheel to complete the energy input;
2. Maintenance mode: The flywheel is charged when the speed reaches the predetermined value. The motor neither absorbs nor outputs electric energy, and operates in no-load mode. The flywheel rotates by inertia, and the kinetic energy is basically unchanged, thus energy storage is completed;
3. Power generation mode: The flywheel slows down and transfers kinetic energy to the motor, which operates as a generator and converts kinetic energy into electrical energy to complete energy output.

2.2. Demands of motor for FESS

The available energy of FESS is shown as follows:

$$E_{use} = \frac{1}{2} J \left( \omega_{\text{max}}^2 - \omega_{\text{min}}^2 \right)$$

$$= \frac{1}{2} J \omega_{\text{max}}^2 \left( 1 - \frac{\omega_{\text{min}}^2}{\omega_{\text{max}}^2} \right)$$

(1)

where $E_{use}$ is the available energy of FESS, $J$ is the moment of inertia of the flywheel, and $\omega$ is the angular velocity of the flywheel.
From the above formula, it could be seen that the available energy of FESS is proportional to the moment of inertia of the flywheel, and is propositional to square of the difference between the maximum and minimum speed of the flywheel. Therefore, to improve stored energy of FESS, the most effective way is to increase the maximum speed of the flywheel and reduce the minimum speed of the flywheel. That is, it requires the motor to run at high speed and maintain high efficiency within the working speed range [3].

The relation between motor speed and flywheel working mode is shown in Table 1.

| $n$/rpm | Working mode       | Control mode          |
|---------|--------------------|-----------------------|
| $0 \sim n_{\min}$ | launch             | constant torque control |
| $n_{\min} \sim n_{\max}$ | charging mode     | constant power control |
| $n_{\max}$     | maintenance mode   | constant power control |
| $n_{\max} \sim n_{\min}$ | power generation mode | constant power control |

The flywheel is directly connected to the motor, and the flywheel can be used for energy storage at a rising speed and energy release at a falling speed. In other words, the motor could be used for motor operation or generator operation.

FESS operates in maintenance mode most of the time. In other words, the motor runs most of the time without load. In order to improve the energy conversion efficiency of the system and reduce self-discharge, the motor is required to have a small no-load loss.

The response time of FESS is millisecond level, which requires the motor to have a large output torque and power.

The flywheel and the motor work together in a vacuum chamber, so the heat dissipation condition is extremely difficult. The rotor of the motor is a moving part, which cannot be cooled by water for heat dissipation, but can only be dissipated by radiation. In the case of extremely limited heat dissipation, the condition can only be improved by reducing the heat source, that is, the rotor eddy current loss is required to be small.

To sum up, the motor for FESS should meet the following demands:
1. Electric motors shall be integrated with electric generation;
2. The motor can run at high speed and efficiently within a wide speed range;
3. The motor has a large torque and output power;
4. Low no-load loss and eddy current loss of motor.

3. Electromagnetic design of high-speed PMSM for FESS

The design requirements of motor for FESS are shown in Table 2.

| Parameters             | Value |
|------------------------|-------|
| rated power/kW         | 250   |
| maximum speed/rpm      | 12000 |
| efficiency/%           | 95    |
| depth of discharge/%   | 75    |
3.1. Design of the stator
The main dimensions of PMSM are stator inner diameter and effective length of the stator core. The relationship between the main dimensions, calculated power, speed and electromagnetic load is shown as:

\[
\frac{D^2 l_{et} n}{P^*} = \frac{6.1}{\alpha' K_{Nm} K_{dp} A B_0}
\]  

(2)

where \( D \) is the inner diameter of the stator, \( l_{et} \) is the effective length of the stator core, \( n \) is the rotational speed, \( P^* \) is the calculated power, \( \alpha' \) is the calculated pole-arc coefficient, \( K_{Nm} \) is the waveform coefficient of the air gap magnetic field, \( K_{dp} \) is the winding coefficient of the armature, \( A \) is the specific electric load, \( B_0 \) is the magnetic load.

The motor is coaxial connected with the flywheel. Considering the overall structure and referring to formula (2), the inner diameter of the motor stator is designed to be 228 mm and the effective length of the stator core is designed to be 330 mm.

In general, high-speed motors adopt 2 or 4 poles. The 2-pole motor can reduce the magnetic field frequency, but the length of end windings of stator is longer and the yoke of stator is thicker. However, the advantages and disadvantages of 4-pole motors are opposite to those of 2-pole motors [4]. In this paper, the motor and the flywheel are sealed together in the vacuum chamber, because the space is limited, and the motor speed is not too high, the number of poles is chosen as 4.

The motor for FESS always runs without load, having a small no-load loss. The no-load loss of PMSM is mainly coming from the loss of stator core. The calculation expression of iron loss separation model is shown in (3) [5]:

\[
P_{fe} = P_h + P_e + P_a = k_h B_m^{1.5} + k_e f^2 B_m^2 + k_a f^{1.5} B_m^{1.5}
\]  

(3)

where \( k_h \) is the hysteresis loss coefficient, \( k_e \) is the eddy current loss coefficient, \( k_a \) is the additional loss coefficient, \( f \) is the frequency, \( B_m \) is the magnetic density amplitude, \( \alpha \) is the hysteresis loss calculation parameter.

One of the features of high-speed motor is high frequency, therefore, to reduce the core loss, it could reduce the magnetic density amplitude or reduce loss coefficient by selecting special core materials.

The air gap magnetic density is designed to be 0.4 T, and the stator outer diameter is designed to be 332 mm. The core material chooses 0.35 mm silicon steel sheet.

The non-uniform air gap flux caused by the stator slotting is one of the reasons for the eddy current loss of the rotor. However, the flywheel motor operates in a vacuum environment with limited heat dissipation conditions, therefore, to reduce the heat source, it is better to use multiple slots. In order to reduce the harmonic magnetomotive force, the number of slots in each pole and each phase is generally taken as an integer. Overall consideration, the number of slots per pole per phase is chosen as 4 and the number of slots is designed to be 48.

The stator winding current frequency of high-speed motor is high, so skin effect and proximity effect is more obvious, resulting in increased copper loss. Generally, according to the principle of wire radius similar or less than penetration depth of the highest frequency magnetic field, multi-strand thin wires can be selected and wound to reduce copper loss. The penetration depth of magnetic field in the conductor is shown as [6]:

\[
r \leq \sqrt{\frac{2}{\omega \mu \sigma}}
\]  

(4)

where \( r \) is the radius of the conductor, \( \omega \) is the angular frequency of the alternating magnetic field, \( \mu \) is the permeability of the conductor, \( \sigma \) is the conductivity of the conductor.
The radius of a single thin conductor is chosen as 0.8 mm. By selecting proper pitch, the double-layer windings can eliminate some subharmonic emf and thus reduce eddy current loss of the rotor. Winding is designed to be double winding, 5/6 short distance, star connection. The wire adopts multi-strand and wound round wire, considering the difficulty of winding and core processing comprehensively, the stator groove is chosen as pear groove with parallel teeth.

3.2. Design of the rotor

The rotor structure of the high-speed PMSM is mainly divided into two types: surface-mounted type and interior type [7]. The surface-mounted type rotor has a relatively simple structure, but it needs sleeve and has a large eddy current loss of permanent magnet. The permanent magnet of interior type rotor is located inside the iron core, and could be directly protected by pole boots when the rotating speed is not high, without the need for additional sleeve. The salient pole structure can realize wide range of constant power operation, and the eddy current loss of the permanent magnet is small. The motor speed is not too high, and the heat dissipation of the motor rotor is difficult, therefore, considering comprehensively, the motor rotor type is chosen as internal type rotor.

The high rotor speed makes the conventional lamination rotor unable to withstand the huge centrifugal force. Equation 5 shows the relationship between centrifugal force and rotational speed:

\[
\sigma = \rho r^2 \omega^2 = \rho v^2
\]

where \(\sigma\) is the centrifugal force, \(\rho\) is the density, and \(v\) is the rotor linear velocity.

From the above formula, it could be seen that with the increase of rotational speed, centrifugal force centrifugal force increases with the square rate, meanwhile, permanent magnet under tensile stress ability is very poor, this makes the rotor strength problem is particularly acute in the high-speed PMSM. In this regard, it is hoped that the ratio of length to diameter of the rotor is larger, that is, the rotor is more slender, and the centrifugal force is reduced by reducing the radius.

In addition to the strength of the rotor, there are also problems of vibration, balance and stability in the rotating state. Rotor rotates, the quality of the rotor center and turning center there will always be a certain deviation, make the rotor produces periodic interference of centrifugal force, when the speed of the rotor is in close proximity to the critical speed of the rotor, the rotor severe bending vibration will happen, cause the entire unit vibration, serious when even make damage to the rotor. In order to avoid resonance, it is necessary to ensure that its critical speed deviates from the operating speed of a certain range. The relationship between the critical speed and the diameter of the rotor is shown as:

\[
\omega_{cr} \approx \frac{D_r}{L_{sh}}
\]

where \(\omega_{cr}\) is the critical speed of the rotor, \(D_r\) is the rotor outer diameter, and \(L_{sh}\) is the rotor length.

In this respect, it is hoped that the rotor length diameter is relatively small, that is, the rotor is relatively short and thick.

The temporal harmonics of stator winding current and the spatial harmonics of stator magnetomotive force are the other two causes of rotor eddy current loss. In order to reduce their influence on the rotor, the air gap can be relatively large. Overall consideration, the air gap is designed to be 4 mm, the shaft diameter is designed to be 120 mm, and the outer diameter of the rotor is designed to be 220 mm.

Due to the large air gap of the flywheel motor, the permanent magnet is required to have high remanent flux density and coercive force. The motor operates at high speed, and the tensile strength of the permanent magnet is required to be high. Considering, the permanent magnet material of the rotor is selected for NdFeB.

Traditional interior PMSM rotor commonly used “1” structure, in order to further reduce the rotor PM eddy current loss, an improved rotor structure with “1” rotor permanent magnets layered and divided where placed in tangential and radial directions is proposed. Hierarchical block of permanent magnets to increase block number, cut off the eddy current path, at the same time by using the combined place in tangential and radial directions to make the part of the permanent magnet
embedded more deep, the influence of stator winding current time harmonic and stator space magnetomotive force on permanent magnets is reduced. The “1” and improved rotor structure are shown in figure 2.

![“1” rotor structure and improved rotor structure](image)

**Figure 2.** The “1” and improved rotor structures

4. FEM simulation results

4.1. No-load

The characteristics of the designed motor with "1" rotor structure and with the improved rotor structure are almost the same at no-load condition. Taking the improved rotor structure motor as an example, figure 3 shows magnetic flux density and magnetic flux distribution of the designed motor under no load condition. Figure 4 shows air-gap magnetic flux density and back electromotive force of the designed motor under no load condition.

It could be seen from the figures that, for the designed motor, the magnetic flux distribution and magnetic flux density is reasonable, the air-gap flux magnetic density meets the design demands, and the no-load back electromotive force changes in a sinusoidal pattern periodically.

![Magnetic flux density and magnetic flux distribution](image)

**Figure 3.** Magnetic flux density and magnetic flux distribution of the designed motor under no-load condition
4.2. Load

The main performance difference between the designed motor with “I” rotor structure and with improved rotor structure is the PM eddy current loss at load condition. Figure 5 shows PM eddy current loss of the designed motor with the two rotor structures at rated conditions.

Figure 5. PM eddy current loss of the designed motor with the two rotor structures at rated condition

Figure 6. PM eddy current loss comparison of the designed motor with the two rotor structures at rated condition
It could be seen from the above figures that PM eddy current loss of the designed motor with improved rotor structure is reduced about 22.8% than that of the designed motor with 1 rotor structure. This is because the PMs in the improved rotor cut off the eddy current path in sections, and some deeply buried PMs are less affected by the stator side.

5. Conclusion
This paper analyzes and summarizes the design features of FESS motor. In combination with the design method of the high-speed PMSM, a 250kW, 12000r/min high-speed PMSM for FESS is designed. The rationality of the design scheme is verified by finite element simulation, and the following conclusions are drawn:
(1) The most prominent design demand of motor for FESS is to reduce no-load core loss and rotor eddy current loss;
(2) In the design process, selecting the 2 or 4 pole structure, large air gab and the thin silicon steel sheet can effectively reduce the core loss;
(3) Under the condition of strength permission, the interior structure motor is more suitable for FESS than the surface-mounted type due to its advantages such as small eddy current loss and wide efficient speed range;
(4) Proper partitioning and deep embedding of the permanent magnet can effectively reduce PM eddy current loss;
(5) The motor used for FESS in vacuum, and generally uses magnetic suspension bearing without mechanical contact. In general, the high numerical value of wind friction loss and mechanical friction loss in high-speed motor can be ignored, so the motor efficiency is relatively high.

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