Performance analysis of superconducting generator electromagnetic shielding

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Abstract. In this paper, the shielding performance of electromagnetic shielding systems is analyzed using the finite element method. Considering the non-iron-core rotor structure of superconducting generators, it is proposed that the stator alternating magnetic field generated under different operating conditions could decompose into oscillating and rotating magnetic field, so that complex issues could be greatly simplified. A 1200KW superconducting generator was analyzed. The distribution of the oscillating magnetic field and the rotating magnetic field in rotor area, which are generated by stator winding currents, and the distribution of the eddy currents in electromagnetic shielding tube, which are induced by these stator winding magnetic fields, are calculated without electromagnetic shielding system and with three different structures of electromagnetic shielding system respectively. On the basis of the results of FEM, the shielding factor of the electromagnetic shielding systems is calculated and the shielding effect of the three different structures on the oscillating magnetic field and the rotating magnetic field is compared. The method and the results in this paper can provide reference for optimal design and loss calculation of superconducting generators.

1. Introduction

In recent years, there is an increasing demand for high power density, high capacity generators. In wind power and other fields, the conventional generator volume and weight is too large, which restricted the further industry development. The magnetic induction intensity of superconducting generators can reach a few Tesla. Relative to the conventional generators, superconducting generators have small volume and weight, compact structure, high power density and efficiency, big ultimate capacity and good stability. Therefore, it is regarded as one of the most attractive and novel generators with business competitiveness in the near future [1].

The electromagnetic shielding system is one of the unique special structures of superconducting generators. When superconducting windings work in an alternating magnetic field, AC losses are produced in the windings. The losses increase the low temperature medium dosage and refrigeration power consumption and cause the temperature rise, so that the efficiency of the generators is reduced. When serious, temperature rise will lead to the quench of superconducting tapes. The electromagnetic shielding is used to shield the superconducting windings from the alternating magnetic field and reduce the effect of alternating magnetic field on the superconducting windings, in order to ensure the normal work of the superconductor in the superconducting state, improve the efficiency of generators. For superconducting generators, the electromagnetic shielding is a very important key part.

Since cryogenic superconducting material had been applied to the first superconducting machine in the 1960s, the electromagnetic shielding became research focus in the field of superconducting
machines. In 1974, Kirtley at the Massachusetts Institute of Technology proposed that the electromagnetic shielding system must provide a high degree of isolation to the rotor from rapidly time-varying magnetic field components due to space harmonics of armature fields, time harmonics on the system, system imbalance resulting in negative sequence currents, and faults, and while providing adequate shielding of the rotor, it must not be too good a shield, for it must allow rotor flux changes due to control to pass through [2].

The calculation of shielding effectiveness of superconducting machine electromagnetic shielding system needs to solve electromagnetic field distribution. The main calculation methods are field analytical method and finite element method. In the paper of T. J. E. Miller et al., the fast Fourier transform was applied to a range of transient-screening problems in the design of a superconducting a.c. generator, and several important characteristics of screens in this type of machine were brought out. The integral-transform approach was shown to have important advantages in obtaining solutions to transient-field problems of electromagnetic screen [3]. A study of P.J. Lawrenson etc. on the screening and damping properties of superconducting a.c. generators shows that a single screen is unlikely to provide both adequate screening and damping. The double screen gives improved performance but is subject to degradation of both properties because of interactions between the screens [4]. Based on finite difference method or finite element method, [5], [6] introduced T-Ω and A*-φ Method to the electromagnetic field distribution calculation of superconducting generator electromagnetic shielding system. The above research subjects are low-temperature superconducting machines.

HTS tape brought new opportunities for the development of superconducting generators. HTS tape can run more stably in the superconducting state, has higher critical current, smaller AC losses in harmonic magnetic fields [7]. In order to maximize the superconducting machine power density, the thickness of a single cylindrical copper shielding is optimized using analytical method in [8]. At present, the research on the theory and optimization design of HTS generator electromagnetic shielding system is still relatively few. With the development of HTS generators, new challenges will be brought for performance analysis and simulation of electromagnetic shielding system.

2. Structure and main parameters of calculation prototype of superconducting generators

In order to analyze and calculate the electromagnetic shielding characteristics of superconducting generator shielding system, we chose a 1200KW, 6-pole synchronous superconducting generator. The generator stator core is made of silicon steel, the stator winding is made of a conventional wire armature, and the rotor field winding is made of superconducting tapes. Its rotor is coreless structure. The structure of the generator is shown in Figure 1.

![Figure 1. Structure of the generator](image-url)
The main parameters and dimensions of the generator are as follows:

- Apparent rated power: 1200KW
- Rated voltage: 6300V
- Number of armature winding phases: 3 phase
- Number of pole pairs: 3
- Stator outer diameter: 800mm
- Stator inner diameter: 570mm
- Stator core length: 500mm
- Number of stator slots: 36
- Number of conductors per stator slot: 32
- Gap width: 5mm
- Shielding tube outer diameter: 560mm
- Shielding tube inner diameter: 530mm
- Rotor inner diameter: 170mm

3. Finite element analysis

When the superconducting generators are operated under steady state or transient operation state, the fundamental or harmonic component of the armature reaction magnetic fields produced by the stator armature winding current may be a transient or alternating magnetic field for the superconducting field windings and other metal components in rotor. The magnetic fields generate AC losses within them. In order to minimize these losses, we need to install an electromagnetic shielding tube on the generator rotor, and do the shielding system performance analysis and optimization.

The magnetic fields needed to be shielded include: the higher harmonic components of armature reaction magnetic field and the vibration magnetic field generated by generator structural asymmetry in symmetrical steady-state operation of superconducting generators; the zero sequence component and negative sequence component of armature reaction magnetic field in asymmetric steady state operation; the transient magnetic fields generated by transient current or short circuit current in transient operation, three-phase or single-phase short circuit; the oscillating magnetic field generated at the oscillation and so on. These electromagnetic processes of superconducting generators are usually very complex and we can not analyze and research one by one. In order to simplify the problem, we can break down these transient or alternating magnetic fields produced at different operating states into two categories: one is oscillating magnetic field, while the other is rotating magnetic field. Below we will analyze separately shielding effect of generator electromagnetic shielding system on these two types of magnetic fields, to achieve electromagnetic shielding system performance analysis and optimization.

Because the magnetic core is not used in the rotor of the superconducting generator analyzed, the axial component of the magnetic field within the space occupied by the rotor is greater than the conventional one, which has magnetic core in rotor. Considering that the radial and circumferential component of alternating magnetic field are maximum in cross-section through the axial center of generator, and as far away from the cross-section, they continue to decrease, we only need to analyze the shielding case of the alternating magnetic in the cross-section. On this basis, reasonable shielding system optimization can guarantee its shielding performance to meet the requirements. Therefore, the analysis of electromagnetic shielding system will be simplified as a two-dimensional field problem.

In order to consider effect of structure and size of the electromagnetic shield system on its shielding performance, we analyzed three different electromagnetic shielding system: scheme I, the electromagnetic shielding system consists of a 15 mm thick copper tube; scheme II, the electromagnetic shielding system consists of the composite structure of a 5 mm thick stainless steel outer tube and 10 mm thick copper inner tube; scheme III, the electromagnetic shielding system consists of the composite structure of a 10 mm thick stainless steel outer tube and 5 mm thick copper
inner tube. The electrical conductivity of copper material is $5.8 \times 10^7$ Siemens/m, the electrical conductivity of stainless steel is $1.1 \times 10^6$ Siemens/m.

1.1. Oscillating magnetic field

The description equation of oscillating magnetic field can be expressed as follows:

$$\nabla \times \frac{1}{\mu} \nabla \times A = (\sigma + j \omega \varepsilon)(-j \omega A - \nabla \phi)$$

(1)

where $A$ is magnetic vector potential, $\phi$ electric scalar potential, $\mu$ permeability, $\sigma$ conductivity, $\varepsilon$ dielectric constant, $\omega$ angular frequency.

In the calculation of oscillating magnetic field distribution, the rotor core is not taken into account. The oscillating magnetic field can be broken down into a series of different frequency oscillating magnetic fields which vary with time according to sinusoidal law. Since the oscillating magnetic field changes in accordance with sinusoidal law, equation (1) can be simplified to:

$$\nabla^2 \hat{A} = j \omega \mu \varepsilon A - \mu \hat{J}$$

(2)

where $\hat{A}$ is the plural form of magnetic vector potential, $\hat{J}$ the plural form of conduction current density.

In addition to the most important fundamental, the 5th and 7th harmonics and tooth harmonics should be considered in analyzing the magnetic field of superconducting generators. The tooth harmonics of the calculation prototype of superconducting generators are the 11th and 13th harmonics. Here, only the fundamental, fifth harmonic and 11th harmonics are considered.

According to the theory of generator windings, when there is a sinusoidal time-varying current only in one phase of the three-phase stator windings of the generator, the magnetic field generated by the stator windings is an oscillating magnetic field. The magnetic field was calculated using the finite element method, when there was a 110A, 50 Hz sinusoidal alternating current only in one phase of the three-phase stator windings of the generator.

![Figure 2. Magnetic field lines without shielding](image1)

![Figure 3. Magnetic field lines with shielding](image2)

Figures 2 and 3 are the distribution of the magnetic field lines on the cross-section of the generator without electromagnetic shielding and with a 15 mm thick copper tube shielding. By comparing Figure 2 and 3, it can be found that most of the oscillating magnetic field generated by stator windings is shielded outside the rotor low-temperature region by the copper tube.
Figure 4 is the magnetic flux density amplitude distribution curve from the starting point coordinate (0,85) to the end point coordinates (0,265) along the Y axis, that is from rotor inner diameter to shielding tube inner diameter, when there is no electromagnetic shielding system and there are three different electromagnetic shielding systems. By comparison can it be learn that: the electromagnetic shielding system dramatically reduces the oscillating magnetic field into the rotor; the greater the thickness of copper tube is, the better the shielding effect is. When the copper tube has larger thickness, not only the amplitude of the oscillating magnetic field into the rotor is smaller, but its decay is accelerated with the increasing depth into the rotor area. The reason for this phenomenon is that the conductivity of copper is greater than stainless steel.

![Figure 4. Magnetic flux density amplitude distribution curves](image)

(a) Without shielding; (b) The shielding of a 15 mm thick copper tube; (c) The composite shielding of a 5 mm thick stainless steel outer tube and 10 mm thick copper inner tube; (d) The composite shielding of a 10 mm thick stainless steel outer tube and 5 mm thick copper inner tube.

The figure 5 shows the eddy-current distribution in the shielding tube of three different electromagnetic shielding systems. It can be seen from the figure: the eddy currents in shielding tube, which are induced by oscillating magnetic field, are mainly distributed in the copper tube, and due to the skin effect, the eddy currents are concentrated on the surface of the copper tube.
The oscillating magnetic field and the eddy currents were calculated, when there was a 110A, 250Hz (corresponding to the 5 magnetic field harmonics) sinusoidal alternating current and a 110A, 550Hz (corresponding to the 11 magnetic field harmonics) sinusoidal alternating current only in one phase of the three-phase stator windings of the generator. The calculation results of the oscillating magnetic field and the eddy current distribution are not given here.

![Eddy-current distributions in shielding tube](image)

**Figure 5.** Eddy-current distributions in shielding tube

(a) The shielding of a 15 mm thick copper tube; (b) The composite shielding of a 5 mm thick stainless steel outer tube and 10 mm thick copper inner tube; (c) The composite shielding of a 10 mm thick stainless steel outer tube and 5 mm thick copper inner tube.

Based on the above calculation of the magnetic field, the shielding factors are calculated respectively, when the three different frequency currents flow in the one phase stator winding of the generator with the three different electromagnetic shielding structures. The calculation formula of the shielding factor [9] is:

\[ S(f) = \frac{H_\theta}{H_{\theta_0}} \]  

(3)

where \( H_{\theta_0} \) is the circumferential component amplitude of the oscillating magnetic field strength at a point inside the rotor without electromagnetic shielding system, \( H_\theta \) is the circumferential component amplitude of the oscillating magnetic field strength at the same point inside the rotor with electromagnetic shielding system.

Table 1 shows the shielding factors of the three different electromagnetic shielding systems at coordinate point (0,205) when there is 50Hz, 250Hz or 550 Hz 110A sinusoidal current in one phase stator windings respectively.
It can be seen from the data in Table 1: the higher the frequency of stator winding current, the smaller the shielding factor, which means that the electromagnetic shielding system has better shielding effect; the shielding factor of scheme 1 is smaller than scheme 2, the shielding factor of scheme 2 is smaller than scheme 3, that is, the shielding effect of scheme 1 is better than scheme 2, the shielding effect of scheme 2 is better than scheme 3. This shows that the thicker the copper tube of electromagnetic shielding system, the better its shielding effect on the oscillating magnetic field.

| Scheme | 50 Hz  | 250Hz | 550Hz |
|--------|--------|-------|-------|
| Scheme1| 0.075  | 0.0074| 0.0055|
| Scheme2| 0.11   | 0.022 | 0.0036|
| Scheme3| 0.21   | 0.07  | 0.022 |

### 1.2. Rotating magnetic field

In calculating the rotating magnetic field of the superconducting generator, a three-phase sinusoidal alternating current with a phase difference of 120 time electrical degrees between phase and phase is applied to the three-phase stator winding with a phase difference of 120 spatial electrical degrees between phase and phase. The different frequency three-phase sinusoidal alternating currents produce the corresponding different speed rotation magnetic fields in the superconducting generator. In the analysis and calculation of these rotation magnetic fields, moving conductor electromagnetic field equation is used as description equation. It can be expressed as:

$$\nabla \times \frac{1}{\mu} (\nabla \times A) = J_s - \sigma \frac{dA}{dt} - \sigma \nabla v$$

(4)

where $A$ is magnetic vector potential, $J_s$ conduction current density, $\mu$ permeability, $\sigma$ conductivity, $V$ velocity of the moving part.

In the generator, the rotating magnetic field generated by a 50 Hz three-phase sinusoidal alternating current is the most important. Here, we assumed that a 110A, 50 Hz three-phase sinusoidal alternating current is applied to the three-phase stator winding and the rotor is stationary. In this case, a 1000 r/min speed rotating magnetic field in the generator is generated by the stator winding three-phase sinusoidal alternating current. Since the rotor is stationary, the rotating speed of the rotating magnetic field is 1000 r/min relative to the rotor. The magnetic field distribution was calculated in the rotor without the electromagnetic shielding system and with the above described three different electromagnetic shielding systems.
Figure 6 and 7 are the magnetic force line distribution on the cross section of the generator without electromagnetic shielding system and with a 15 mm thick copper tube respectively. Comparing the two figures, it can be found that most of the rotating magnetic field generated by the stator windings is shielded outside the rotor by the electromagnetic shielding tube.

According to the calculation results of the magnetic field, the shielding factor was obtained. For scheme 1, 2, 3, the shielding factor value is 0.067, 0.125, 0.286 respectively. The results show that the shielding effect of the scheme 1 on the rotating magnetic field is better than scheme 2, the shielding effect of Scheme 2 is better than scheme 3. This conclusion is consistent with oscillating magnetic field.

4. Conclusion
For any working condition of the non-iron-core rotor superconducting generators, the magnetic field from the stator windings, which is able to generate the loss in superconducting windings or rotor parts, can be decomposed into oscillating magnetic field and rotating magnetic field. The shielding effect of electromagnetic shielding systems on the oscillating magnetic field and the rotating magnetic field are then analyzed respectively, so that the original complex problem is simplified.

The comparison of the shielding factors of the three electromagnetic shielding tubes shows that both the copper tube and the stainless steel-copper composite tube can better shield oscillating magnetic field and rotating magnetic field. The better the electrical conductivity of electromagnetic shielding tube, the better the shielding effect.

The calculation method presented here can be used to analyze the performance of electromagnetic shielding systems and calculate the losses of generator parts in low temperature area when considering various complex operating conditions.

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References
[1] Snitchler G, Gamble B, King C, Winn P 2011 10 MW class superconductor wind turbine generators IEEE Transactions on Applied Superconductivity vol 21 n 3 Part 2, pp 1089-1092
[2] Kirtley J L, Furuyama J M 1975 A design concept for large superconducting alternators IEEE Transactions on Power Apparatus and Systems vol 94 pp. 1264-1269
[3] Miller T J E and Lawrenson P J 1976 Penetration of transient magnetic fields through conducting cylindrical structures with particular reference to superconducting a.c. machines Proceedings of the institution of Electrical Engineers vol 123 pp. 437-442
[4] Lawrenson P J, Miller T J E, Stephenson J M 1976 Damping and screening in the synchronous superconducting generator Proceedings of the institution of Electrical Engineers vol 123 n 8 pp787-794
[5] Leurs L and Stoll R L 1986 Three-dimensional quasi-static magnetic field in superconducting-rotor synchronous generators with a magnetic steel rotor screen Generation, Transmission and Distribution, IEE Proceedings C vol 133 pp 69-80
[6] Takuma T, Akita S, Kawamoto T, and Yasuda H 1990 Calculation of eddy current in the damper of a superconducting generator IEEE Transactions on Magnetics vol 26 pp 921-924
[7] Barnes P N, Sumption M D, and Rhoads G L 2005 Review of high power density superconducting generators: Present state and prospects for incorporating YBCO windings Cryogenics vol 45 pp 670-686
[8] Elhaminia P, Yazdanian M, Zolghadri M R and Fardmanesh M 2011 An analytical approach for optimal design of rotor iron for superconducting synchronous machine 37th Annual Conference on IEEE Industrial Electronics Society pp 1741-1745
[9] Bumby J R 1983 Superconducting rotating electrical machines Clarendon Press