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Study on the adjustment capability of the excitation system located inside superconducting machine electromagnetic shield

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Abstract. The ability for the excitation system to adjust quickly plays a very important role in maintaining the normal operation of superconducting machines and power systems. However, the eddy currents in the electromagnetic shield of superconducting machines hinder the exciting magnetic field change and weaken the adjustment capability of the excitation system. To analyze this problem, a finite element calculation model for the transient electromagnetic field with moving parts is established. The effects of three different electromagnetic shields on the exciting magnetic field are analyzed using finite element method. The results show that the electromagnetic shield hinders the field changes significantly, the better its conductivity, the greater the effect on the superconducting machine excitation.

1. Introduction

Comparing to conventional electrical machines, the superconducting synchronous machine has smaller volume and weight, higher efficiency and power density, and bigger ultimate capacity. Therefore, it is regarded as one of the most attractive electrical machines in wind power, ship driving and other fields [1]-[3].

Generally, the field winding of superconducting synchronous machines is made of superconducting tapes. Although only DC current flows through the superconducting field winding, the alternating magnetic field generated by the armature winding will reach the field winding. Because the superconducting field winding works in an alternating magnetic field, AC losses are produced in the field winding. The losses reduce the efficiency of the superconducting machines and cause the rise in temperature and the quench of superconducting tapes. In order to shield the superconducting field winding from the alternating magnetic field and reduce its effect on the superconducting field winding, an electromagnetic shield must be used [4]-[8].

The exciting current of the field excitation system must be adjustable, when the synchronous machine is working. As an important part of synchronous machines, the excitation adjustment capability of the field excitation system directly affects the operating characteristics of the machines, and has an important impact on the operation of power systems. Especially for the wind power or the marine power station with a relatively small capacity, a greater fluctuation of grid voltage will be produced when the power system load changes. Therefore, higher requirements for adjustment capability of the field excitation system will be put forward.

Generators are considered as an example below. The main tasks of the field excitation adjustment include [9]: (1) During normal operating conditions, the load of power system always fluctuates, the output power of the synchronous generator must also change accordingly. The exciting current should be adjusted so that the generator output voltage remains within an allowable range. (2) The field excitation system is also responsible for the reactive power rational allocation between parallel operation units, the reactive power output must be changed according to the needs of the power system by adjusting the exciting current. (3) When a short circuit fault occurs during low load operation of the power system, the small short-circuit current may result in that the protection device does not work correctly. The force excitation should be carried out to increase the short-circuit current so that the protection device can act instantly. (4) When the internal fault of the generator or the connected transformer occurs, the fast de-excitation of the generator excitation system is required in order to reduce the damage caused by the fault. Thus, the quick adjustment capability of the excitation system plays a very important role in maintaining the normal operation of generators and power systems.

Since the field winding of the superconducting machine excitation system is located in the electromagnetic shield, its exciting current change will induce eddy currents in the electromagnetic shield tube. The eddy currents will hinder the exciting magnetic field change and weaken the adjustment capability of the excitation system. Currently, the study of the superconducting machine electromagnetic shield focus on the aspect how to prevent the alternating magnetic field produced by the stator armature winding into the rotor [3]-[5], and few studies have looked at this issue of how it affects the fast adjustment capability of excitation system. Therefore, an in-depth research on this issue is very necessary.

2. Finite Element Analysis Model

The electromagnetic shield of superconducting synchronous machines is composed of cylindrical metal material tubes. Since the induced eddy currents inside the metal material tubes must be considered in our analysis, the analysis method for conventional electrical machines is no longer suitable. In addition, the effects of electromagnetic shield on the excitation adjustment capacity belong to the problem of the transient electromagnetic field with moving parts, which further increases the difficulty of the analysis. In order to obtain more accurate results, finite element method is thereby adopted.

The description equation of the analyzed transient electromagnetic field with moving parts can be expressed as follows:

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

where A is magnetic vector potential, J_s conduction current density, μ permeability, σ conductivity, v velocity of moving part.

A 6-pole superconducting synchronous generator was calculated using finite element method. The main parameters and dimensions of the generator are listed in [10]. The generator stator core is made of silicon steel 1010. The stator armature winding is made of conventional copper wires and the number of conductors per slot is 20. The rotor field winding is made of superconducting tapes and the number of turns per pole is 100. The rotor is a coreless structure and the electromagnetic shield tube is located in the rotor surface. The structure of the superconducting synchronous generator is shown in Figure 1.

In order to consider the effect of the structure, material and size of the electromagnetic shield on the quick adjustment capability of the excitation system, we have analyzed three different electromagnetic shield solutions:

The electromagnetic shield consists of a 15 mm thick copper tube (**Scheme 1**); a 5 mm thick stainless steel outer tube and a 10 mm thick copper inner tube (**Scheme 2**); a 10 mm thick stainless steel outer tube and a 5 mm thick copper inner tube (**Scheme 3**).

The electrical conductivity of copper wires is assumed to be 5.8×10^7 Siemens/m, the electrical conductivity of stainless steel is assumed to be 1.1×10^6 Siemens/m. The sort from large to small by the conductivity of the three electromagnetic shield solutions is Scheme 1, 2, 3.

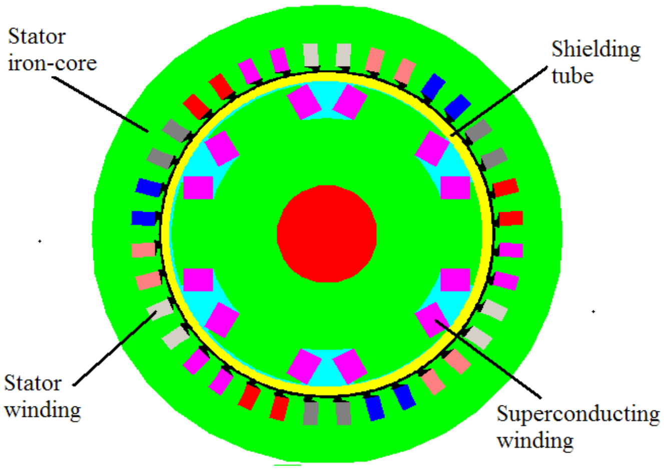


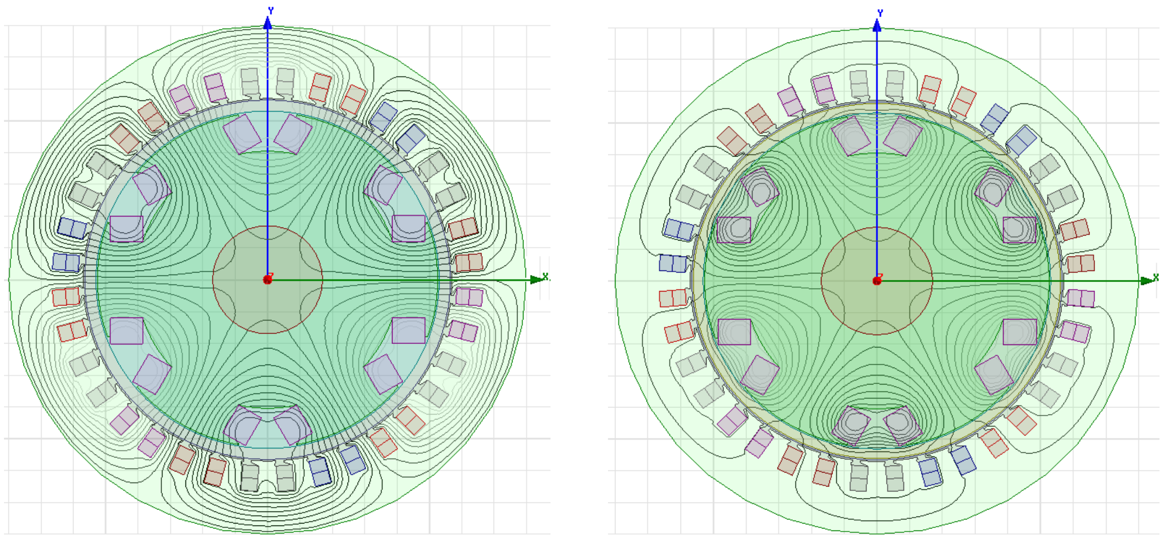
Figure 1. Structure of superconducting synchronous generator

3. Calculation Results and Analysis

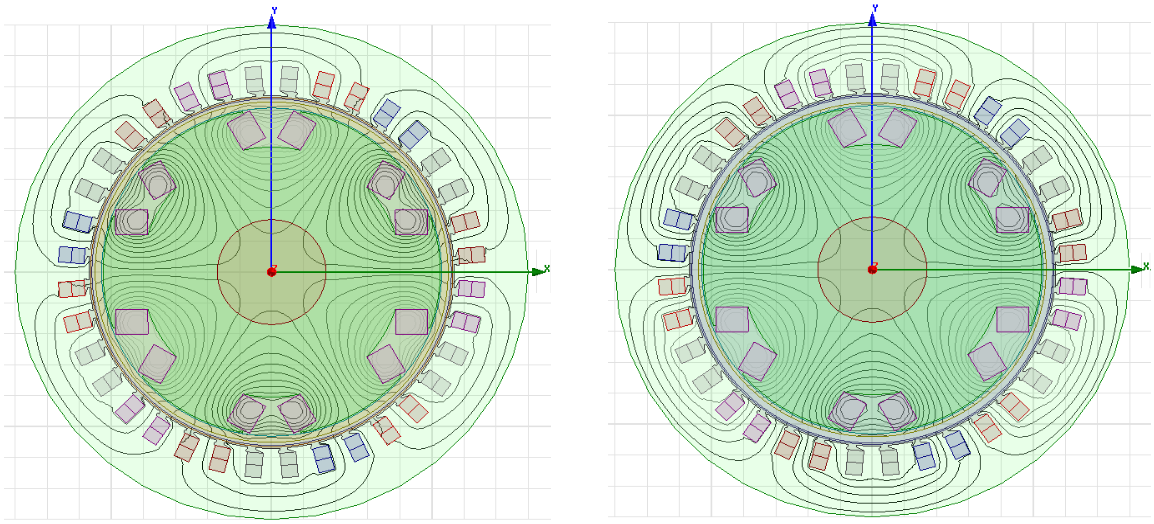
Referring to the working state of the field windings in regulating the magnetic field, we have calculated the following three different cases.

3.1 Applying DC voltage to the field winding terminal

In no-load steady state operation, the initial exciting current in the generator field winding is 0. At time t = 0, by applying 500 V of DC voltage to the field winding terminal, the exciting current is produced. Figure 2 and Figure 3 show the magnetic field line and flux density distribution on cross section of the generator at t = 20ms respectively.

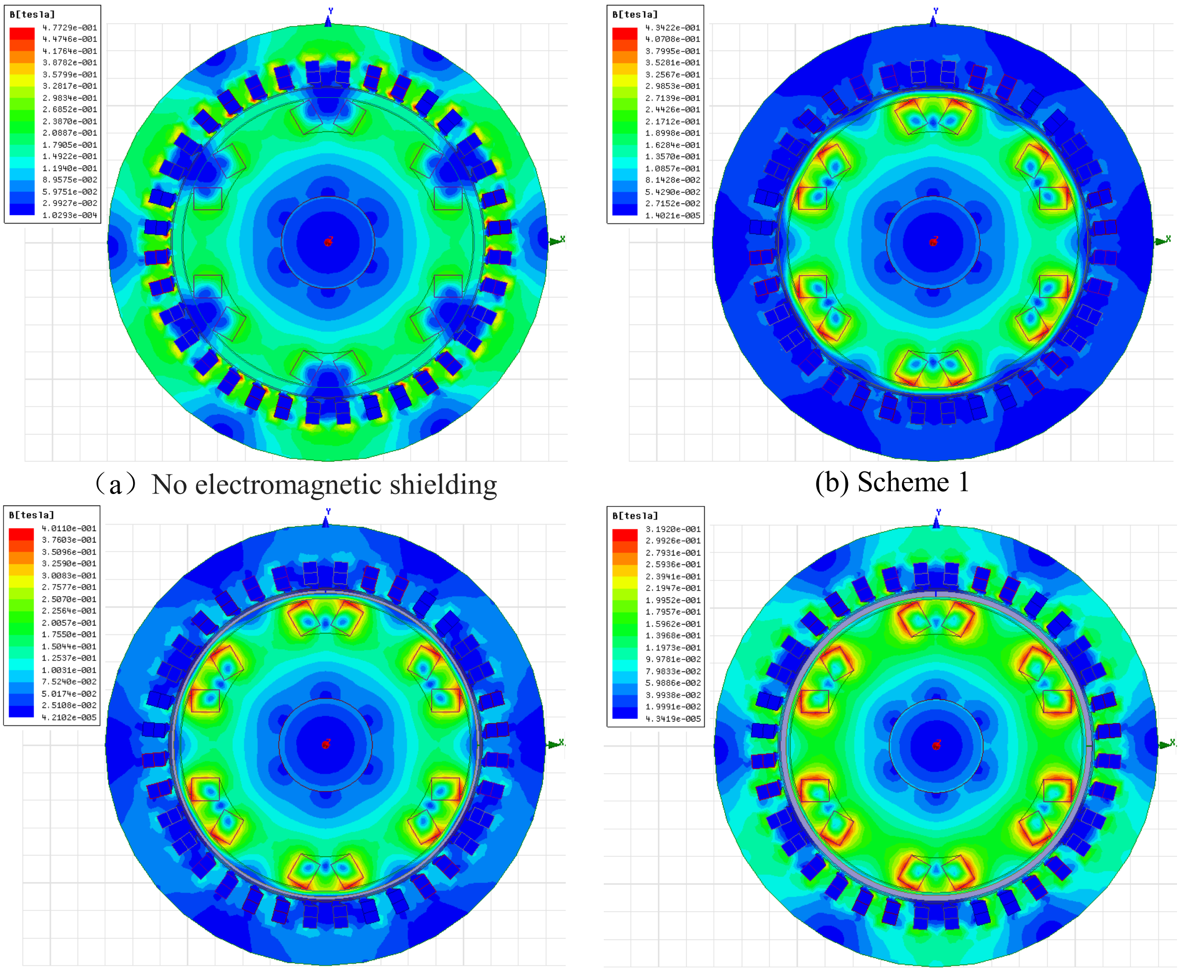


（a）No electromagnetic shielding (b) Scheme 1



(c) Scheme 2 (d) Scheme 3

Figure 2. Magnetic field line distribution on cross section of generator at t = 20ms



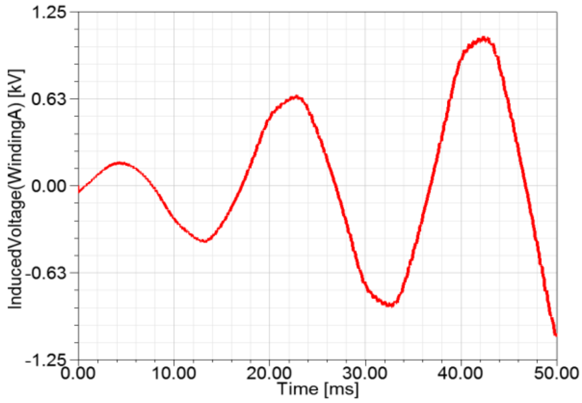
(a) No electromagnetic shielding (b) Scheme 1

(c) Scheme 2 (d) Scheme 3

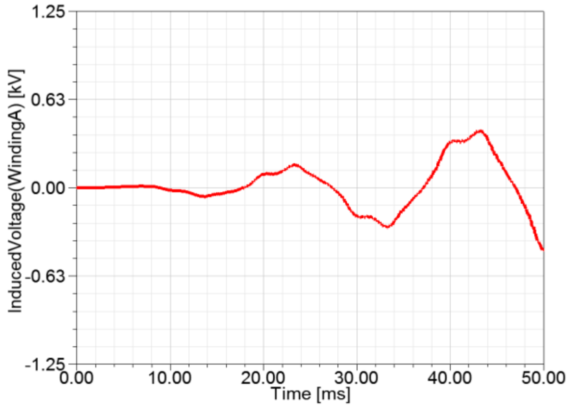
Figure 3. Flux density distribution on cross section of generator at t = 20ms

In Figure 2, when the generator has no electromagnetic shield, the magnetic field line distribution in the stator region is the densest, when the generator has an electromagnetic shield, it is relatively sparse, and the magnetic field line distribution in Scheme 1 is the sparsest. In Figure 3, when the generator has no electromagnetic shield, the magnetic flux density in the stator region is the strongest, when the generator has an electromagnetic shield, it is relatively weak, and the magnetic flux density in Scheme 1 is the weakest. This means that the electromagnetic shield hinders the exciting magnetic field change and weakens the adjustment capability of the excitation system.

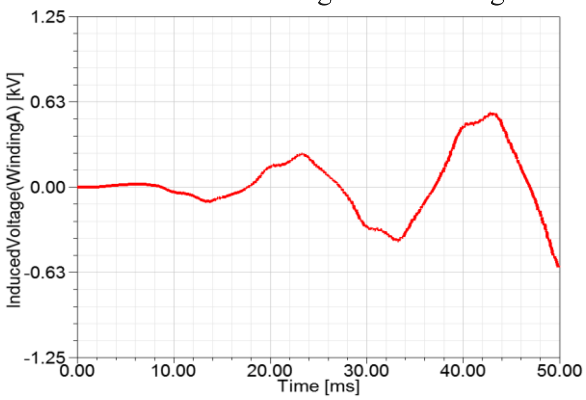
Figure 4 shows the terminal voltage curves of the A phase stator armature winding in the cases of no electromagnetic shield and the three different electromagnetic shields when the field winding terminal voltage is applied 500 V since t = 0.



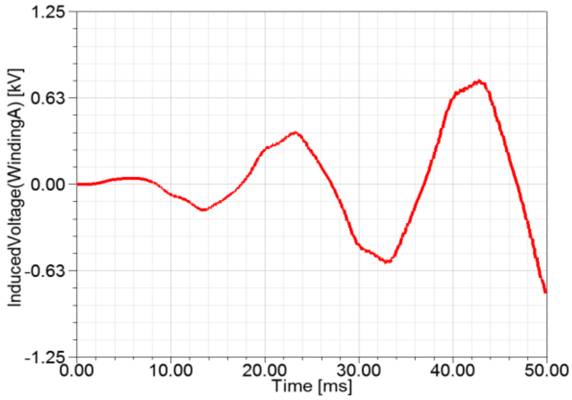
（a）No electromagnetic shielding



(b) Scheme 1



(c) Scheme 2



(d) Scheme 3

Figure 4. Terminal voltage curves of A phase armature winding

By comparison can it be seen that: When the generator has no electromagnetic shield, the terminal voltage increase of its armature winding is the fastest. When the generator has electromagnetic shield, the terminal voltage increase of the stator armature winding becomes slow, and the terminal voltage increase is the slowest in Scheme 1, but it is relatively the fastest in Scheme 3. It also shows that the better the conductivity of the electromagnetic shield, the greater the effect on the excitation regulation.

3.2 Reversing the field winding terminal voltage

In no-load steady state operation, the initial exciting current in the generator field winding is 1000A. At time t = 0, by reversing the field winding terminal voltage, the exciting current is changed. Figure 5 shows the terminal voltage curves of the A phase stator armature winding in the cases of no

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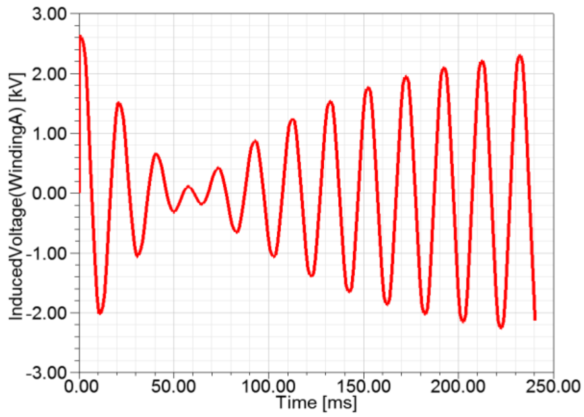
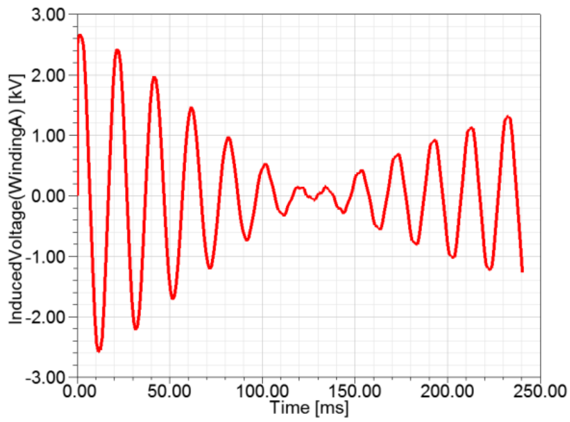
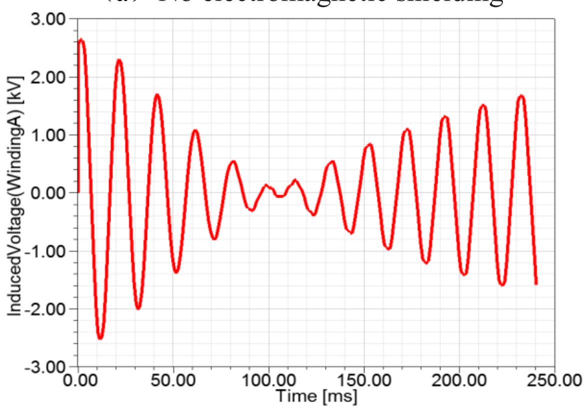
electromagnetic shield and the three different electromagnetic shields when the field winding terminal voltage is reversed by the same.



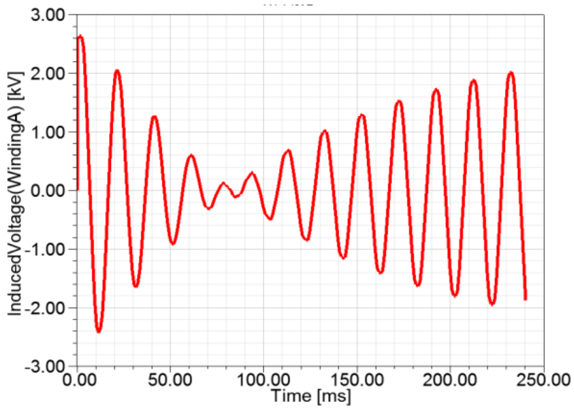
（a）No electromagnetic shielding



(b) Scheme 1



(c) Scheme 2



(d) Scheme 3

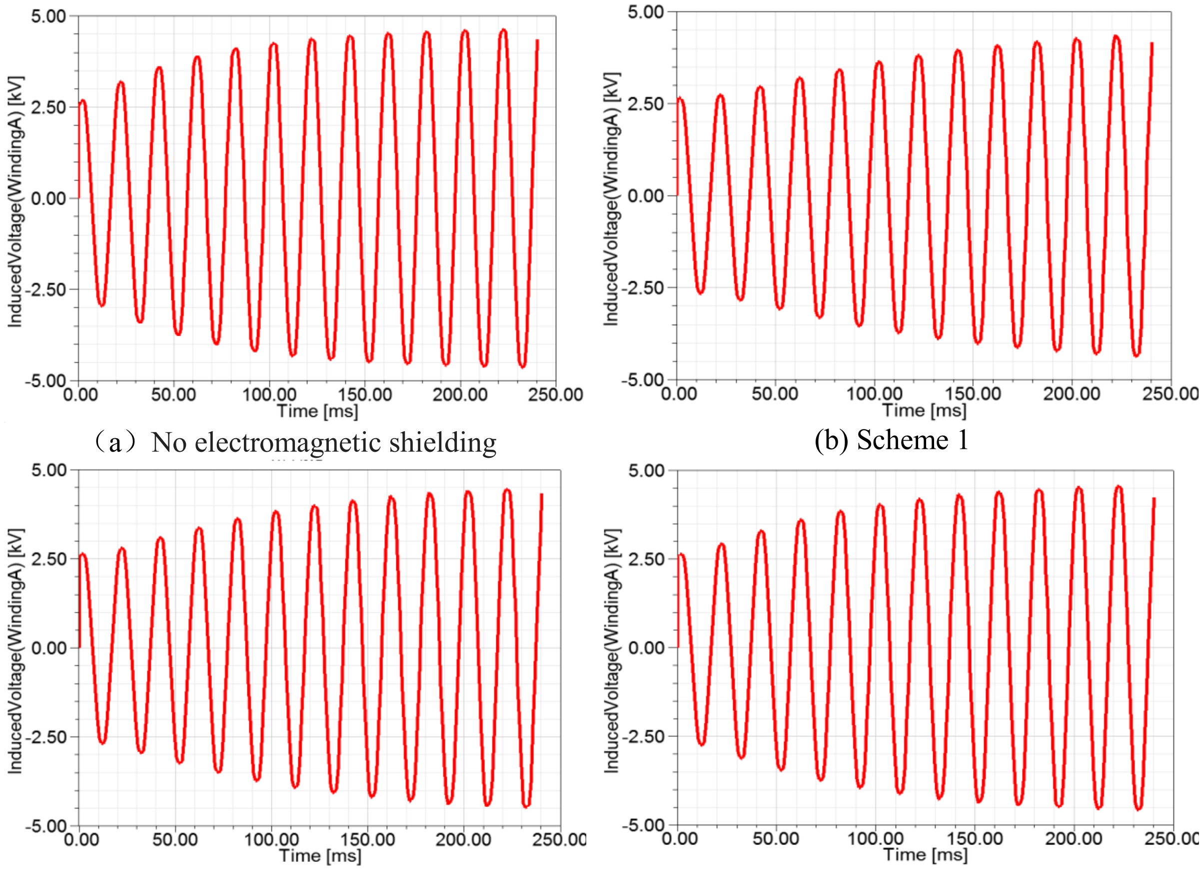
Figure 5. Terminal voltage curves of A phase armature winding

As can be seen from the figure: When no electromagnetic shielding, the stator armature winding terminal voltage reaches the zero-crossing point at fastest, but for Scheme 1, the most time is required.

3.3 Doubling the field winding terminal voltage

In no-load steady state operation, the initial exciting current in the generator field winding is 1000A. At time t = 0, by doubling the field winding terminal voltage, the exciting current increases.

Figure 6 shows the terminal voltage curves of the A phase stator armature winding in the cases of no electromagnetic shield and the three different electromagnetic shields when the field winding terminal voltage is increased by the same.



（a） No electromagnetic shielding (b) Scheme 1

(c) Scheme 2 (d) Scheme 3

Figure 6: Terminal voltage curves of A phase armature winding

By comparison can it be seen that: When the generator has no electromagnetic shield, the increase of its armature winding terminal voltage is the fastest. The electromagnetic shield makes the stator armature winding terminal voltage increase slower. For the different solutions of the electromagnetic shield, the terminal voltage increase of the stator armature winding is the slowest in Scheme 1, but it is relatively the fastest in Scheme 3. This means that the better the conductive property of the electromagnetic shield, the bigger the impact on the armature winding terminal voltage increase.

To find out the quantity relationship of the effect of the different electromagnetic shields on the armature winding terminal voltage change, we chose two different time points t = 22.5 and 231.5ms to be compared. Table 1 shows the terminal voltage of the A phase stator armature winding and the terminal voltage ratio against no electromagnetic shield at the two time points.

Table 1. A phase armature winding terminal voltage and ratio

	Time(ms)	Voltage(V)	Ratio	Time(ms)	Voltage(V)	Ratio
No shield	22.5	3202.29	1	231.5	-4599.99	1
Scheme 1	22.5	2743.38	0.857	231.5	-4369.91	0.950
Scheme 2	22.5	2813.12	0.878	231.5	-4484.01	0.975
Scheme 3	22.5	2939.73	0.918	231.5	-4563.05	0.992

It can be seen from the table: The better the conductive property of electromagnetic shield, the smaller the terminal voltage at a same time point. This conclusion is consistent with the previous. The terminal voltage ratio at the time point t = 22.5ms is less than at the time point t = 231.5ms. This indicates that with the time increasing, the influence of the electromagnetic shield becomes smaller and smaller.

4. Conclusion

A 6-pole superconducting synchronous generator without electromagnetic shield and with three different electromagnetic shields was calculated using finite element model for the transient electromagnetic field with moving parts. By means of applying, reversing and doubling the field winding terminal voltage, the exciting current in the field winding of the superconducting generator is altered. The changing process of the magnetic field, the eddy current inside electromagnetic shield and the terminal voltage of the A phase stator armature winding with the exciting current is obtained through the calculation. The study shows, a better conductive property of the electromagnetic shield can improve its shielding capability, while reducing the excitation adjustment capability of superconducting synchronous machines.

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