Review of Numerical Simulation to Reduce the AC Loss of High Temperature Superconducting Generators

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Abstract: This review of the literature on numerical simulation of high temperature superconducting(HTS) generators and associated structures via finite element method(FEM) software COMSOL MUTIPHYSICS to improve generator efficiency. This paper expounds the optimal design of HTS generator by different modeling, and finally summarizes the similarities of different designs, forming a literature review.

Keywords: HTS Generators; FEM; COMSOL MUTIPHYSICS; Generator Efficiency

Introduction

Classical electromagnetic theory which has been developed for more than 140 years is widely used in People's daily life recently. With increasing awareness for the protection of natural resources gradually increasing while novel electricity machines consume electrical energy much faster than the old ones, human beings urgently need more efficient generators to meet various usage scenarios. The efficiency of traditional generators has almost reached the performance limit of the conventional conductor. However HTS generators have a smaller volume, a larger capacity of current transmission and can be used in boats. This review focuses on using finite element software to simulate the loss and efficiency of HTS generators. In this paper, the finite element software COMSOL MUTIPHYSICS is mainly discussed to model and simulate high frequency current losses of yttrium barium copper oxide(YBCO) superconducting generator.

Literature Review

For a superconductor, it has zero resistance in DC transmission without a magnetic field. When it comes to the performance in alternating magnetic fields or when a superconductor transmits an alternating current, the superconductor loses electromagnetic energy, which is called AC loss. It is the one of main factors that influences the efficiency of HTS generators.

Currently, high temperature superconducting power generation technology has immense potential. However, high temperature superconducting generators face AC loss during operation which affects their efficiency and stability. Hence, it is necessary to conduct numerical simulation to study AC loss. Sensitivity analysis of different parameters such as current density and temperature can be carried out to better optimize the performance of high temperature superconducting generators. It is essential to consider the unique properties of high temperature superconducting generators such as coupling effect and mutual inductance effect. By means of numerical simulation, high precision results can be obtained, thereby enhancing the reliability and practicability of design. In this paper, COMSOL MUTIPHYSICS is utilized to solve the coupling problem of multiple physical fields.

Nowadays, T-A equation is used for modeling in most newly published articles[4].

In the 2D model, the boundary condition of the T formulation is shown as:

$$I_{tape} = \int_0^1 J_z \, d = \int_0^1 \frac{\partial T}{\partial x} dx = T_2 - T_1 = T_1$$

The magnetic vector potential A is used in the entire domain, and the A formulation is shown as:

$$\frac{1}{\mu} \nabla \times (\nabla \times A) + \sigma \frac{\partial A}{\partial t} = 0$$

The boundary condition for A-formulation is set as:

$$A = 0$$

Coupled 2D T-A formulation is shown as:

$$-\frac{\partial}{\partial x}(E(\frac{\partial T}{\partial x})) = -\frac{\partial}{\partial t}(\frac{\partial A_z}{\partial t})$$
$$\frac{\partial}{\partial x}(\frac{\partial A_z}{\partial x}) + \frac{\partial}{\partial y}(\frac{\partial A_z}{\partial y}) = -\mu\frac{\partial T}{\partial x}$$

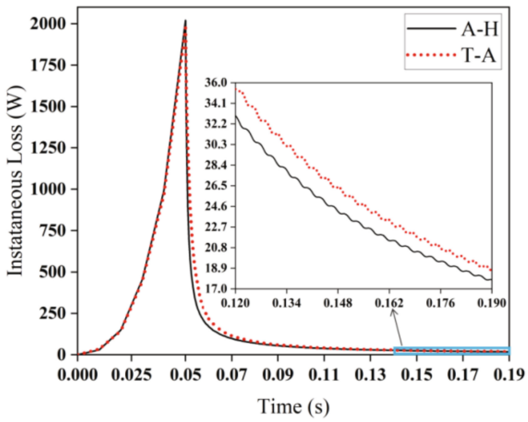

Fig1.[4] two results of AC loss waveform of HTS winding simulated by A-H and T-A formulation

As for the coincidence, it can be seen from the instantaneous AC loss waveform of HTS winding fig.1 that the calculation results of the two models are in good agreement. However T-A formulation has a much faster calculation speed than H-A formulation. In order to make the numerical simulation easier, people tend to use T-A formulation due to the speed and accuracy.

The H and A-V formulations, known as the H-A formula, are also employed to perform numerical calculations of the designed HTS generator. Furthermore, finite element software COMSOL is utilized to conduct numerical simulation. The Dirichlet boundary condition is selected for H-A formulation, which assumes magnetic isolation for the outermost surface of the superconducting generator in contact with air. In case the T-A equation has reached a mature state, the T-A equation with superior fast statistical performance may be chosen. Since the simulation time starts from zero, the coil's current rises from zero after the power-up. It is observed that before the alternating current (AC) loss presents itself as a simple harmonic dynamic output with rotor rotation, the loss rapidly increases with the increase in current and then decreases at a maximum value.

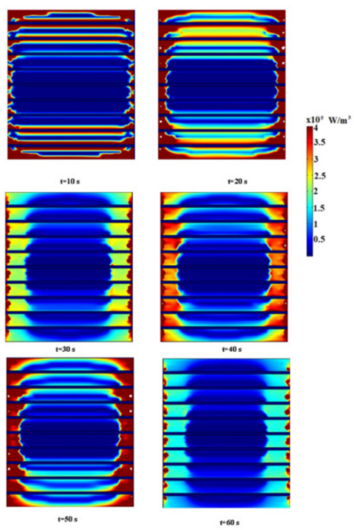

Fig.2 Instantaneous volume loss density distribution every 10 s during current excitation in rotor superconducting magnetic field coil τ= 20

Self-inductance in and between the rotor coils causes a rapid increase in AC loss due to the very high initial current rise rate. During the process of recharging and discharging, the current generated in the opposite direction in the racetrack coil impedes the charging and discharging of the coil. As the DC state approaches, the change rate decreases, leading to a decrease in the AC loss of the coil. Numerical simulations of each layer of coils reveal that the top and bottom coils have the greatest AC loss. Moreover, in the cross-section direction, the outer section of the superconducting coil will produce greater AC loss due to the uneven distribution of the magnetic field outside the coil.

In order to suppress the vertical magnetic field on the surface of YBCO tape in the coil, a part of the distributed winding of an AC rotating motor is simulated. Additionally, FEM is used to numerically analyze the magnetic field distribution around the racetrack coil. By inserting a magnetic material into a slot below the coil and affecting the magnetic field around the coil of the HTS racetrack fig.3; the vertical magnetic field is twisted and mostly bypasses the coil. Small magnetic materials must be inserted to reduce the vertical magnetic flux of the coil directly affecting AC loss, resulting in a reduction by about 50%. Further optimization of the size and weight of magnetic materials and searching for suitable magnetic materials is an important research direction.

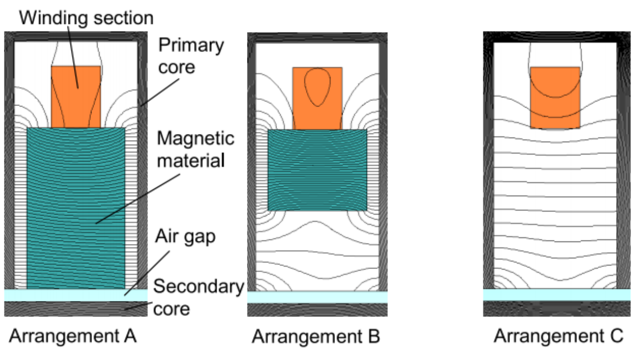

Fig.3. [5]By COMSOL simulation, the magnetic induction intensity changes generated by inserting different sizes of magnetic materials are compared with the magnetic induction line without inserting magnetic materials

Cooling the outer coil and protecting it from the vertical component of the magnetic field through measures such as magnetic deflectors should be employed to reduce AC losses. Improving the cooling system can, therefore, enhance the efficiency of the HTS generator. Compared with traditional HTS generators' relatively simple structures, the new generator with built-in refrigeration can obtain better power density. Additionally, the AC loss of the magnetic field winding reduces to 1/3 of the original. Importantly, the AC loss of the magnetic field winding of HTS generator accounts for only a small part of the sum of AC loss, iron loss, and winding loss. Furthermore, since the new HTS has a built-in thermostat, its structure is more complex, and its safety and practicability still need further verification. Optimizing the design of new HTS generators further using system engineering theory is crucial, while the model of built-in thermostatic refrigeration remains an essential development direction.

Conclusion

This paper answered one research question:

How can numerical simulation be used to reduce the AC Loss of HTS generators?

And also three possible vice questions:

1. What is the AC loss of HTS generators?
2. Why is the numerical stimulation widely used in conducting the AC Loss in HTS materials?
3. Why T-A formulation is used in those papers?

This paper expounds the reasons for the wide applicability of the T-A equation and also explains the reasons why the numerical simulations are widely applicable during HTS generator's design and manufacture. Through numerical simulation of the HTS generator and its associated structures, it is found that Armature winding is the main AC loss. Therefore, most studies focus on the optimal design of the stator coil, and the different designs aim to reduce the coil temperature and the perpendicular magnetic field component. Due to the complex structure of the ultra-high power HTS generators, it is possible to upgrade the cooling system and change the heat dissipation mode to further improve the efficiency. However, complex systems are often accompanied by high manufacturing cost and low reliability. In most articles, the design of airborne HTS synchronous generator still stays at the design level. Currently, HTS generators have broad applications in on-board or offshore equipment.

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