Multi-physics coupling finite element analysis of 10kV tri-axial HTS cable

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Abstract: As an important equipment of power transmission, power cable has been required better performance on cable line loss and current ampacity to achieve its high reliability. This paper proposes an advanced application of superconducting transmission technology in power grid, namely tri-axial high-temperature superconducting (HTS) cable. The corresponding simplified model is established for multi-physical field analysis, and the size of each structure is determined through structural design. The temperature distribution of the cable body is analyzed according to multi-physical field coupling, and the influence of flow rate, size and other factors on the stability of the system is studied. In this paper, it is found that increasing liquid nitrogen volume and flow rate have saturation limit for lowering cable body temperature, and the axial temperature rise rate of cable body tends to be stable when it is greater than 4m. Multi-physical field analysis provides a basis for the design of HTS cable length without having system quench or liquid nitrogen gasification.

1 Introduction

At present, the transmission challenges towards the future grid are mainly solved by changing the transmission mode and adopting new materials, including superconducting transmission technology. Compared with the traditional XLPE cable, the superconducting cable has the advantages of high current density, zero resistance and phase transition from superconducting state to normal state ^[1].

With the development of the second generation of HTS cable tape materials, superconducting cables can be sorted into Conductor on Round Core (CORC), twisted stacked-tape cable (TSTC), and Roebel cable. The superconducting cables can be sorted into single-phase, three-phase parallel and three-phase coaxial (tri-axial) according to the interphase arrangement. In addition, according to the cooling mode of the system, it can be also sorted into liquid nitrogen single-channel superconducting cable and double-channel superconducting cable. The tri-axial HTS cable occupies less space and costs less, compared with single-phase superconducting cable ^[2].

Currently, a 1km-long 1kV/2MVA tri-axial HTS cable developed by Russia is connected to the grid and operated in Essen, Germany ^[3]. Kepco, a Korean power company, started a 3km-long, 23kV/120MVA tri-axial HTS cable project in 2017 ^[4]. This paper firstly introduces the structure and parameter range of tri-axial HTS cable, and then simplifies the simulation calculation by the equivalent model. Finally, the multi-physical field

coupling in the finite element software Comsol is used for simulation analysis to compare the stability and reliability of the system under different structural parameters and external conditions, providing guidance and basis for the design of tri-axial HTS cable.

2 Modeling and structure design for tri-axial HTS cable

2.1 Basic structure and establishment of equivalent simulation model

The basic structure of tri-axial HTS cable is shown in Fig. 1. The protection layer consists of support pipe of copper, yttrium barium copper oxide (YBCO) superconducting tapes, polypropylene laminated paper (PPLP), cryostat, and protection layer. Inside the copper support pipe is the flowing channel of liquid nitrogen (LN₂). YBCO superconducting tape and PPLP are wound by controlling the winding intercept (winding angle). The superconducting tapes are coated with carbon paper on both side (semi-conducting layer) to conduct a uniform electric field.

Fig. 1 Basic structure of two-channel tri-axial HTS cable

The superconducting tape produced by a US company named Superpower is shown in Fig. 2.

Fig. 2 Superconducting tape structure of Superpower

The superconducting layer, buffer layer and silver protective layer of superconducting tape have no more than 4% of the total volume, and the mesh generation is limited by model geometry size in simulation. Considering that the influence of axial heat transfer of tape on temperature field distribution cannot be ignored in the multi-physics coupling simulation analysis, only the superconducting layer, crystal buffer layer, and silver stabilizer layer are ignored, and the superconducting tape model is simplified to the copper-Hastelloy-copper composite structure, whose simplified model is shown in Fig. 3.

Fig. 3 Simplified equivalent model of superconducting tape

According to the design, the spacing of each phase superconducting tape is controlled within a certain range to ensure that the volume between the tape gaps is lower than a certain value. The gap of tape is filled with liquid nitrogen due to the infiltration of PPLP. The superconducting layer composed of liquid nitrogen and

superconducting tapes can be simplified into a layer of rings, and the three-dimensional equivalent model is formed by sweeping along the axis. The equivalent model of tri-axial HTS cable body and its cross-section diagram are shown in Fig. 4.

Fig. 4 Equivalent model of tri-axial HTS cable body

The setting of material properties of tri-axial HTS cable body is shown in Table 1.

Table 1 Material property of tri-axial HTS cable

Material	Density kg/m ³	Thermal Conductivity W/(m·K)	Constant pressure heat capacity J/(kg·K)	Dynamic viscosity Pa·s
LN ₂	810	0.165	2000	220×10 ⁻⁶
Support pipe of copper	8940	410	152	/
Hastelloy	8890	6.8	91	/
PPLP	900	0.22	1900	/
cryostat	0.01	0.001	0.1	/

The structural parameters of tri-axial HTS cable are shown in Table 2.

Table 2 Structural parameters of tri-axial HTS cable

Geometric parameter	Thickness(mm)	Remaining parameter values
Support pipe of copper	Variable	Internal diameter 30mm-40mm
Superconducting layer	0.3mm (Including two 0.1mm carbon papers)	Winding number of each phase strip is 20
Insulation layer	2mm	/
Grounding layer	0.1mm	/
Protection layer	1mm	/
cryostat	20mm	The thickness of inner bellows is 1 mm and outer bellows is 2 mm.

3 Physical field condition setting

In the superconducting cable transmission system, the heat source inside the cable body is mainly the hysteresis loss, coupling loss, and induced eddy current loss on the copper support pipe and bellows pipe. The heat will be distributed to the surrounding medium through conduction, convection and other ways, and the combined action with heat leakage of the cryostat will increase the overall temperature of the cable body. The heat generated by the cable body is cooled by liquid nitrogen. The simulation process of multi-physical field coupling is shown in Fig. 5.

Fig. 5 Schematic diagram of magnetic-thermal-flow coupling simulation process

3.1 Temperature field

3.2.1 Heat source

The hysteresis loss and eddy current loss of the conductor in the tri-axial HTS cable are respectively loaded in the form of heat source in the superconducting tapes, copper support pipe and bellows pipe. The eddy current loss is simulated by electromagnetic field analysis. Hysteresis loss is calculated by the Bean critical model, and a coaxial formula applicable to three phases is proposed as follows: [5]

$$\begin{aligned} Q_{hl} &= \frac{3B^2}{3u_0} (1 + 3\beta^2) & \beta < i \\ Q_{hl} &= \frac{3B^2}{3u_0} (\beta^3 + 3\beta) & i < \beta < 1 \\ Q_{hl} &= \frac{3B^2}{3u_0} \cdot 4\beta & \beta > 1 \end{aligned} \quad (1)$$

where, $\beta = B_k/B$, $B = I/2\pi d$; Q_{hl} is the hysteresis loss per unit volume of cable within one period; I is the phase transfer current; d is the diameter of each phase superconducting layer; B_k is the magnetic induction intensity of the magnetic field generated by the current in the superconducting layer of other phases of the cable in the direction perpendicular to the phase transmission current.

The magnetic field analysis is conducted on the B-phase. The three superconducting layers from the inside to the outside are defined as A, B and C phases respectively. If the phase angle of B phase current is zero, then the current of A and C phase and the magnetic field generated in B phase are as follows.

$$I_A = I \sin(\omega t - 120^\circ)$$

$$I_C = I \sin(\omega t + 120^\circ)$$

$$B_b = I_A \cos \alpha_b / \pi d_A + I_C \sin \alpha_b / l_{inC} \quad (2)$$

Where, α_b is the winding angle of B-phase superconducting tape, which is taken as 20° in this paper.

From equation (2), B_k can be obtained as a periodic function. Taking the derivative of B_b , the maximum point B_k is substituted into the Bean critical model to calculate the hysteresis loss within one period. Since the diameter of each phase winding in this paper is linearly related to the copper support pipe, hysteresis loss is set to a certain value. The hysteresis loss of the three phases A, B and C in this paper is 1W/m.

3.2.1 Heat transfer modes

The heat transfer in the tri-axial HTS cable mainly includes heat conduction and convection. Since aluminum foil is used as insulation material in the cryostat, the thermal radiation has less influence on the temperature field distribution of the cable body than the other two heat transfer modes, so it can be ignored.

The natural convection includes convection heat transfer between the shell of the cryostat and the air. Forced convection includes convective heat transfer between the support pipe and the liquid nitrogen flowing in the pipe. In this paper, the convective heat transfer between the shell and the natural air is replaced by the boundary condition of convection heat transfer. The natural convection heat transfer is used as convection heat transfer, so the fluid is air, set temperature and pressure as 293.15K and 1atm respectively. The natural converter wall height is the cable length. The natural convection heat transfer coefficient is obtained by the given parameters above, which calculated by software.

The remaining boundary conditions of the temperature field are set as follows:

- 1) Set liquid nitrogen as fluid, the inflow temperature is 70K, and the inflow port pressure range is 1atm-2atm.
- 2) The initial temperature of the liquid nitrogen region is set at 70K, and the temperature of the other regions is set at room temperature of 293.15K.

3.2 Fluid field

According to the fluid mechanics theory, the flow characteristics of liquid flowing in the pipe depend on the Reynolds number. Based on the theory of fluid mechanics, the critical Reynolds number is about 2300, and its value is in the transition state in the range of 2300~4000. When the value is above 4000, the liquid is in a turbulent state. In this paper, the minimum value of Re is about 5500, so the liquid nitrogen flow is a full turbulent movement. Considering the convergence rate and memory requirements, the k- ϵ turbulence physical field interface is adopted, and the boundary conditions are set as follows:

- 1) The inlet of liquid nitrogen is set as the turbulent inlet, and its normal inflow velocity ranges from 0.05 to 0.2m/s.

2) The other side of liquid nitrogen is set as liquid nitrogen flow outlet.

4 Analysis of simulation result

The results show that the critical magnetic field, the critical current and the critical temperature are the stable factors of the tri-axial HTS cable system. Therefore, the multi-physical field coupling model of the tri-axial HTS cable is established in this paper to calculate the temperature field distribution more accurately and provide some references for the design of the tri-axial HTS cable.

3.1 Analysis of simulation results for multi-physical field coupling

The multi-physical field coupling is formed by loading electromagnetic losses, and temperature field analysis of superconducting cables with different structural parameters is carried out. In the following cases without special instructions, the default radius of the copper support pipe is 15mm and the axial length of the cable is 3m. The gasification temperature of liquid nitrogen at ordinary pressure is 77K, and its gasification temperature increases with the increase of pressure. In this paper, the liquid nitrogen gasification temperature is 77K, and the temperature of superconducting tape quench is 105K. When one of the two factors reach its temperature, the system is considered unable to maintain stable operation state.

Fig. 6 Temperature changes of superconducting layers at different radii

As can be seen from Fig. 6, the average temperature of each phase decreased significantly within the radius range of 15-30mm. After 30mm, the trend is flat and stabilized at 60mm. The cooling temperature of each phase is 70.05K, 70.2K and 70.32K, respectively.

Fig. 7 Temperature changes of each phase superconducting layer and liquid nitrogen center at different flowing rate

As can be seen from Fig. 7, with the increase of liquid nitrogen normal inflow velocity, the average temperature of each phase and liquid nitrogen outflow temperature decrease significantly. For this paper, when the inflow velocity exceeds 0.1m/s, the increase of liquid nitrogen cooling capacity slows down significantly.

Fig. 8 Temperature changes of each phase superconducting layer at different cable lengths

Fig. 9 Distribution range of liquid nitrogen temperature varies with different cable lengths

As can be seen from Fig. 8, with the increase of cable length, the average temperature of each phase decreases rapidly and reaches the extreme value at 1.5m. As the

cable length continues to increase, the temperature of each phase gradually increases at a constant rate. The radial liquid nitrogen temperature presents nonlinear distribution. Fig. 9 shows that when the cable length is greater than 2m, its temperature distribution interval tends to be stable. In this paper, the stable temperature distribution interval of 15mm radius copper support pipe cable is 0.1K.

According to Fig. 8 and 9, when the length of the cable body is larger than a certain value, the temperature change rate of liquid nitrogen and superconducting layer gradually tends to be stable. Therefore, the temperature change rate of the superconducting layer and liquid nitrogen layer are analyzed, as shown in Fig. 10 and 11.

Fig. 10 Temperature variation rate of each phase superconducting layer at different cable lengths

Fig. 11 Liquid nitrogen temperature change rate at different cable lengths

According to Fig. 10, when the axial distance gradually increases but is no more than 2m, the temperature of each phase superconducting layer presents a downward trend, and its temperature decline rate gradually decreases, indicating that the cooling effect of liquid nitrogen as a refrigerant plays a leading role in heat exchange when the cable is less than 2m. When the cable length exceeds 2m, the temperature of each phase superconducting layer starts to rise and the temperature rise rate keeps increasing, and then tends to

be stable when the cable length reaches 4m, and its stability value is about 0.0175. It can be seen from Fig. 11 that the temperature rise of liquid nitrogen is obvious when the cable length is less than 2m, and the temperature rise rate also tends to be stable when the cable length is more than 4m, with a stable value of about 0.0175. It is proved from another aspect that the axial heat exchange process of the superconducting cable is first dominated by liquid nitrogen and then dominated by loss. Its stable temperature rise rate provides a reliable basis for the design of cable length.

5 Conclusion

This paper designs a 10kV tri-axial HTS cable, and establishes a simplified three-dimensional simulation model based on Multi-physical field coupling. The following conclusions are obtained.

1) The simulation results of multi-physical field coupling of the cable body show that the temperature field distribution of the tri-axial HTS cable body can be effectively improved by increasing the radius of copper support pipe and liquid nitrogen flow velocity, but the effect is significantly reduced when the value is higher than a certain threshold. As a result, it is necessary to select appropriate structural parameters based on economic benefits.

2) The simulation results show that the temperature rise rate of the tri-axial HTS cable body tends to be stable when the cable length is longer than 4m. The stable value provides a reliable basis for the design of cable length.

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References

1. Liu Dong, Zhang Hong, Wang Jianchun, *Electric Power Engineering Technology(EPET)*, **36**(2017)
2. Yingjie Wang, Bo Yang, Huifang Zuo, Dongqian Qi, *Electric Power Engineering Technology(EPET)*, **36**(2017)
3. Sergey S. Fetisov, Vasily V. Zubko, Sergey Yu Zanegin, Alexander A. Nosov, Sergey M. Ryabov, Vitaly S. Vysotsky, *IEEE Trans. Appl. Supercond.* **27**(2017)
4. Chulhyu Lee, Jongho Choi, Hyungseok Yang, Minwon Park, Masataka Iwakuma, *IEEE Trans. Appl. Supercond.*, **29**, 5(2019)
5. Bo Hou, Feng Ye, Zhiqian Xiong, *Power System Technology(PST)*, **30**, 14(2006)