Research on Fault Current Endurance Capability of Concentric HTS Cable

Xiaochen Wu¹, Ziheng Hu¹, Bin Zhang¹, Zhenzi Wang¹, Wei Wang¹, Zhe Wang¹ and Bangzhu Wang²,*
¹Shenzhen Power Supply Bureau Co., Ltd., Guangdong, China
²School of Electrical Engineering, Beijing Jiaotong University, Beijing, China

*Corresponding author e-mail: bzwang@bjtu.edu.cn

Abstract. Based on the resistance response of high temperature superconducting (HTS) YBCO tape under overcurrent, a physical model of compact three-phase concentric HTS cable under fault current was established using adiabatic approximation. We consider the endurance criteria of no irreversible damage to the superconducting tapes and no significant vaporization of LN2. The fault current endurance capability of concentric HTS cable was obtained at different fault currents. The safety of the superconducting cable can be ensured by adding current limiting device to reduce the fault current magnitude or by improving the relay system to reduce the protection action time.

1. Introduction
The demand for energy conservation, emission reduction and environmental protection increases year by year and local underground transmission and distribution corridors become saturated. HTS power transmission technology, which has many advantages such as large transmission capacity, low transmission losses, small corridor footprint, and environmental friendliness, provides a solution for the challenges faced by future transmission and distribution. Within the last two decades, HTS cable demonstration projects have been carried out in United States, Japan, the European Union, South Korea, Russia, and China [1-6].

In 2017 China Southern Power Grid launched a HTS cable demonstration project. The cable will operate in Shenzhen power grid for long term and is expected to provide an optimized grid structure for solving high-load power supply in China's megacities. The project places high demands on the HTS cable, one of which is the capability to withstand high fault currents. Unlike conventional conductors, HTS tapes undergo a superconducting to normal state transition under fault current, which may make HTS cable suffer irreversible performance degradation. A common way to improve the endurance of HTS tapes to fault currents is to connect copper stabilizers to the superconducting layer in parallel. However, the concentric HTS cable has little potential to adopt the method since the three phases are wound on one former and the stabilizers will cause the cable core to lose flexibility [7-10].

In this paper, the fault current response of the concentric HTS cable core is modelled based on the current transition characteristic of HTS tape. Based on the criteria of thermal stability and cooling system’s working pressure, the fault current endurance capability is summarized.
2. Model of HTS Cables under Fault Current

2.1. Fault Current Response of HTS Tape

The YBCO HTS tape is multilayer structure and a typical tape consists of superconducting layer, reinforcement layer and other functional layers. The most important one for mechanical properties and thermal stability is the reinforcement layer (brass or copper) outside the superconducting layer.

Figure 1 shows the resistance response of YBCO tape under AC fault overcurrent. It can be seen that under fault current, the HTS tape appears resistance for a very short time and grows at a very fast rate to a complete loss of superconductivity. Then the resistance continues to increase with the current. In fact, after the HTS tape’s complete quench, the response depends on the conventional conductor connected in parallel and the conductor temperature increases continuously due to the Joule heat generated by the fault current, which in turn increases the resistance.

![Figure 1. The resistance response of YBCO tape under overcurrent](image)

2.2. Thermodynamic Model of HTS Cable under Fault Current

The duration of the fault current is in the order of second. According to the laws of thermodynamics, the heat transfer between the HTS layers and the surrounding structure can be considered as an adiabatic process. In other words, the heat transfer to PPLP and LN2 can be neglected. The power of the refrigeration system is ~5 kW and its cooling effect is also negligible compared to the heat generation. In the approximation, the energy balance formula can be written as follows

\[
Q(t) = \int_0^t i^2(\tau) \cdot R(\tau) d\tau = C_{HTS} \cdot m_{HTS} \cdot \Delta T_{HTS}
\]

where the Joule heat due to resistance of the HTS tape from 0 to \( t \) is expressed as integration of the fault current \( i \) and the resistance \( R \) of the HTS tape in time domain. \( C_{HTS} \) and \( m_{HTS} \) are the specific heat capacity and mass of HTS tape respectively. \( \Delta T \) is the temperature rise of HTS tape. It should be noted that the specific heat capacity is a function of temperature.

2.3. Resistance Model of HTS Cable under Fault Current

The resistance model of the HTS cable core can be regarded as parallel connected shunt resistance and HTS tapes in the presence of fault overcurrent. The resistance of the HTS cable core (single phase) is

\[
R_c(T) = \frac{\rho_c(T) \cdot L_c}{N_c \cdot \cos \theta}
\]

where \( \rho \) is the resistivity of the HTS tapes, \( N_c \) is the number of tapes connected in parallel, \( L_c \) is the equivalent length of the cable and \( \cos \theta \) is the helix angle of the HTS tape. The cross-section of the YBCO tapes is 4.8*0.43 mm and the thickness of the copper reinforcement layer is 0.35 mm. Since
the other layers are much thinner than the copper layer, the resistivity of the HTS tapes after quench is approximately equal to the resistivity of the copper layer.

2.4. Criterion of HTS Cable’s Fault Current Endurance Capability

The endurance ability of the HTS cable to withstand fault current depends on the thermal stability of the cable. The criterions to evaluate the endurance are to protect the HTS cable from irreversible damage, to avert LN2 from vaporization, and to avoid LN2 pressure not to exceed the safety setting value. As the HTS tapes is in a closed vessel, the cryogenic liquid is difficult to compress. Once the HTS cable core causes the liquid to vaporize, the resulting gas will rapidly increase the pressure inside and make the relief valve act, which will cause the system to stop service for safety reasons. So we should not allow the temperature rise of the cable core in the fault current to cause the LN2 to vaporize significantly. In normal operation, the cryogenic pipe is filled with subcooled LN2 (70-72 K) and the relief pressure is set to 0.8 MPa, where the boiling temperature of LN2 is about 100 K.

3. The Endurance Capability Analysis of HTS Cable under Fault Current

The largest short circuit current flows through the superconducting cable when the HTS cable is in open-loop and three-phase short-circuit occurs in the bus on the Xinghe substation. According to the system’s prediction, the fault current consists of periodic component 23.424 kAmps and non-periodic component 33.127 kA with a delay time constant of 0.161 s.

Based on the operation condition, endurance criterion, material parameters and expected fault current given above, the permissible cumulative heat generation \((Q_{\text{max}})\) by the HTS cable under fault current is 4.9 kJ/m/phase. Figure 2 shows the relationship between heat per length and fault duration for the HTS cable at different fault currents. When the fault current is high, the heat generation of the cable increases rapidly. Only the conditions below the maximum permissible heat line are allowed.

![Figure 2. Heat generated of HTS cable vs. time under different fault current](image-url)
Using $Q_{\text{max}}$ as the boundary condition, the permissible duration of the HTS cable under different fault currents can be obtained as shown in Figure 3. The permissible fault current and its duration have a strong nonlinear relation. It can be seen that as the amplitude of the fault current increases, the permissible duration decreases rapidly.

4. Conclusion
In this paper, we establish a physical model for fault current endurance estimation of the concentric HTS cable adopted in Shenzhen project based on the resistive response of YBCO tape under fault overcurrent and the adiabatic approximation conditions. We consider the endurance criteria of no irreversible damage to the superconducting tapes and no significant vaporization of LN2.

It is shown that the fault current endurance capability is characterized as a strong nonlinear relation of endurance magnitude and duration. The safety of the superconducting cable can be ensured by adding current limiting device to reduce the fault current magnitude or by improving the relay system to reduce the protection action time.

5. Acknowledgments
This work was financially supported by China Southern Power Grid Major Science and Technology Program (SZKJXM20170410).

References
[1] Sohn S H, Lim J H, Yang B M. Design and Development of 500 m Long HTS Cable System in The KEPCO Power Grid in Korea. Physica C, 2010, 470(20): 1567-1571.
[2] Maruyama O, Ohkuma T, Masuda T. Development of 66 kV and 275 kV Class REBCO HTS Power Cables. IEEE Transactions on Applied Superconductivity, 2013, 23(3): 5401405.
[3] Volkov E P, Vysotsky V S, Firsov V P. First Russian Long Length HTS Power Cable. Physica C, 2012, 482(0): 87-91.
[4] Marchionini B G, Yamada Y, Martini L. High Temperature Superconductivity: A Roadmap for Electric Power Applications. IEEE Transactions on Applied Superconductivity, 2017, 27(99): 1-6.
[5] Maguire J F, Schmidt F, Bratt S. Installation and Testing Results of Long Island Transmission Level HTS Cable. IEEE Transactions on Applied Superconductivity, 2009, 19(3): 1692-1697.
[6] SHABAGIN E, HEIDT C, Strauß S. Modelling of 3D Temperature Profiles and Pressure Drop in Con-centric Three-Phase HTS Power Cables. Cryogenics, 2017, 81: 24-32.
[7] Adachi K, Shiohara K, Sugane H. Sudden Short-Circuit Test of 22-kV YBCO Triaxial Superconducting Cable. IEEE Transactions on Applied Superconductivity, 2018, 28(4): 4.
[8] Yin L, Ma X F, Li X N. Overcurrent Analysis of YBCO Cable under Fault Current. IEEE Transactions on Applied Superconductivity, 2016, 26(7): 5402705.

Figure 3. Endurance duration vs. fault current
[9] Maguire J, Folts D, Yuan J. Development and Demonstration of a Fault Current Limiting HTS Cable to Be Installed in the Con Edison Grid. IEEE Transactions on Applied Superconductivity, 2009, 19(3): 1740-1743.

[10] Yagi M, Mukoyama S, Amemiya N. Development of a 10 m Long 1 kA 66/77 kV YBCO HTS Cable with Low AC Loss and a Joint with Low Electrical Resistance. Superconductor Science & Technology, 2009, 22(8): 085003.