Influence of longitudinal temperature distribution on current limiting function of Superconducting Fault Current Limiting Cable (SFCLC)

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Abstract. We have proposed a Superconducting Fault Current Limiting Cable (SFCLC), which is an HTS cable with fault current limiting function. SFCLC is expected to limit the fault current and also immediately recover the cable function after the fault clearance. In the SFCLC operation, a longitudinal temperature distribution will exist due to heat penetration, AC loss, dielectric loss and the performance of cryocooling system, which will influence its current limitation characteristics. In this paper, we investigate the influence of the longitudinal temperature distribution on current limiting function and temperature rise after the current limitation of SFCLC. We suggested the effective measures of parameter control, i.e. decreasing the critical current ($I_c@77K$), $n$ value at flux flow region ($n_{f,0}$), increasing the coefficient of longitudinal temperature gradient ($\alpha$), inflow temperature ($T_{in}$) to achieve both the higher current limiting function and the lower temperature rise.

1. Introduction

Superconducting technology is expected as next generation electric power technology with higher capacity, efficiency and also higher stability by protection of electric power apparatus and systems from a large fault current, namely as the HTS fault current limiter. In recent years, various researches and development are performed about superconducting power apparatus with these features. Then, we have proposed a Superconducting Fault Current Limiting Cable, abbreviated to “SFCLC” [1]. In the steady state, SFCLC operates as an HTS power cable with high capacity and low loss power transmission. Under the fault condition, SFCLC is expected to generate resistance as a fault current limiter. Additionally, after the fault clearance, SFCLC should recover to the superconducting state with low temperature rise in the fault current limitation.

Excellent fault current limiting function of SFCLC is produced by the generation of uniform resistance along the cable length. However, SFCLC have a longitudinal temperature distribution due to heat penetration, AC loss, dielectric loss and the performance of cryocooling system [2 - 4], which will influence its current limitation characteristics and may induce the fatal temperature rise by the local generation of limiting resistance. In this paper, by using a numerical simulation of SFCLC behaviour, we evaluate the influence of longitudinal temperature distribution on the current limitation characteristics of SFCLC.
2. Simulation method for behaviour of SFCLC

2.1. Simulation model

The numerical model for calculation of current limitation characteristics of SFCLC is developed, where SFCLC is introduced in a distribution system composed of a generator, a transformer and a load [5]. The voltage and length of SFCLC is 77 kV and 10 km, and the prospective fault current \( I_{\text{PRO}} \) is 20 kA_{\text{peak}}. The details of the structure and YBCO tapes of SFCLC can be referred to [1]. The temperature dependence of critical current \( I_c(T) \) is shown in figure 1(a).

Assuming a longitudinal temperature distribution of SFCLC, an equivalent circuit of the model system is developed using the circuit equation (1) and the heat equation (2),

\[
V = (L_{\text{T}} + L_{\text{SFCLC}}) \frac{dl}{dt} + (R_{\text{T}} + R_{\text{SFCLC}})I + R_L I
\]

\[
c(T) \frac{dT}{dt} = R_{\text{SC}}(x) I^2 - Q_{\text{in}} - Q_{\text{out}} + S \frac{\partial}{\partial x} \left( \kappa \frac{dT}{dx} \right)
\]

where \( V \) is the system voltage, \( I \) is the current of SFCLC, \( T \) is the temperature of YBCO conductor layer, \( L_{\text{T}}, R_{\text{T}}, L_{\text{SFCLC}} \) and \( R_{\text{SFCLC}} \) are the inductance and resistance of the transformer and SFCLC, \( l \) is the cable length, \( R_{\text{SC}}(x) \) is the resistance of SFCLC at the position \( x \) (\( 0 \leq x \leq l \)), \( R_L \) is the load resistance, \( c(T) \) and \( \kappa \) are the thermal capacity and thermal conductivity of the YBCO conductor layer with the copper former, \( Q_{\text{in}} \) and \( Q_{\text{out}} \) are the cooling power by the inner and outer cooling layer, \( S \) is the cross-sectional area of YBCO conductor layer. \( R_{\text{SC}}(x) \) fulfills the E-I-T characteristics of the YBCO tape as shown in figure 1(b), where the resistive voltage \( E \) per unit length of YBCO tape in superconductivity region is based on N value model, and that in flux flow region is based on the experimental results [1]. N value in each domain of figure 1(b) is set to \( n_0 \) at superconductivity region, \( n_1(T) \) at flux flow (1) region, \( n_2(T) \) at flux flow (2) region, respectively, where \( n_1(T) \) and \( n_2(T) \) are expressed by the following equations:

\[
n_1(T) = 4.5 + n_{1.0} \times \exp(-0.14T)
\]

\[
n_2(T) = 1 + n_{2.0} \times \exp(-0.068T)
\]

2.2. Longitudinal temperature distribution

We assumed that the longitudinal temperature distribution of SFCLC in operation is expressed by the following equation:

\[
T_{\text{op}}(x) = T_{\text{in}} + \Delta T \frac{1 - \exp(-\alpha x)}{1 - \exp(-\alpha \Delta T)}
\]

where \( T_{\text{op}}(x) \) is the temperature of SFCLC at the position \( x \), \( \alpha \) is the coefficient of longitudinal temperature gradient, \( T_{\text{in}} \) is the inflow temperature of SFCLC, and \( \Delta T \) is the difference in temperature along the SFCLC (figure 1(c)).

In this paper, we examined the effects of 7 parameters (\( \Delta T = 0.01 - 6 \) K, \( \alpha = 0.0001 - 0.005 \) m\(^{-1} \), \( T_{\text{in}} = 71 - 76 \) K, \( I_{\text{v}}@77K = 1.9 - 3.8 \) kA, \( n_0 = 1 - 40, n_{1.0} = 1.5 \times 10^5 - 4 \times 10^5, n_{2.0} = 330 - 900 \) ) on SFCLC behaviour.

![Figure 1](image_url)

**Figure 1.** Examined parameters for SFCLC.
3. Results and discussions

3.1. Current limiting characteristics

Figure 2 shows the simulation results for different values of \( \alpha \) at \( \Delta T = 6 \text{ K} \), \( T_{\text{in}} = 71 \text{ K} \), \( I_{@77\text{K}} = 3.1 \text{ kA} \), \( n_0 = 36.5 \), \( n_{1,0} = 2.5 \times 10^5 \), \( n_{2,0} = 460 \). Figures 2(a) - (d) show longitudinal temperature and critical current distribution, current waveform, temperature distribution after 5 cycle \((T_{\text{5cycle}})\), and resistance waveform of SFCLC, respectively. The limited current \((I_{\text{limit}})\) at the 1st half cycle in figure 2(b) is 7.2 kA peak (36% of \(I_{\text{PRO}}\)) by the resistance in figure 2(d). At each longitudinal temperature distribution in figure 2(a), heat by the generated resistance concentrates at \( x = 9 – 10 \text{ km} \) of SFCLC in figure 2(c), where \( T_{\text{5cycle}} \) exceeds 100 K and reaches 300 K at \( \alpha = 0.0001 \text{ m}^{-1} \). \( \alpha \) has little influence on \( I_{\text{limit}} \) in figure 2(b), because the lowest \( I_c \), which is fixed in figure 2(a), is decisive for the initiation of fault current limitation. However, we should note that \( \alpha \) has a strong influence on \( T_{\text{5cycle}} \), because the cable length contributing to the current limiting resistance is attributed to the longitudinal temperature distribution, i.e. the cable length with the almost lowest \( I_c \). In other words, for the temperature distribution at \( \alpha = 0.001 \text{ m}^{-1} \), SFCLC has the longer length with the almost lowest \( I_c \), and shares the resistance generation by the longer region of the cable, which can prevent the local heat generation.

![Figure 2](image_url)

**Figure 2.** Example of current limiting characteristics of SFCLC.
\((\Delta T = 6 \text{ K}, T_{\text{in}} = 71 \text{ K}, I_{@77\text{K}} = 3.1 \text{ kA}, n_0 = 36.5, n_{1,0} = 2.5 \times 10^5, n_{2,0} = 460)\)

3.2. Maximum temperature after current limitation

Table 1 summarizes the SFCLC behaviour, i.e. current limiting effect \((I_{\text{limit}} / I_{\text{PRO}})\) and maximum temperature \( T_{\text{max}} \) at 5cycle for the increase in each parameter. As shown in table 1, increasing \( \Delta T, T_{\text{in}}, n_0 \) and decreasing \( I_{@77\text{K}} \) are expected for the effective current limitation (lower \( I_{\text{limit}} / I_{\text{PRO}} \)). For the lower \( T_{\text{max}} \), increasing \( \alpha, T_{\text{in}} \), decreasing \( I_{@77\text{K}}, n_0, n_{1,0} \) and optimum \( \Delta T \) are expected. Therefore, as
the effectiveness for the total SFCLC function in table 1, SFCLC can achieve both a higher current limiting function and a lower temperature rise for the subsequent recovery function, by decreasing $I_{c@77K}$ and $n_{1,0}$ from the viewpoint of HTS tape specifications as well as by increasing $\alpha$, $T_{in}$ from the viewpoint of temperature distribution in operation. These results will contribute to the design and operation of SFCLC.

| Table 1. SFCLC behaviour for the increase in each parameter. |
|-------------------------------------------------------------|
| Current limiting effect ($I_{\text{limit}}/I_{\text{PRO}}$) | Maximum temperature ($T_{\text{max}}$ at 5cycle) | Effectiveness for total SFCLC function |
| $\alpha \uparrow$ | $\downarrow$ | $\downarrow$ | Effective |
| $\Delta T \uparrow$ | $\downarrow$ | $\bigcirc$ | Effective |
| $T_{in} \uparrow$ | $\downarrow$ | $\downarrow$ | More effective |
| $I_{c@77K} \uparrow$ | $\uparrow$ | $\uparrow$ | More effective |
| $n_{0} \uparrow$ | $\downarrow$ | $\uparrow$ | Less effective |
| N value $n_{1,0} \uparrow$ | $\downarrow$ | $\bigcirc$ | Effective |
| $n_{2,0} \uparrow$ | $\downarrow$ | $\downarrow$ | Non-effective |

$\uparrow$: increase  $\downarrow$: decrease  $-$: almost no change  $\bigcirc$: have a maximum

4. Conclusion
This paper described the influence of the longitudinal temperature distribution of SFCLC in operation on its current limiting characteristics. Simulation results revealed that the resistance and temperature rise of SFCLC during the current limitation may concentrate on the region with the almost lowest $I_c$. We demonstrated the critical parameter for current limiting effect and maximum temperature. Then, we suggested the effective measures of parameter control, i.e. decreasing $I_{c@77K}$ and $n_{1,0}$ from the viewpoint of HTS tape specifications as well as increasing $\alpha$, $T_{in}$ from the viewpoint of temperature distribution in operation, in order to achieve both higher current limiting function and lower temperature rise for the subsequent recovery function. These results will contribute to the design and operation of SFCLC.

Acknowledgement
This work was supported by JSPS KAKENHI Grant Number 24760228.

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