Feasibility Study on High Temperature Superconducting Fault Current Limiting Cable (SFCLC) Using Flux Flow Resistance

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***Abstract*—We propose a High Temperature Superconducting Fault Current Limiting Cable (SFCLC), which is a HTS cable with fault current limiting function. The SFCLC is expected to achieve the fault current limitation by flux flow resistance of long cable length. Particularly, in this paper, we focus on *E-I-T* characteristics of YBCO coated conductor at the flux flow region. Based on the obtained *E-I-T* characteristics, we develop a numerical model and investigate current limiting characteristics of the SFCLC for different cable lengths and fault conditions into a model power system.**

***Index Terms*—fault current limiter, flux flow, power transmission cable.**

I. Introduction

High temperature superconducting (HTS) power application has been expected to improve transmission capacity and stability of power systems. In recent years, the HTS power apparatus such as transmission cables, fault current limiters, transformers and SMES have been investigated and demonstrated [1]-[3]. Especially, HTS power cable is expected because of its high transmission capacity and low impedance, and various projects are carried out [1], [4]-[6]. On the other hand, regarding future directions of development for the superconducting power technology, the HTS power apparatus should be coordinated with a power system for the overall stability, controllability and efficiency of the power system [7].

From the viewpoint of system coordination and multifunction of the HTS power apparatus, we propose a "High Temperature Superconducting Fault Current Limiting Cable" (SFCLC). In steady state, the SFCLC operates as a HTS power cable, and under fault condition, the SFCLC is expected to generate resistance as a fault current limiter. Although few projects point to the similar concept [8], our feature is aiming to achieve the fault current limiting function of the SFCLC without a parallel connected reactor using the flux flow resistance, which will also help the SFCLC to recover into the superconducting state after the fault clearance.

In this paper, we acquire the *E-I-T* characteristics of a YBCO coated conductor and evaluate the temperature rise at the flux flow region by the circuit and heat equations. Based on the obtained *E-I-T* characteristics, we develop a numerical model to calculate the generated resistance and the temperature rise of the SFCLC under the fault condition. The current limiting characteristics of the SFCLC are discussed in a model power system by changing the parameters such as the cable length and the prospective fault current.

II. Concept of SFCLC

Generally, a resistive-type superconducting fault current limiter (SFCL) generates large limiting impedance with a rapid response time due to quenching of a HTS element under the fault condition. After the transition to the normal state, a parallel-connected reactor can be used to adjust limited current if required e.g. by grid protection scheme [9]. However, the SFCLC will exhibit the fault current limiting function by using its long HTS conductor, which is expected to generate flux flow resistance at the fault occurrence. On the *E-I* characteristics of HTS tapes, the electric field at the flux flow region is lower than that of the normal region. We can increase the resistance generated at the flux flow region up to the current limitation level by the long length of the power transmission cables. In addition, the temperature rise per unit length by Joule heat can be suppressed by enlarging a heat capacity of the SFCLC, which will contribute to the recovery of the SFCLC into the superconducting state after the fault clearance.

Fig. 1 shows an example of the application of the SFCLC into a power distribution system. In a future power distribution system with distributed generators, the larger fault current will be unavoidable, and then the fault current limiting function such as the SFCLC will be quite important and imperative. Furthermore, the multifunction of a HTS power cable and a

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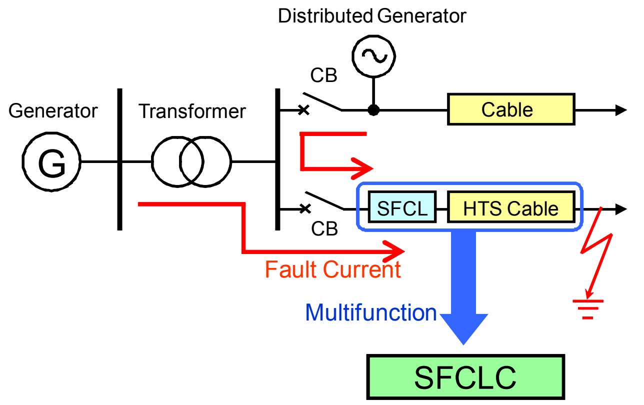


Fig. 1. Application concept of SFCLC.

TABLE I
SPECIFICATIONS OF THE YBCO COATED CONDUCTOR

Substrate layer	Hastelloy (100 μm)
Buffer layer	IBAD MgO
Superconductor layer	YBCO (2 μm)
Stabilizer	Ag (2 μm)
Width	12 mm
Total thickness	0.105 mm
Critical current I_c	254 A (77 K, 1 μV/cm, self field)
N value @ I_c	36.5

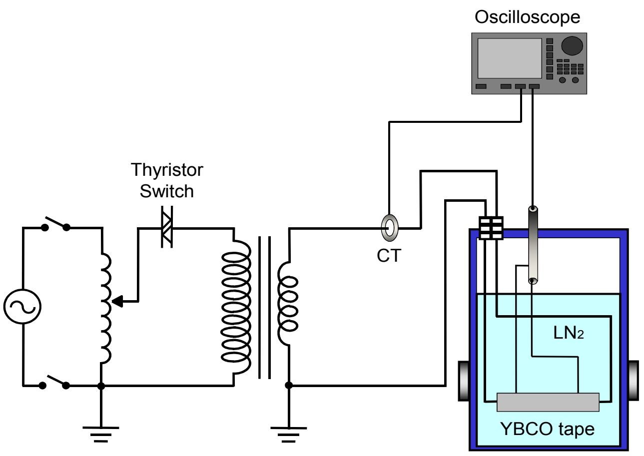


Fig. 2. Experimental setup.

SFCL results in the low-cost and high-efficiency power system construction and operation. In addition, the SFCLC has the probability of the recovery into superconductivity state after the fault clearance, by the promising low temperature rise due to the long cable length. The purpose of this paper is to assess the feasibility of the SFCLC using the flux flow resistance introduced into a power system.

III. *E-I-T* CHARACTERISTICS OF HTS CONDUCTOR

A. *Experimental Setup and Procedure*

In order to consider the technical feasibility of the SFCLC, it is essential to clarify the *E-I* characteristic of HTS tapes at the flux flow region. The specifications of a YBCO coated conductor as one of possible HTS tapes for the SFCLC are shown in Table I. This YBCO tape with the effective length 90 mm was immersed in liquid nitrogen at 77.3 K and atmospheric pressure. AC current was supplied for 5 cycles (60 Hz) by the operation of thyristor switch, as shown in Fig. 2, in consideration of the time for circuit breaker operation with some margin. The transient current and terminal voltage waveforms were recorded.

Assuming a uniformity of the YBCO tape, the obtained current I and voltage V were applied to the circuit equation (1) and the heat equation (2), and were analyzed to calculate the electric field E, which means the generated voltage per unit tape length, and the temperature T of the YBCO tape.

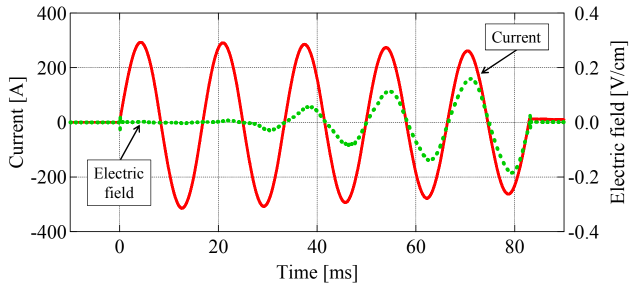
$$E = \left(V - L_t \frac{dI}{dt}\right) \Big/ l \tag{1}$$

$$c(T)\frac{dT}{dt} = El \cdot I - \alpha(\Delta T) P \Delta T \tag{2}$$

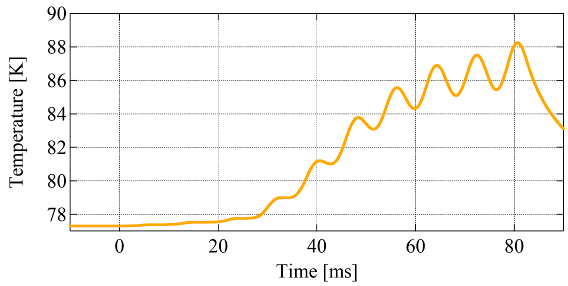
where L_t is the inductance of the YBCO tape, which was measured under small current condition, l is the tape length, $c(T)$ is the thermal capacity of the YBCO tape, $\alpha(\Delta T)$ is the thermal transfer coefficient of LN_2 [10], P is the area of the tape surface and ΔT is the temperature rise of the tape. Based on the experimental data, we could obtain the relationship between the electric field, current and temperature (*E-I-T*) of the YBCO tape.

B. *E-I-T Characteristics at Flux Flow Region*

Fig. 3 shows an example of current, electric field and temperature waveforms of the YBCO tape for the prospective current I_{PRO} of 304 A_{peak} (= $I_c \times 1.2$). The electric field is



(a) Current and electric field.



(b) Temperature.

Fig. 3. Current, electric field and temperature of YBCO tape with the effective length of 90 mm (I_{PRO} = 304 A_{peak}).

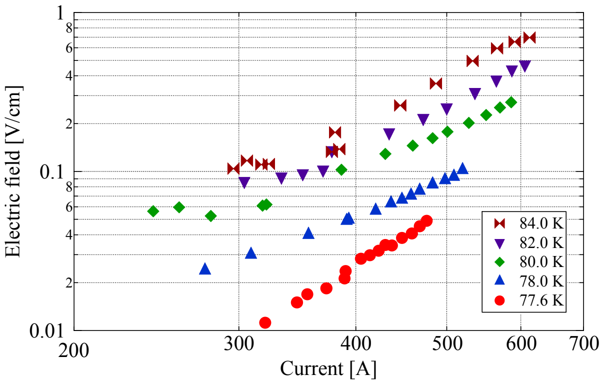


Fig. 4. *E-I-T* characteristics of YBCO tape (effective length 90 mm).

generated at the second cycle and the temperature rises at the same time. The temperature rises and falls below 90 K because of the balance between the Joule heat by the generated resistance and the cooling of LN_2.

Fig. 4 shows the *E-I-T* characteristics of the YBCO tape by analyzing many current, electric field and temperature waveforms. The current was instantaneous value at each temperature. The *E-I* characteristics at each temperature tend to be proportional to the power law with N values of 2–5 in the electric field of 0.01–1.0 V/cm. This indicates that the YBCO tape is in the flux flow region.

IV. Feasibility of SFCLC

A. Simulation Method

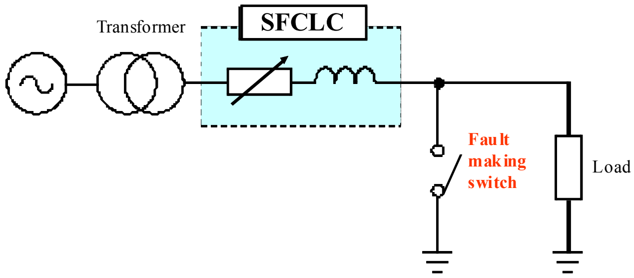
The *E-I-T* characteristics obtained in the previous section were formulated as electric field E is a function of current I and temperature T. Using this formulation, a numerical simulation model is developed, where the SFCLC is introduced into a simplified 77 kV / 6.6 kV distribution system as shown in Fig. 5(a). Assuming a uniformity of the SFCLC, an equivalent circuit in Fig. 5(b) was developed using the circuit equation (3) and the heat equation (4),

$$V = (L_s + L \cdot l)\frac{dI}{dt} + (R_s + R \cdot l)I \quad (3)$$

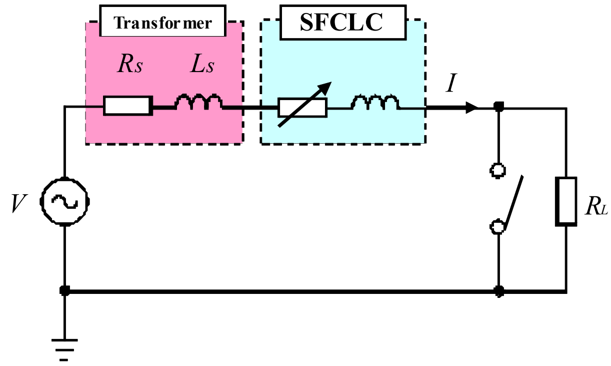
$$c(T)\frac{dT}{dt} = (R \cdot l)I^2 \quad (4)$$

where V is the system voltage, L_s and R_s are the inductance and resistance of leakage impedance of the transformer, L and R are the inductance and resistance per unit length of the SFCLC and l is the cable length. R fulfills the obtained *E-I-T* characteristics. The limited current, temperature rise and generated resistance of the SFCLC for 5 cycles during the fault were calculated by these equations.

The configuration of SFCLC in this simulation was based on a cold-dielectric type HTS cable [11]. The total heat capacity of the SFCLC includes the cylindrical copper former with the cross section of 325 mm^2 and 22 HTS tapes [12], i.e. I_c of the SFCLC at 77 K is 254 A × 22 = 5588 A. Since the HTS tapes

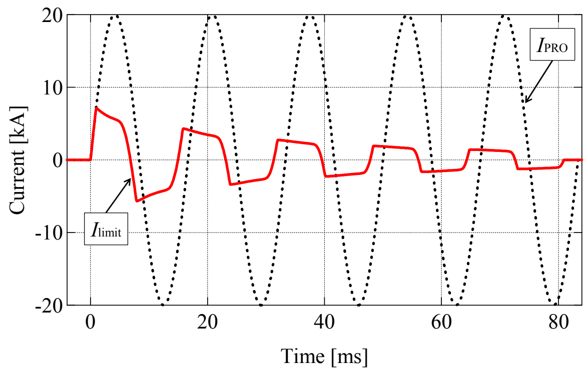


(a) Model system

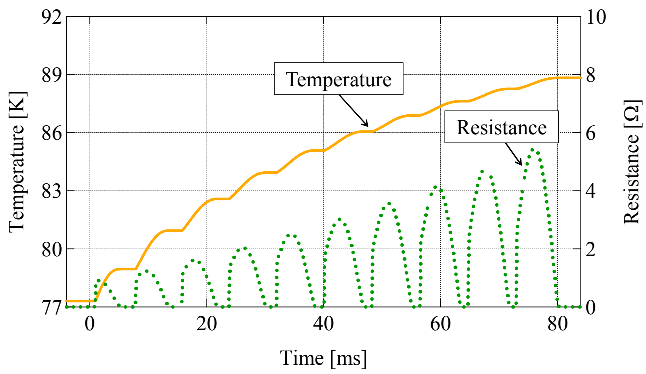


(b) Equivalent circuit on fault occurrence.

Fig. 5. 77 kV / 6.6 kV distribution system.



(a) Current



(b) Temperature and resistance.

Fig. 6. Current limiting characteristics of SFCLC at I_{PRO} = 20 kA$_{peak}$ and l = 1000 m.

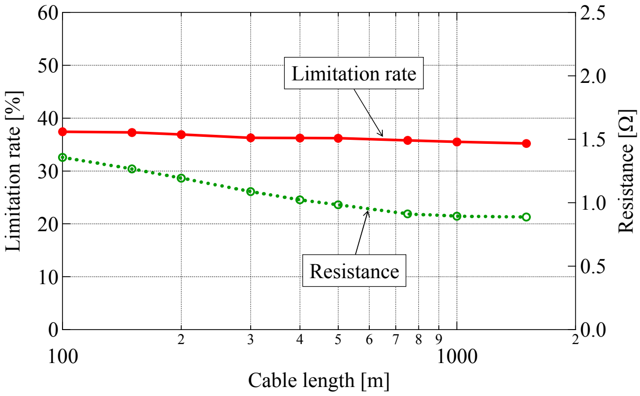


Fig. 7. Cable length dependence of limitation rate and peak resistance at the first half cycle.

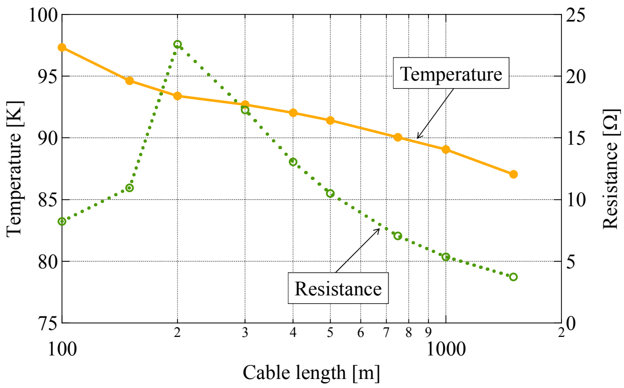


Fig. 8. Cable length dependence of temperature and peak resistance after 5 cycles.

are cooled through the dielectric layer, we can assume that the HTS tapes are kept in the adiabatic condition for the short fault duration.

B. Current Limiting Characteristics of SFCLC

Fig. 6 shows a simulation example for current, temperature and resistance waveforms of the SFCLC at I_{PRO} = 20 kA$_{peak}$ (= I_c × 3.6) and l = 1000 m. The limited current I_{limit} in Fig. 6(a) is suppressed to 7.1 kA$_{peak}$ (35% of I_{PRO}) at the first half cycle. The waveform of I_{limit} is similar to a square-wave, because the resistance in Fig. 6(b) is rapidly generated at the flux flow region with non-linear *E-I* characteristics. Although the value of total resistance of the SFCLC reaches approximately 6 Ω, the resistance per unit length is small. Therefore, the temperature rise is suppressed below 90 K, even in the adiabatic condition.

Fig. 7 shows the cable length dependence of the limitation rate (the peak value of I_{limit} divided by I_{PRO}) and the peak resistance at the first half cycle. For l = 100 m to 1500 m, the limitation rate is approximately 40% and the generated resistance is approximately 1 Ω. This means that the SFCLC adequately limits the fault current at the first half cycle.

Fig. 8 shows the cable length dependence of the temperature and the peak resistance after 5 cycles. For l < 200 m, the temperature rises largely because of the small heat capacity of the short SFCLC. The SFCLC transfers to the normal resistance region after 5 cycles, where the generated resistance tends to increase with the cable length. On the other hand, for l > 200 m, the temperature decreased because of the enough heat capacity of the long SFCLC. The SFCLC could maintain the flux flow resistance region even after 5 cycles, where the generated resistance tends to decrease with the increase in the cable length. Thus, when the cable length becomes longer, the temperature of the SFCLC can be suppressed, and the SFCLC can achieve the fault current limitation and recovery functions.

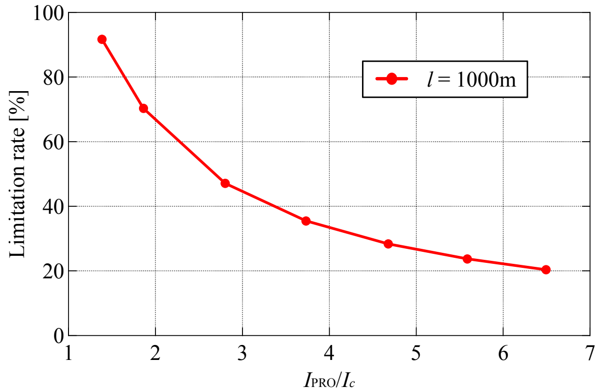


Fig. 9. Prospective current dependence of limitation rate at the first half cycle.

Fig. 9 shows the prospective current I_{PRO} dependence of the limitation rate at the first half cycle. The horizontal axis denotes the overcurrent factor, defined by I_{PRO} normalized by the critical current I_c of the SFCLC at 77 K, and in this case, l = 1000 m. The SFCLC demonstrates the current limiting performance against the fault current exceeding I_c. When the fault current becomes larger, the current limitation becomes remarkable.

V. Conclusion

This paper described the feasibility of the High Temperature Superconducting Fault Current Limiting Cable (SFCLC) using the flux flow resistance. We focused on the *E-I-T* characteristics at the flux flow region of the YBCO tape. The *E-I* characteristics at each temperature were found to be proportional to the power law with N values of 2–5.

Based on the obtained *E-I-T* characteristics, we calculated the current limiting characteristics of the SFCLC. The SFCLC was verified to adequately limit the fault current by using flux flow resistance of the long cable, and also to reduce the temperature rise of HTS tapes. From these results, the technical feasibility and basic property of the SFCLC using the flux flow resistance were confirmed. The concept of SFCLC will contribute to establish a future urban distribution network associated with the HTS power cable, owing to its high transmission capacity, low impedance and fault current limiting function.

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