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Superconducting fault current limiting cable (SFCLC) with current limitation and recovery function

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Abstract

We have proposed a Superconducting Fault Current Limiting Cable (SFCLC), which is an HTS cable with fault current limitation function. SFCLC will transmit the bulk power with low loss in steady state, and also limit the fault current during the fault condition, and recover into the superconducting state after the fault clearance. Using a numerical model, we investigated the current limitation and recovery characteristics of SFCLC for different voltage and current levels, and cable lengths. We verified the feasible conditions and performance of SFCLC with the current limitation and recovery function.

Keywords: Superconducting cable; current limitation function; recovery function; flux flow; YBCO coated conductor

1. Introduction

In a future power system, a larger fault current will be unavoidable, and then the development of the power apparatus with fault current limitation function will be quite important and imperative from the viewpoint of system stabilization [1-3]. Then, we have investigated a Superconducting Fault Current Limiting Cable, abbreviated to “SFCLC” [4]. In steady state, SFCLC operates as an HTS power cable, i.e. high capacity and low loss power transmission is realized. Under fault condition, SFCLC is expected to generate resistance as a fault current limiter. Then, the system capacity and stability can be increased by SFCLC without other countermeasures for fault current like an increment of the interrupting capacity of circuit breaker. Figure 1 shows an example of the introduction of SFCLC into a power system. The installation of SFCLC is expected to limit the fault current flowing around the distributed generators, and also to improve the stability, efficiency and reliability of the power system.

We have verified that SFCLC can not only exhibit the current limitation function using the flux flow resistance during the fault by virtue of its long cable length, but also facilitate the recovery function into

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the superconducting state under the load current after the fault clearance [4]. We have also acquired the characteristics between resistive voltage per unit length E, current I and temperature T of a YBCO coated conductor at the flux flow region, as shown in Fig. 2 [4]. In a numerical method using these characteristics, in this paper, we evaluate the consistency between current limitation and recovery characteristics of SFCLC during and after the fault condition. These characteristics are discussed from the viewpoint of the feasible conditions and performance of SFCLC with the current limitation and recovery function using the flux flow resistance.

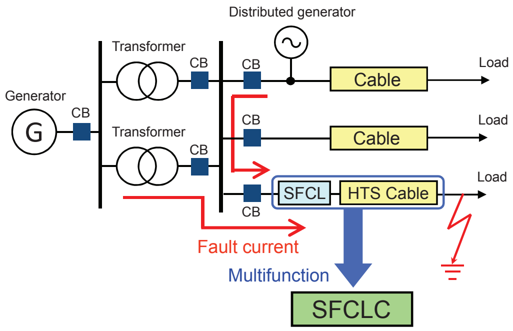


Fig. 1. Introduction concept of SFCLC

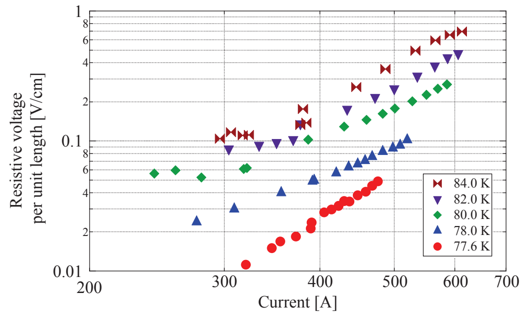


Fig. 2. *E-I-T* characteristics of YBCO coated conductor [4]

2. Simulation method for current limitation and recovery characteristics of SFCLC

SFCLC in this paper is composed of an inner cooling layer with hollow copper former, an HTS conductor layer, an electrical insulation layer and an outer perimeter cooling layer. The specifications of the YBCO coated conductor as one of the possible HTS tapes for SFCLC are shown in Table 1. The HTS conductor layer includes 22 HTS tapes [5], i.e. critical current I_c of SFCLC at 77 K is 254 A × 22. Using the *E-I-T* characteristics of the HTS tape in Fig. 2, a numerical model for calculation of current limitation and recovery characteristics of SFCLC is developed, where SFCLC is introduced into a simplified power system, as shown in Fig. 3. The system voltage of SFCLC is set at 6.6 kV-66 kV. Assuming a longitudinal uniformity of SFCLC, an equivalent circuit of the model system is developed using the circuit equation (1) and the heat equation (2),

$$V = (L_S + L_{SC} \cdot l)\frac{dI}{dt} + (R_S + R_{SC} \cdot l)I + R_L I \tag{1}$$

$$c(T)\frac{dT}{dt} = (R_{SC} \cdot l)I^2 - Q_{in} - Q_{out} \tag{2}$$

where V is the system voltage, L_S and R_S are the inductance and resistance of the transformer, L_{SC} and R_{SC} are the inductance and resistance per unit length of SFCLC, R_L is the load resistance, l is the cable length, $c(T)$ is the thermal capacity of the HTS conductor layer with the copper former, Q_{in} is the cooling power by the inner cooling layer, and Q_{out} is the cooling power by the outer perimeter layer through the electrical insulation layer. R_{SC} fulfills the *E-I-T* characteristics of the HTS tape in Fig. 2. The fault is simulated by short-circuiting the load, i.e. R_L is turned to zero. The limited current, temperature rise and generated resistance of SFCLC for 5 cycles during the fault, in consideration of the time for circuit breaker operation, were calculated by these equations.

From the acquired characteristics, we calculated the flux flow loss Q_{loss} under the rated current after the fault clearance. We defined SFCLC is recoverable after the fault current limitation and the fault clearance when Q_{loss} is less than 1 W/m, which corresponds to the cooling ability of the HTS cable projects [3,6]. At various system voltages, fault current, utilization factor, i.e. the ratio of the rated current I_N to the critical current I_c, and cable length, we evaluated the current limitation and recovery characteristics of SFCLC.

Table 1. Specification of YBCO coated conductor

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

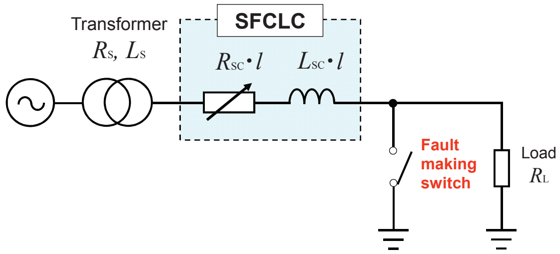


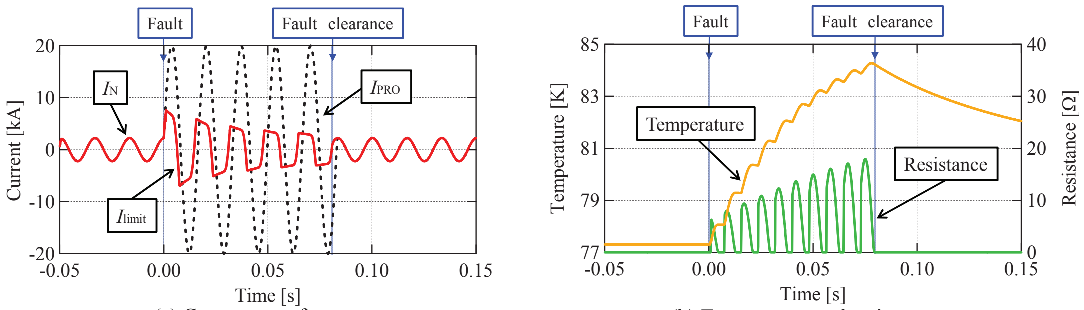
Fig. 3. Model system of SFCLC

3. Results and discussion

3.1 Current limitation and recoverable cable length of SFCLC

In this section, we investigate the recoverable cable length of SFCLC after the fault current limitation for different system voltages at the fixed prospective fault current I_{PRO} and the utilization factor I_N / I_c. Figure 4 shows a simulation example for current waveforms, temperature and resistance of SFCLC at $V = 66$ kV, $I_{PRO} = 20$ kA$_{peak}$ (= $I_N \times 9.0$), $I_N / I_c = 0.4$, and $l = 19.8$ km. During the fault, the limited current I_{limit} in Fig. 4 is 7.6 kA$_{peak}$ (38 % of I_{PRO}) at the 1st half cycle due to the generated resistance of 18 Ω (10 % of the full normal resistance). The temperature rise is only 7.9 K during the fault since the resistance per unit length is small, and the temperature decreases after the fault clearance because of the effective cooling by the inner cooling layer. Since Q_{loss} in this example is 1 W / m, we can regard SFCLC to be recoverable.

Figure 5 shows the shortest cable length capable of recovery for $V = 6.6$-66 kV at I_{PRO} = 20 kA$_{peak}$ and $I_N / I_c = 0.4$. The recoverable cable length less than 20 km increases proportionally with the system voltage under the fixed parameters of I_{PRO} and I_N / I_c.



(a) Current waveforms (b) Temperature and resistance

Fig. 4. Current limitation characteristics ($V = 66$ kV, $I_{PRO} = 20$ kA$_{peak}$, $I_N / I_c = 0.4$, $l = 19.8$ km)

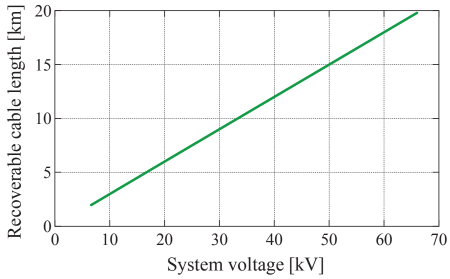
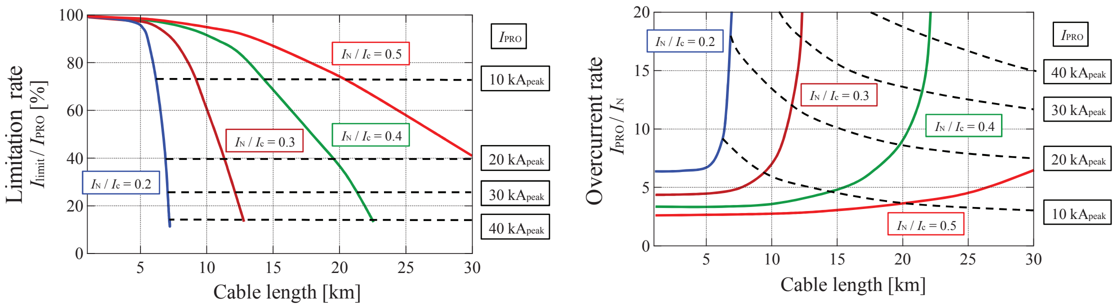


Fig. 5. Recoverable cable length after fault current limitation as a function of system voltage ($I_{PRO} = 20$ kA$_{peak}$, $I_N / I_c = 0.4$)

3.2 Recoverable limitation rate and recoverable overcurrent rate of SFCLC

In this section, we discuss the fault current limitation and recovery characteristics of SFCLC for different cable lengths, recoverable I_{PRO} and the utilization factor (I_N /I_c) at the fixed system voltage. Figure 6 shows the recoverable limitation rate (I_{limit} / I_{PRO}) at the 1st half cycle and the recoverable overcurrent rate (I_{PRO} / I_N) against the cable length in the case of V = 66 kV. The solid lines in Fig. 6(a) show the lower limit of recoverable I_{limit} / I_{PRO} for fixed I_N / I_c, whereas those in Fig. 6(b) show the upper limit of recoverable I_{PRO} / I_N. The broken lines in Figs. 6(a) and 6(b) represent the trace of the same I_{PRO} values on each solid line. SFCLC with the longer cable length can achieve the effective fault current limitation with the lower limitation rate, as shown in Fig. 6 (a), and also recover after the fault clearance at the larger I_{PRO} and with the higher I_N / I_c, as shown in Fig. 6 (b).

From the above results, the introduction scheme of SFCLC in power system can be discussed. When SFCLC with the short cable length is introduced into the power system where the fault current is relatively large, the current limitation and recovery performance of SFCLC can be enhanced with the low utilization factor. On the other hand, in the power system with small fault current and the long cable length, the current limitation and recovery function of SFCLC can be manifested with the high utilization factor.



(a) Recoverable limitation rate I_{limit} / I_{PRO} at the 1st half cycle (b) Recoverable overcurrent rate I_{PRO} / I_N

Fig. 6. Current limitation and recovery characteristics (V = 66 kV)

4. Conclusion

This paper described Superconducting Fault Current Limiting Cable (SFCLC) with the current limitation and recovery function. In the numerical method, the current limitation and recovery characteristics of SFCLC were discussed for different system and fault conditions. Simulation results revealed that the consistency between effective fault current limitation and recovery function with high utilization factor, i.e. high transmission capacity, can be brought about by SFCLC with the flux flow resistance under fault conditions. This consistency will depend upon the characteristics of power system with SFCLC, i.e. fault current, rated current, system voltage, required limitation rate and so on.

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