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Experimental and numerical analysis of high resistive coated conductor for conceptual design of fault current limiter

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ABSTRACT

Resistive superconducting fault current limiters (FCLs) using coated conductor (CC) have been developed to reduce fault current which exceeds ratings of circuit breaker in power grid. Our group has participated in the development of distribution level non-inductive winding type FCL using stainless steel-stabilized CC, as one of the 21st century Frontier R&D program. Recently, stabilizer-free CC with Hastelloy substrate was developed for FCL application. Since the CC has higher average resistivity than existing CCs with metallic stabilizer, required amount of wire can be reduced. Short-circuit tests were performed by increasing voltage applied to the small-scale FCL coil using stabilizer-free CC in sub-cooled liquid nitrogen of 65 K. Experimental results of the tests were compared with numerical analysis of current limiting characteristics of the CC by using finite element method (FEM). Conceptual design of the FCL was performed using test results and was compared with FCL using existing CC in regards to current limiting characteristics.

1. Introduction

In present electric power grid the levels of fault current may exceed the short-circuit ratings of circuit breakers (CBs) at some points as the new power generation is being added and electric power systems become more interconnected. Thus there is the need to provide effective and reliable protection of power equipment against fault currents. The resistive type superconducting fault current limiter (FCL) using high temperature superconductors (HTS) is expected to be the most promising solution of fault problems [1,2]. Coated conductors (CCs) are rapidly commercialized over the world and have several benefits suitable for FCL application for these reasons: (1) high critical current density and high n-value; (2) flexibility in the design of its layer structure to make high resistance such as adopting thin or negligible metal stabilizer; (3) large cooling surface area related with fast recovery; and (4) thin tape type which enables various design of coils.

Our group and Hyundai Heavy Industries Co., LTD. have succeeded in the development and test of 13.2 kV/630 A non-inductive winding type FCL using stainless steel-stabilized CC as one of the 21st century Frontier R&D program in 2006 [3]. However, due to its long length of CCs, the size of the FCL system including cryogenic system was too large to three-phase power application. Reduction of CCs enables cutting expenses, volume decrease, and reducing cryogenic heat load related with cooling cost. So, investigation of suitable CC for FCL is required and many researches on experiments and analyses of HTS wire for FCL have been performed [4,5].

In this research, the CC which has no metallic stabilizer on silver layer, called stabilizer-free CC, was used for experiments and numerical analysis and was compared with stainless steel-stabilized CC. The short-circuit characteristics of CCs were investigated at various applied voltage in liquid nitrogen (LN_2) and sub-cooled LN_2. Then, thermal and electrical analysis by using finite element method (FEM) was performed and the results were compared with experimental data. Maximum temperature rise of the CC during the quench was analyzed with respect to electric field intensity, E (V/m), applicable to the CC. The temperature rise of the CC is important to prevent the performance degradation, and it is possible to reduce the total length used for FCL as E applicable to the CC is high in the same condition of maximum temperature rise. This paper concludes with investigation of feasibility and basic conceptual design of FCL using recently developed stabilizer-free CC from numerical and experimental analysis.

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2. Experimental and numerical method

2.1. CC samples

Two kinds of CCs were used for short-circuit tests in this research. Recent commercialization of stabilizer-free YBCO CCs manufactured by Superpower Inc. (SP) is expected to boost the development of SFCLs with more improved performances. Higher resistivity of Hastelloy C-276 substrate compared with copper or stainless steel that were conventionally used as a stabilizer is attributable to improvement in current limiting characteristics when the fault current is bypassed to substrate. In addition, considering current sharing among layers including substrate, elimination of stabilizer enables larger total resistance. The CC consists of, silver shunt, YBCO film, buffer, Hastelloy substrate, and silver over-layer by sputtering. Then, the stabilizer-free CC was chosen as sample 1. Sample 2 was the CC with stainless steel (SUS316L) stabilizer made by American Superconductor Inc. (AMSC) called 344s used for a 13.2 kV/630 A FCL that we have been developed previously. Its layer structure was similar with sample 1 except substrate materials and stabilizers attached by solder. These samples would be representative CCs commercialized for FCL application. Schematic configurations of cross section and detail specifications of each sample are shown in Fig. 1 and Table 1, respectively.

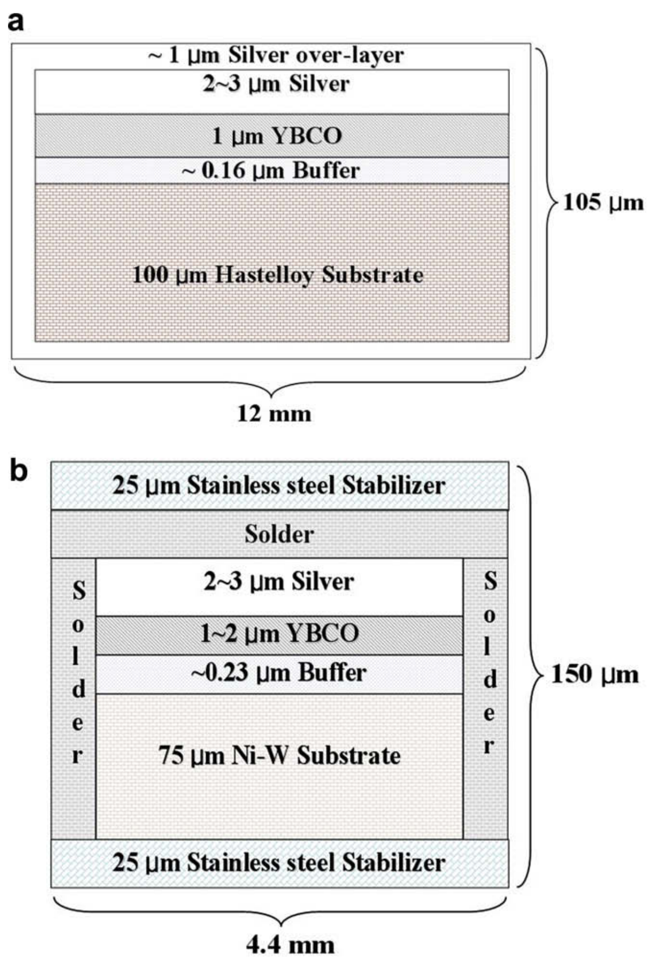

Fig. 1. Schematic configurations of cross-section of (a) Superpower SF12100, and (b) AMSC 344s.

Table 1
Specification of Samples.

	Sample 1	Sample 2
Trade name (manufacturer)	SF12100 (SuperPower)	344s (AMSC)
Stabilizer	No (called stabilizer-free)	Stainless steel (SUS316)
Width (mm)	12	4.4
Thickness (mm)	0.105	0.15
Length (mm)	200	200
Substrate (thickness in mm)	Hastelloy (0.1)	Ni–5%W (0.075)
Resistance per unit length at 300 K (mΩ/cm)	4	3.5
Critical current at 77 K, self-field (A)	254 (610 at 65 K)	75 (182 at 65 K)

2.2. Experimental setup

In order to investigate characteristics of CCs, some preceding tests have been performed in advance of short-circuit tests. Critical current (I_C) was measured and resistance per unit length with respect to temperature was measured with cooling down by crycooler. Since it is hard to measure temperature of CCs during quench, calculated resistance was used for estimation of temperature. In addition, to verify the thermally stable design of FCLs, maximum permissible temperature rise of CCs were determined by applying repetitive over-current and observing I_C degradation and there was no degradation up to 400 K [6].

Fig. 2 shows schematic of equivalent circuit for low voltage short-circuit tests. Fault duration was set 0.1 s (6 cycles in 60 Hz) and CBs was opened right after fault duration to detach the sample from circuit. Short-circuit tests were performed with increasing AC voltage and maximum temperature rise of a sample was estimated from its resistance in both saturated and sub-cooled LN_2, 77 K and 65 K respectively.

2.3. Thermal and electrical modeling: numerical analysis

We analyzed a sample 1 with thermal and electrical analysis. Fig. 1a shows detail layer configuration for numerical analysis except buffer layer. The effect of buffer layer is expected to be negligible and thus not consider in the model. Sample 1 has stacked layers structure configuration and surrounded thin silver over-layer. So, two-dimensional thermal conduction equation in the sample 1 was used for analysis as follows:

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) + q = Q \qquad (1)$$

where ρ is density, C is specific heat, k is thermal conductivity, q is cooling of superconductor, and Q is heat source from joule heating of each layer material. As the temperature of the CC increased during a fault, material properties such as resistivity, specific heat, and thermal conductivity were varying as function of temperature. In order to perform thermal analysis precisely, Q should be determined by considering resistances of all layers. Electrical and thermal analysis of the sample 1 started from fault occurrence. Also, boundary conditions were required. The sample was under boiling saturated LN_2 during quench so that heat flux, q, from surfaces of the sample to LN_2 was determined against temperature difference between surface and LN_2 of 77 K. We determined heat transfer coefficient, h, as a function of temperature, to be approximately 1400 W/m^2· K, and it was derived from heat fluxes in boiling liquid nitrogen. Fig. 3 shows an equivalent electric circuit for quench simulation of the sample 1 and R_{line} was determined to be 0.02 Ω similar with experimental value. All materials except buffer were electrically connected so that the layers were connected in parallel. Thus, distributed current to each layer could be calculated as follows: