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# A Study on the Short Circuit Characteristic of Metallic Stabilizer Free Coated Conductor for FCL Application

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***Abstract*-- As power demands increase, development of the superconducting fault current limiter (SFCL) is being watched with interest. Many types of SFCLs using various superconducting materials have been developed. Especially, the FCL using coated conductor (CC) has been investigated actively at present. CCs have many advantages for the FCL application. YBCO materials used in CCs have a high n-value, and it is relatively easy to choose a matrix of the CC for high resistivity. If the CC has high resistivity, high voltage can be applied to the CC. Then total length of the CC used in SFCL, which has effects on total price and volume of the SFCL, can be reduced. Short circuit tests of two different types of CCs in the liquid nitrogen bath and its sub-cooled condition were performed and analyzed. An effect of high resistivity of the CC and cooling methods on fault current limiting characteristics could be verified in this paper.**

## 1. INTRODUCTION

Recently, FCLs have been suggested in power distribution and transmission systems against increasing fault current level. Those are promising apparatus to limit the fault current efficiently to a certain level during a fault such that it can be applied to the power systems such as feeders, transformers, and interconnections [1]. A resistive SFCL has zero impedance at normal operating state while it generates certain impedance when the fault occurs. So it is important to analyze the quench impedance characteristics of conductors. There are many superconducting materials for FCLs such as BSCCO bulks, Bi-2223 tapes, YBCO thin films, and CCs. Among them, the CC, called the second generation HTS wire, is good for high class FCL application. It has high critical current density and high n-value and flexibility of its structure to make high resistance, and has large cooling surface area related with fast recovery [2].

This paper deals with the short circuit characteristics of two different CCs which can be used in resistive SFCLs. AC voltage was applied to the CC during short circuit duration. Maximum temperature rise of the CC during the fault state was analyzed with respect to the applied voltage per unit length (V/m) of the CC. It is possible to reduce the total length of the CC for FCL design when the electric field intensity ($E$), voltage per unit length, applied to the CC is high in the same condition of maximum temperature rise. Highly resistive CCs with high uniformity are the most proper conductors for resistive SFCLs. Theoretical approach and empirical verification on recently developed metallic stabilizer free CC was performed. Then, feasibility of the CC for FCL application was investigated.

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## 2. CONCEPT OF FCLs USING CCs

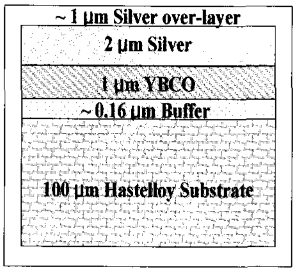
### 2.1. Samples

Generally, stabilizer and matrix of HTS wires including CCs play a role of bypassing the current and heat when a quench occurs. Since a quench of the wire is an unwanted phenomenon in most HTS applications such as a motor, a cable, and so on, the stabilizer is commonly thick for higher stability. However, the stabilizer and sometimes the substrate of the CC play a role of limiting the fault current in SFCL. The stabilizer should be designed optimally for SFCL [3].

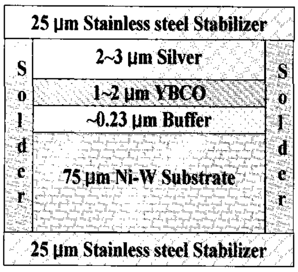
Two CCs were used for short circuit tests in this research. Recent commercialization of stabilizer-free (SF) YBCO CCs manufactured by Superpower is expected to boost the development of SFCLs with more improved performances. Higher resistance of hastelloy substrate compared with copper or stainless steel that were conventionally used as a stabilizer is attributable to improvement in current limiting characteristics when all of the fault current is bypassed to substrate. In addition, considering current sharing among layers including substrate, elimination of stabilizer enables larger total resistance. Then, the stabilizer-free CC was chosen as sample 1. Another sample was American Superconductor (AMSC)'s stainless steel-stabilized YBCO CC called 344s (Sample 2). A 13.2 kV/630 A class FCL using this CC had been developed and tested successfully already by Hyundai Heavy Industries Corporation in partnership with this research group. Thus, these are representative CCs commercialized for FCL application. Schematic configurations of cross section and specifications of each sample are detailed in Fig. 1 and Table 1.

### 2.2. Methods of FCL Design

Design proposal of resistive FCLs using CCs is based on assumptions: the fault current entirely bypassed to stabilizer and substrate; thermal condition during fault is adiabatic.




(a)




(b)

Fig. 1. Schematic configurations of cross-section of (a) SuperPower SF CC, and (b) 344s CC.

TABLE I
SPECIFICATIONS OF CC SAMPLES.

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

There is negligible heat transfer between the CC and liquid nitrogen. When quench occurs, nitrogen adjacent to the CC is boiled intensively due to joule heating of the CC. Visualization experiment revealed that the gaseous nitrogen covers the heating surface during the fault state [4]. Since the thermal conductivity of nitrogen gas is small enough, it is reasonable to assume the adiabatic condition between the CC and liquid nitrogen. Conductive cooling by glass fiber reinforced plastic (GFRP) is also negligible because the short sample used in this research has high thermal contact resistance between the CC and the GFRP holder. Detail experimental setup was dealt in next chapter. Based on the assumption, following power balance equation is derived.

$$\frac{V^2}{R}\Delta t = C_v \cdot A \cdot l \cdot \Delta T \quad (1)$$

where V is the voltage applied to the CC, R is the generated resistance, $\Delta t$ is the fault duration, $C_v$ is volumetric specific heat, $A$ and $l$ is the cross-sectional area and length of the CC, respectively and $\Delta T$ is temperature rise. Thermal and electrical analysis on CCs provides clues on current distribution among layers [5].

In this case, each parameter used in the above equation should be substituted by its effective value. From the above equation,

$$E = \sqrt{\frac{C_V \cdot \rho \cdot \Delta T}{\Delta t}} \quad (2)$$

where $E$ is applied voltage per unit length and $\rho$ is resistivity of the CC. The higher E is, the shorter length of wire is needed. For the FCL design, $\Delta T$, determined by operating temperature and maximum temperature rise of the CC, and $\Delta t$ are fixed. Finally, the required amount of the wire is determined by $C_v$ and $\rho$. To minimize the amount of the wire, a material whose resistivity is high in cryogenic condition should be adopted as the stabilizer of the CC.

## 3. EXPERIMENT

### 3.1. Preceding tests

In order to investigate the CC used in FCL, short circuit test is certainly needed but there are some tests which should be performed antecedently. Critical current of samples were measured and specified in Table 1. Critical current of sample 1 is higher than sample 2. It is clear an advantage for high rated superconducting power equipments. Next, resistance per unit length of each sample was measured with respect to its temperature as shown in Fig. 2. Conventional four point probe method was used to measure and samples were cooled in a small-scale cryocooler system. Resistance data from 300 K to 500 K were extrapolated from the former results. Since it is hard to measure temperature of samples during fault state, we calculated resistance from applied voltage to the sample and current, and then temperature could be estimated from resistance. In addition, to verify the stable design of FCLs, maximum permissible temperature rise of the CC was determined considering repetitive over-current applied to it. Temperature rise up to 400 K was available for FCL design without any diminishing the critical current [6].

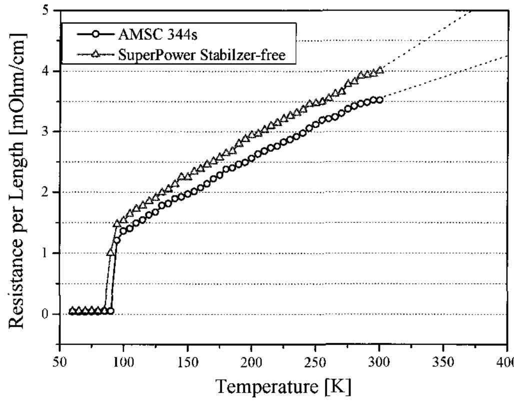



Fig. 2. Resistance per centimeter of CCs versus their temperature.

### 3.2. Experimental Setup

Each sample was 30 cm long and mounted on G10-FRP holder. Samples were immersed in liquid nitrogen bath and sample 2 was tested in sub-cooled liquid nitrogen additionally. Fig. 3 shows schematic of equivalent circuit of the short circuit test. Two thyristors were used to make a short and a magnet relay was used to break the circuit after fault duration, which was chosen to be 0.1 s in this research.

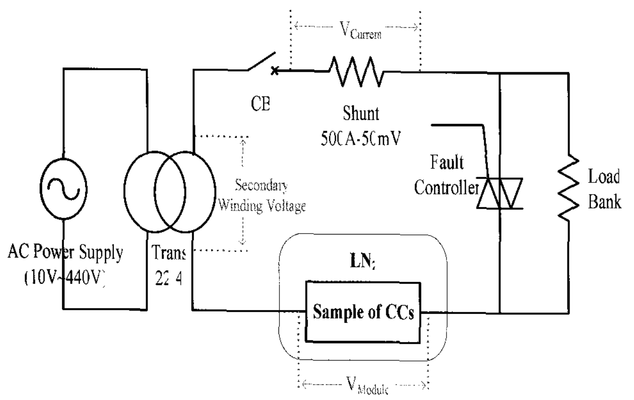



Fig. 3. Schematics of equivalent circuit of short circuit test.

## 4. RESULTS AND DISCUSSION

One of the results of short circuit tests using sample 1 at 77 K was shown in Fig. 4. The solid line shows $E$ applied to the sample and the value is 60 $V_{rms}$/m. The curve of scattered circles is the pattern of calculated resistance of the sample per centimeter. The current was increased up to 537 A in its first swing and 211 A in the last swing during fault. So the calculated value at the end of the fault duration is 4 mΩ/cm and it corresponded to 300 K according to Fig. 2 and resistance patterns after fault duration has no meaning because CB in Fig. 3 was opened right after fault duration. The current waveforms of tests were used for calculating resistance and not so important how much the current limited in this research. Thus, currents were not shown in graphs.

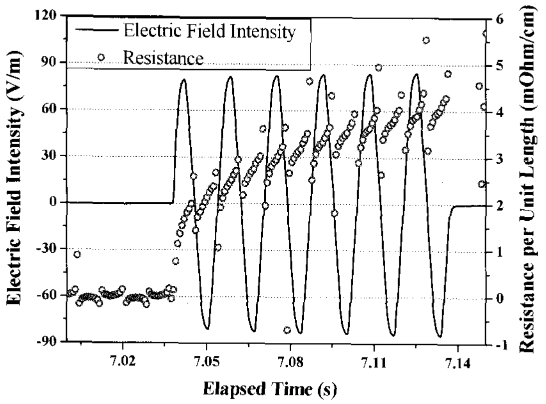



Fig. 4. Electric field intensity and generated resistance per unit length of the sample 1 at 77 K.

Test results employing sample 2 is shown in Fig. 5. The test result performed at 77 K is shown in Fig. 5 (a). When $E$ of 29 $V_{rms}$/m was applied to the sample 2, its maximum temperature rise during fault state was also 300 K, and this value of $E$ is a half of $E$ in case of sample 1 in the same condition. It is available to design the same rated FCL using half length of the CC with sample 1.Equation (2) shows the relation between $E$ and temperature rise of the CC, and $E$ applicable to the CC is determined by $C_v$ and $\rho$. The resistivity, $\rho$, of each sample can be calculated considering effective cross section area and sample 1 has higher resistivity. In case of sample 2, the current flows through solder layer which has low $C_v$ compared with substrate and stabilizers during fault. So effective value of $C_v$ of sample 2 was lower and it causes higher $E$ on the sample 1. Also, because sample 1 has simple layer structure, it would have advantages on thermal conducting and cooling factors although there was no mention in (2).

Fig. 5 (b) shows the results in the same condition except cooling method of the sample, in which the sample was cooled in sub-cooled nitrogen of 65 K. Resistance increased up to the value corresponding to 300 K when we applied $E$ of 37.5 $V_{rms}$/m to the sample. From the results, short circuit characteristics can be seen to have been affected by cooling method. Sub-cooled nitrogen has many advantages not only for temperature difference, $\Delta T$, as shown in (2).

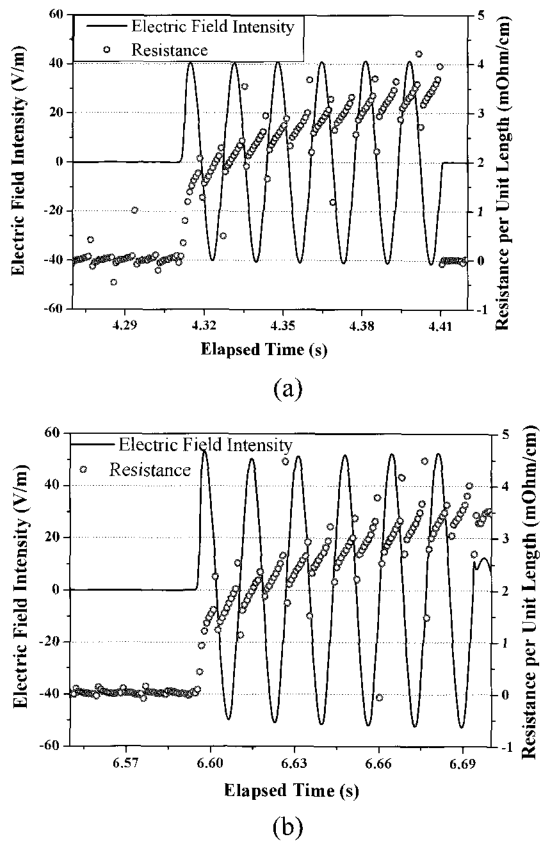



Fig. 5. Electric field intensity and generated resistance per unit length of the sample 2 (a) at 77 K and, (b) 65 K.

In this cooling temperature of 65 K, the critical current was increased about 2.5 times of the one at 77 K. There were different cooling characteristics of the CC between sub-cooled and saturated nitrogen. Sub-cooled method compensates joule heating with effective cooling on both surfaces of the CC, so higher *E* can be applied to the CC.

This is due to their lower initial temperature and good characteristic of bubble suppression [4]. Detailed analysis by thermal and electrical method will be dealt later.

Fig. 6 shows *E-T* curves of test results. It is clear that the CC with high resistivity and cooling method with sub-cooled nitrogen of 65 K allows high *E* on the CC. These results are expected to be helpful reference in deign of the FCL using CCs. The higher E is applied, the shorter length of the CC is used in FCLs. Reduction of the total amount of wires make effects on efficient FCL design such as cutting expenses, volume decrease, and reducing cryogenic heat load like ac loss.

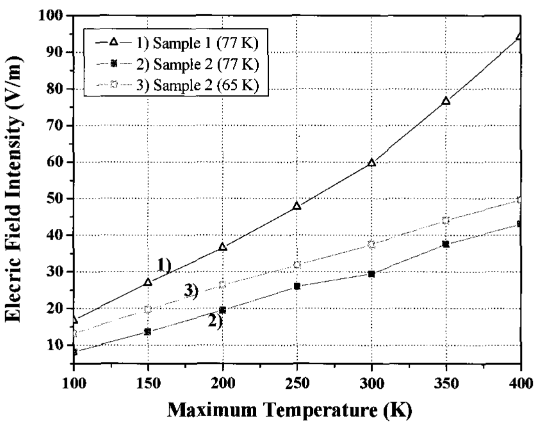



Fig. 6. Tendency curves of Electric field intensity of CC samples vs their maximum temperature rise during 0.1 s.

## 5. CONCLUSION

The short circuit tests of two CC samples in saturated liquid nitrogen of 77 K and sub-cooled nitrogen of 65 K at various applied voltage and an analysis of their quench characteristics were performed. From the result of short circuit tests, we concluded as follows:

(1) Sample 1 was efficient in design of FCL using CC. That is, *E* of 60 $V_{rms}$/m could be applied to the sample 1 for maximum temperature of 300 K while about 30 $V_{rms}$/m was applied to the sample 2 at 77 K for the same maximum temperature.

(2) Sub-cooled nitrogen cooling improved *E* applicable to the CC and the total amount of wires are expected to be reduced in FCL design.

As shown in test results, CCs which have high resisitivity and sub-cooled cooling is efficient to design FCLs using CCs. We also make a plan to perform the test using sample 1 at 65 K and detailed thermal and electrical analysis is in progress.

## ACKNOWLEDGMENT

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## REFERENCES

[1] Kalsi, S.S., Malozemoff, A, "HTS fault current limiter concept," *IEEE Power Engineering Society General Meeting, 2004*, vol. 2, pp. 1426-1430, 2004.

[2] D. K. Park, M. C. Ahn, S. E. Yang, Y. S. Yoon, B.-Y. Seok, C. Lee, H.-M. Chang, and T. K. Ko, "Development of 220 V/300 A Class Non-inductive Winding Type Fault Current Limiter Using 2G HTS Wire," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 1855–1858, 2007.

[3] M. C. Ahn, D. K. Park, S. E. Yang, Y. J. Kim, H. M. Kim, H. Kang, K. Nam, B.-Y. Seok, J.-W. Park, and T. K. Ko, "A Study on the Design of the Stabilizer of Coated Conductor for Applying to SFCL," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 1863–1866, 2007.

[4] K. Nam, H. Kang, C. Lee, T. K. Ko, and B. Y. Seok, "Visualization study on boiling of nitrogen during quench for fault current limiter applications," *IEEE Trans. Appl. Supercond.*, vol. 16, pp. 727–730, 2006.

[5] K. Nam, C. Lee, D. K. Park, T. K. Ko, B.-Y. Seok, "Thermal and Electrical Analysis of Coated Conductor Under AC Over-Current," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 1923–1926, 2007.

[6] M. J. Kim, M. C. Ahn, S. E. Yang, D. K. Park, Y. J. Kim, T. K. Ko, C. Lee, and B.-Y. Seok, "Determination of Maximum Permissible Temperature Rise Considering Repetitive Over-Current Characteristics of YBCO Coated Conductors," *20th International Conference on Magnet Technology*, Philadelphia, Pennsylvania USA, August 27–31, 2007.