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Manufacture and Test of Small-scale Superconducting Fault Current Limiter by Using the Bifilar Winding of Coated Conductor

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Abstract— **The Resistive Type High Temperature Superconducting Fault Current Limiter (SFCL) has been developed in many countries. Until now, materials of the resistive SFCL were *Bi2212 bulk and YBCO thin film*. Although YBCO coated conductor (CC) has many advantages such as high n-value and critical current for applying resistive SFCL, the resistive SFCL using CC doesn't have developed yet. The bifilar winding type SFCL was manufactured and tested rated on 30V/80A. In normal state, the SFCL using pancake type bifilar winding had very low impedance. When a fault occurred, the SFCL limited the fault current efficiently. Through these results of experiment, large-scale SFCL using CC should be developed in the future.**

1. INTRODUCTION

Recently the commercialization of the resistive Superconducting Fault Current Limiter (SFCL) is near at the hand such as CURL 10 project of Germany and MFCL project of America etc. However the resistive SFCL using YBCO coated conductor (CC) that is being researched with activity has been still developing. Although YBCO CC has some problems what are still low critical current, short piece length and cost, these problems will be solved presently when considering development process. CC manufacturers like American Superconductor (AMSC), THEVA and IGC-Superpower® which are developing C.C for applying the resistive SFCL have been advanced on many cases such as structure, stabilizer and width etc. So it is hurry to develop the resistive SFCL with C.C in acquiring a priority. In Yonsei University, the development of this type SFCL has been going through 2004 as one of 21st Century Frontier R&D Program.

Using HTS tape as the material for SFCL, it is relatively easy to design and fabricate SFCL that has various structures. Our group has researched a resistive SFCL using Bi-2223 tape wire recently. From the research, the feasibility of applying Bi-2223 to the SFCL could be investigated [1]. On the other hand, YBCO CC has high index number [2]. When the fault occurred, it can be limited effectively by high n-value. Thus CC may be an attractive choice for the SFCL.

In manufacturing the resistive SFCL using CC, winding method is very important factor to reduce the AC loss. For reducing the capacity of cryocooler and production cost, AC loss must be reduced efficiently.

In this paper, describes manufacture and test of SFCL using YBCO the bifilar winding of YBCO CC

2. MANUFACTURE OF BIFILAR WINDING COIL

2.1. YBCO Coated Conductor

Wire used was YBCO CC made by IGC-SuperPower®. Table I shows specifications of the tape. In general applications of HTS tape, a stabilizer plays the role of protecting the tape during the quench. In SFCL, the stabilizer makes the resistance and limits the fault current during the fault. Therefore, the specification of the stabilizer is very important factor in SFCL. As shown in Fig. 1, the tape is surrounded by the copper stabilizer whose thickness is 20 ㎛. The copper stabilizer was attached by electroplating.

2.2. Manufacture of Bifilar Winding Coil

A current limiting coil was manufactured using YBCO coated conductor. The coil was non-inductively wound coil and called as "bifilar coil."

It is one of key technologies for the SFCL using HTS tape to design the winding type. There are two kinds of bifilar winding; solenoid and pancake. For more effective canceling of inductance, pancake type bifilar winding was adopted. Fig. 2 shows the bobbin for the bifilar pancake winding.

TABLE I
SPECIFICATIONS OF YBCO CC

Critical Current	152 A @ 77K, self field (122A/cm-w)
N value	19 (0.1-1 ㎶/㎝)
Width	12.4 mm
Thickness	0.15 mm
Structure (thickness, ㎛)	Copper(20)/silver(3)/YBCO(1)/buffer(1)/ Substrate(100)/copper(20)*
Stabilizer	Copper, 20㎛ (all sides)
Piece length	10 m

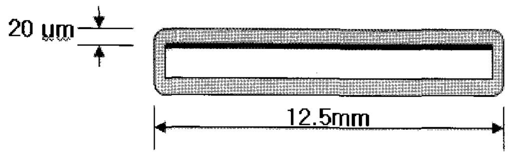


Fig. 1. Stabilizer structure of CC

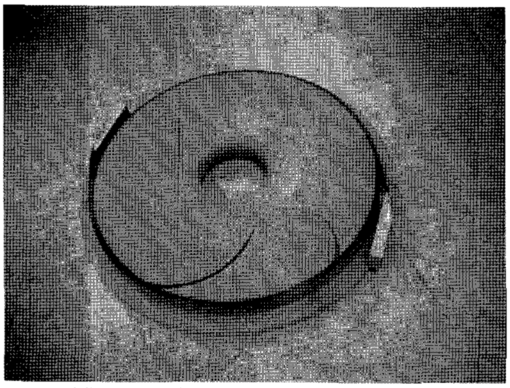


Fig. 2. Bifilar winding SFCL using YBCO C.C

In Fig. 2, T'aegŭk symbol indicated a groove for bifilar winding. As the center of CC tape was wound at the groove, the non-inductively wound coil could be fabricated.

The polyimide film whose width was 15 mm and thickness was 0.04 mm was attached on both sides of YBCO CC for the electrical insulation. YBCO CC tape of 8 meters was wound and the number of winding turns was 12. Since the coil was bifilar, 6 turns were wound clockwise and the other 6 turns counterclockwise. For supporting of the wire during the fault, the coil was impregnated by epoxy resin, Stycast®. Table II is specifications of the coil.

3. EXPERIMENTS OF THE BIFILAR COIL

3.1. Experiment setup

For investigating the characteristics of the bifilar coil, its critical current was measured and the short-circuit tests were performed.

Current-voltage characteristics of the bifilar coil were measured at 77 K as shown in Fig. 3. From the curve, critical current of the coil was 123 A. Some mistakes at handling the tape could be the reason why the critical current decrease from 152 A to 123 A.

TABLE II
SPECIFICATIONS OF BIFILAR COIL

Inner diameter	200 mm
Outer diameter	207 mm
Resistance	295 mΩ @ 300K
Inductance	0.5 μH
Turns	12 (6+6)
Wire length	8 m

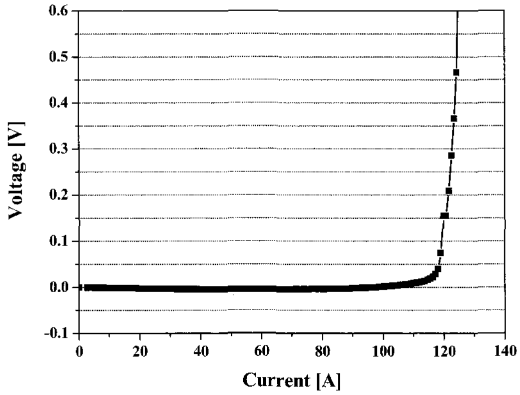


Fig. 3. Current-voltage curve of the bifilar coil

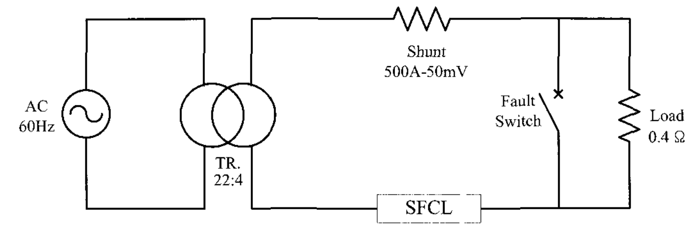


Fig. 4. Circuit diagram for the test

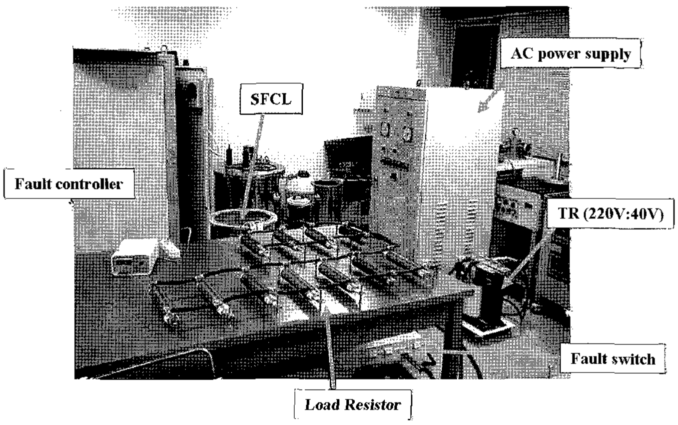
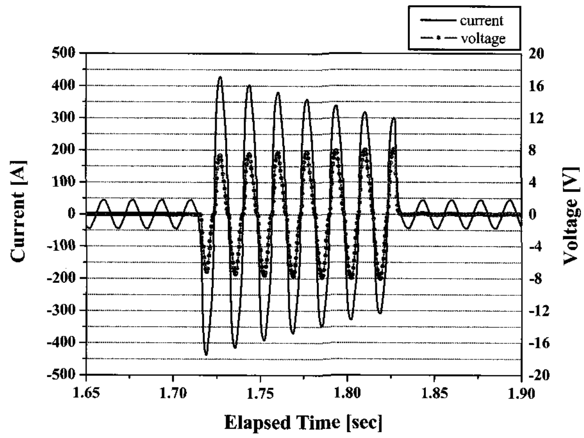


Fig. 5. Experiment setup for short-circuit test

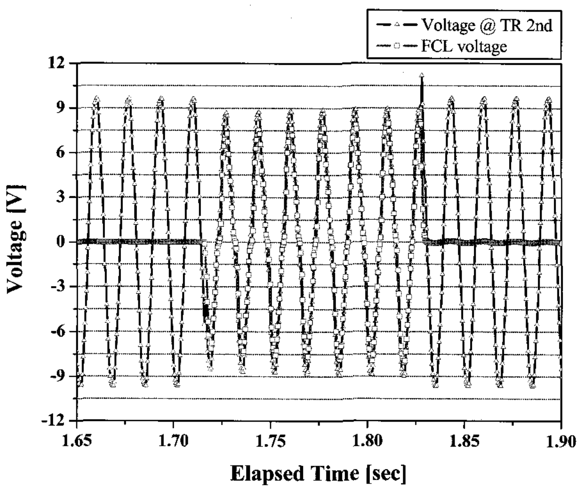
Current limiting characteristics of the bifilar coil were investigated by short-circuit test. Fig. 4 shows the circuit diagram for the test. A transformer was used for generating large current. The fault switch made the circuit fault condition. Fault duration was 0.1 sec. The line impedance was 0.4Ω . Fig. 5 is the experiment setup for short-circuit test. The bifilar coil was immersed in opened cryostat.

3.2. Results of Experiments

Fig. 6 shows the short-circuit test result rated on 7 V_{rms}/35 A_{rms}. In Fig. 6(a), voltage line indicates the voltage at bifilar coil. A fault occurred at the moment of 1.715 sec. Line current increased rapidly. If the bifilar coil did not insert to the line, expected fault current was 800 A_{peak} at first peak and then 700 A_{peak} during the fault. Voltage at the bifilar coil was near zero before the fault. When the fault occurred, voltage increased immediately. It means that bifilar coil has zero impedance before while has large



(a)



(b)

Fig. 6. Short-circuit test result of 7V/35A; (a) line current and voltage, (b) voltage at SFCL during the fault.

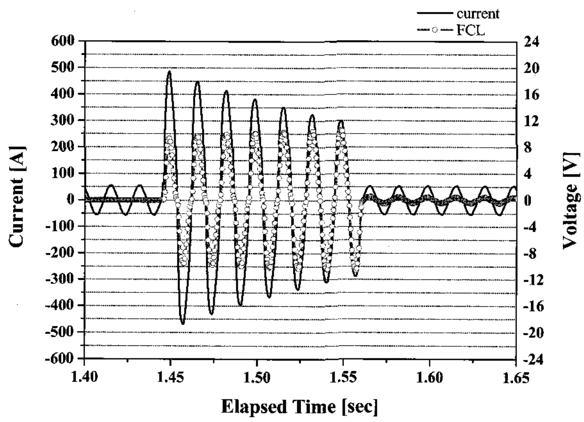


Fig. 7. short-circuit test result of 8.5V/35A

impedance during the fault. Fault current restricted to 420 A at the first peak. In Fig. 6(b), voltage at the SFCL of the bifilar coil was near voltage at the secondary winding of the transformer during the fault. The fault kept up for 0.1 sec, and then the fault switch in Fig. 4 opened again. Therefore, current of 35 A_{rms} flowed in the coil after the

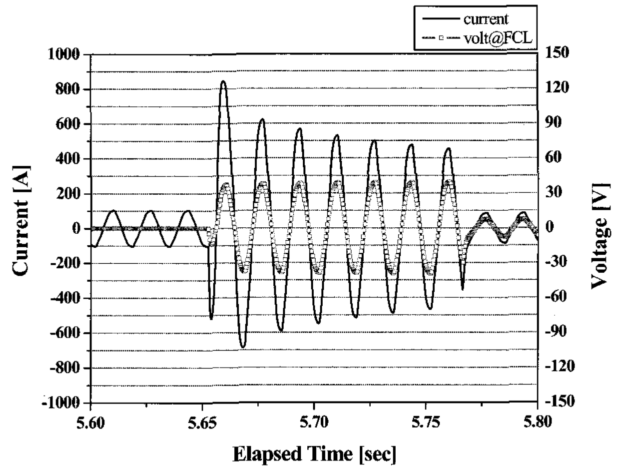


Fig. 8. Line current and voltage of short-circuit test result rated on 32V/78A.

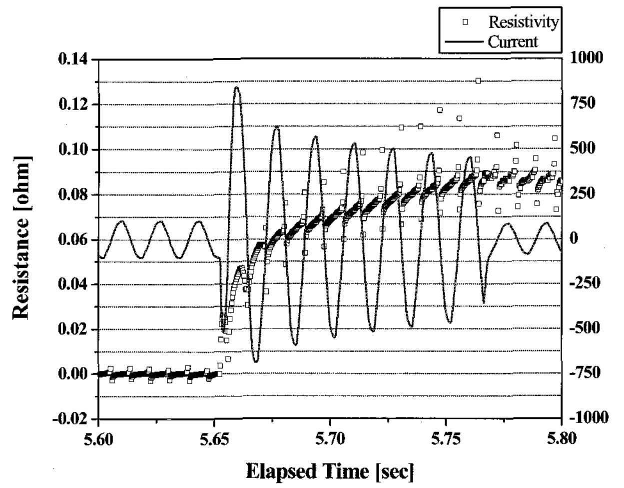


Fig. 9. Resistance during the fault.

fault duration.

At that time, voltage at the coil came back to near zero, it means that the SFCL could be instant recovery.

Short-circuit tests were performed with various rated power up to 32 V_{rms}/78 A_{rms}. The test results were shown as Fig. 7 to Fig. 9. Fig. 8 shows line current and SFCL voltage. Expected fault current was about 8.3 kA_{peak} at first peak and then about 7 kA_{peak} during the fault. As the SFCL was inserted in the line, fault current limited to about 830 A_{peak} at first peak and then fault current decreased gradually. Voltage at the SFCL was near zero before the fault while voltage was about 40 V_{peak} immediately when the fault occurred. While the SFCL could be instant recovery in the test of 7 V/35 A shown as Fig. 6, voltage at the SFCL could not come back to near zero after the fault in Fig. 7.

Fig. 9 shows the variation of resistance of the SFCL during the fault. When the fault occurred, resistance of the SFCL increased immediately and rapidly. When the current flowing in the CC was above its critical current, the wire quenched and current sharing between YBCO layer and stabilizer occurred. Since the YBCO CC has high index number, N value, resistance of the SFCL could increase very rapidly at the moment of fault. Resistance of the SFCL was about 0.09 Ω at the moment of 0.1 sec after the fault. Applying the specifications of the stabilizer such as thickness of 40 micron and width of 12.4 mm, electrical resistivity could be calculated at that time. From the calculation, resistivity was 5.6 nΩm, and temperature of CC tape was about 135 K at that time. Even if the SFCL did not have instant recovery characteristics at the rated power, the SFCL was thermally stable at the rated power test because maximum temperature was just 135 K.

From the Fig. 8 and Fig. 9, it can be confirmed that the SFCL using CC bifilar coil has very small impedance in normal operation and large and immediate impedance during the fault.

4. CONCLUSION

A resistive superconducting fault current limiter using YBCO coated conductor (2G wire) has been developed for the first time. Most of the resistive SFCLs have very long recovery time because current limiting devices are bulk or thick film. The new SFCL using CC can reduce the time epochally. YBCO CC has many merits for applying current limiting device; high index number, high critical current density, flexibility of stabilizer, cheap prime cost and so on.

From this research, it could be confirmed that the SFCL has very small impedance in normal operation and effective current limiting performance.

In the future, optimal design of the stabilizer of CC, non-inductively winding structure and AC loss of CC tape should be investigated for developing large-scale SFCL using CC tape.

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