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Current Limitation by Bi-2223 Bifilar Winding Coils

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Abstract— **There are many kinds of high temperature superconducting (HTS) application using Bi-2223 tape which is the most commercialized HTS material. Also, resistive superconducting fault current limiters (SFCLs) have been developed using many kinds of superconducting material such as YBCO thin film, Bi-2212 bulk and so on. However, SFCL using Bi-2223 tape has never been developed. This paper deals with the feasibility study on SFCL using Bi-2223 wire. The over-current behaviors of Bi-2223 short-length sample were measured. To make the resistive SFCL, two small-scale bifilar winding modules using 7m Bi-2223 wire were fabricated; i.e. solenoid type bifilar coil and pancake type one. The short-circuit tests of the coils were successfully performed up to 16 V_{rms}. From these tests, the current limiting capabilities of Bi-2223 bifilar coils were confirmed and current limiting performances between two winding types were compared. In addition, the feasibility of resistive SFCL using another HTS wire, i.e. YBCO coated conductor, was also investigated.**

1. INTRODUCTION

There are two types of SFCL; one is resistive type and the other is inductive type. Many resistive SFCLs have been developed using various superconducting materials such as YBCO thin film, Bi-2212 tube, Bi-2212 thick film and so on. However, the SFCL using high temperature superconducting (HTS) tape wire has never been developed. Using HTS tape as the material for SFCL, it is relatively easy to design and fabricate SFCLs that have various structures. In this paper, the feasibility of SFCL using Bi-2223 wire was investigated. Bi-2223 tape is the most commercialized HTS wire at present.

For this research, the over-current behaviors of Bi-2223 short-length sample were measured. In addition, two small-scale bifilar winding modules using Bi-2223 wire were fabricated; i.e. solenoid type bifilar winding module and pancake type one. The short-circuit tests of the modules were performed. In bifilar winding type SFCL, most of design factors such as inductance, ac loss, system size, current limiting performance, temperature during a fault and so forth are affected by its winding type. Therefore, it is very useful to investigate the current limiting characteristics with respect to winding type.

In addition, the feasibility of resistive SFCL using another HTS wire, i.e. YBCO coated conductor, was also investigated.

2. OVER-CURRENT TEST OF BI-2223 TAPE SAMPLE

For the feasibility research on applying Bi-2223 tapes to the resistive SFCL, over-current tests of Bi-2223 short-length sample were performed. HTS tape used was the high-strength reinforced Bi-2223 wire made by AMSC®. Table I shows specifications of the tape. AC currents above its critical current were applied. The currents were generated by the circuit shown in Fig. 1. For generating large current, a 22:1 transformer was used. Over-currents were applied for 0.1 sec and 0.2 sec because 0.1 sec is the average fault duration time. Two sets of voltage tap were installed on the tape. The distances between taps were 50 and 100 mm. The length of sample tape was 100 mm. For comparing current behaviors, short-circuit tests without Bi-2223 tape were also performed. Various voltages were applied and maximum applied voltage on the secondary winding was 8.2 V_{peak}. In this case, current of 890 A_{peak} was generated.

Applying over-current above critical current induces a quench of Bi-2223 tape. Since large resistance in Bi-2223 core is induced when a quench occurs, the over-current is bypassed through matrix material (AgAl) and coated material (stainless steel). Therefore, current can be limited.

Fig. 2 shows the result waveform of over-current test. Applied voltage on the secondary winding was 8.2 V_{peak}. Using 100 mm Bi-2223 tape, current of 890 A_{peak} could be limited to 718 A_{peak} after 0.1 sec. The current limitation means that Bi-2223 tape can be used for current limiting device. Fig. 3 shows resistance and voltage during the fault. The resistance increased gradually because the temperature of the tape increased. Resistance increased up to 3.5 mΩ after 0.1 sec. Voltage across Bi-2223 tape increased during the fault. However, voltage could not be

TABLE I
SPECIFICATIONS OF BI-2223 TAPE.

Critical current	115 A @ 77K, self field
Width	4.1 mm
Thickness	0.3 mm
Laminated material	SUS 315L
SUS thickness	0.1 mm (both sides)

zero immediately after the fault. That means Bi-2223 could not recover instantly. Recovery time was about 1.4 sec in this case. Moreover, a lot of bubble was observed during the 1.4 sec.

Over-current for 0.2 sec was also applied to the tape. Fig. 4 shows a test result of over-current for 0.2sec. As the expectation, voltage increased and current was decreased rapidly. The current of 890 A_{peak} could be limited to 560 A_{peak} after about 0.2 sec. At elapsed time 7.975 sec in Fig. 4, the Bi-2223 tape was burned out partially. At that moment, maximum power density was 600 W/cm^2.

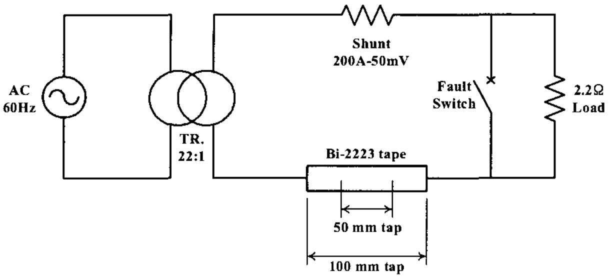

Fig. 1. Circuit of over-current test.

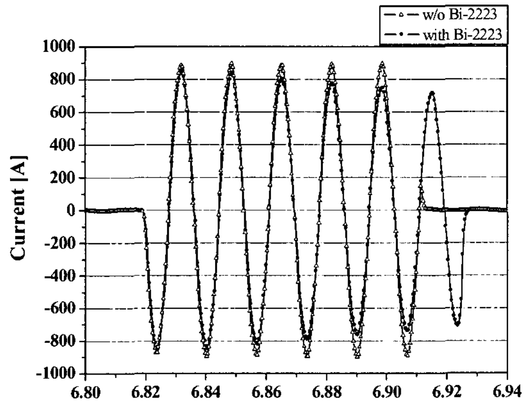

Fig. 2. Result of over-current test with Bi-2223 tape.

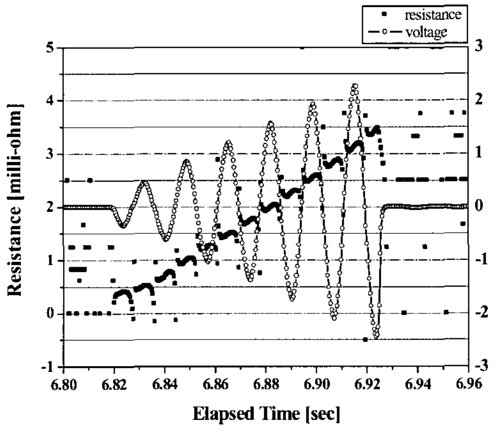

Fig. 3. Resistance and voltage during the fault.

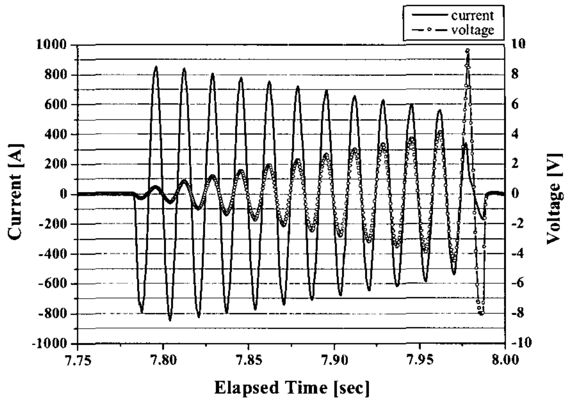

Fig. 4. Test result of over-current for 0.2 sec.

3. CURRENT LIMITATION BY BIFILAR WINDING COILS USING BI-2223 TAPE

For fabricating the current limiting device using HTS wire, wire should be co-wound because inductance of coil leads to the loss during normal operation. In this research, two types of bifilar coils were fabricated; one is solenoid type and the other is pancake type. Fig. 5 shows solenoid bifilar coil. Bobbin was made of G10-FRP and has two grooves for winding of Bi-2223 wires. A pancake type bifilar coil was also fabricated. The length of wire used for pancake type was as much as that of solenoid type. In pancake type, insulating tapes, Kapton®, were laminated on the both sides of the Bi-2223 tape. Bi-2223 wire was wound with winding tension of 10 N, which do not cause the electrical degradation [1]. The specifications of the coils are as shown in Table II. Fig. 6 shows pancake bifilar coil.

For current limiting test, short-circuit tests were performed. Experimental setup of the short-circuit test is the same as Fig. 1, except that bifilar coil was used instead of tape sample. Fig. 7 and Fig. 8 show short-circuit test results of solenoid and pancake respectively. The voltage on secondary winding of transformer was 16 V_{rms} and fault duration time was 0.1 sec. For solenoid, first peak current was about 660 A_{peak} when a fault occurs. The current decreased continuously during the fault. Finally, current of 500A_{peak} was transported after 0.1 sec. The voltage increased continuously during the 0.1 sec period because temperature would increase at that time. Before the fault, the voltage across the coil is very small because impedance of the coil is much smaller than load resistance. However, after the fault the voltage of 14 V_{rms} or above was applied to the coil. In pancake type, first peak current was 725A_{peak}. However, current was limited to about 400A_{peak} during 0.1sec. Fig. 9 shows resistances of solenoid and pancake type bifilar coil when fault occurs. Current limiting performance of pancake bifilar coil was more effective than that of solenoid because pancake has the structure in which wound wires are overlapped each other. Therefore, surface of wire in contact with liquid nitrogen is relatively small and temperature of wire increases easily.

TABLE II
SPECIFICATIONS OF BIFILAR COILS.

Solenoid	Diameter	94 mm
	Height	200 mm
	Turns	24 (12 + 12)
	Wire length	7200 mm
	Inductance	2.08 μH
	Resistance	261 mΩ @ 300 K
Pancake	Diameter	250 mm
	Height	15 mm
	Turns	12 (6 + 6)
	Wire length	7200 mm
	Inductance	0.53 μH
	Resistance	251 mΩ @ 300 K

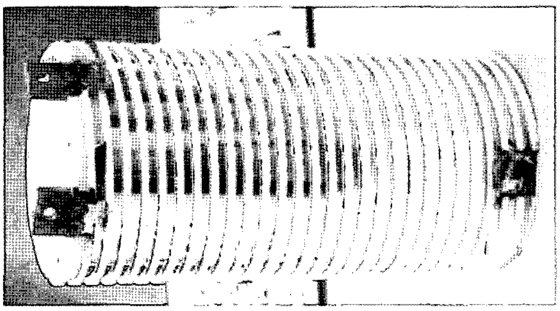

Fig. 5. Solenoid type bifilar coil.

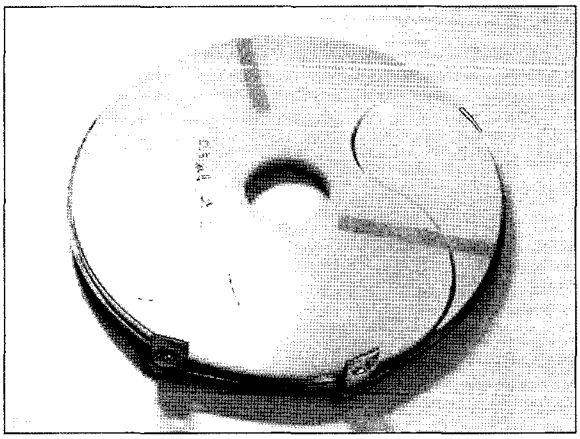

Fig. 6. Pancake type bifilar coil.

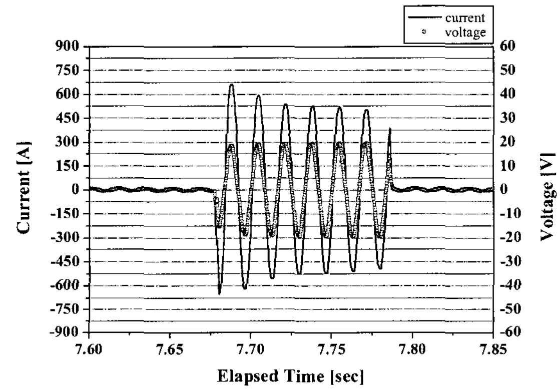

Fig. 7. Short-circuit test result of solenoid bifilar coil.

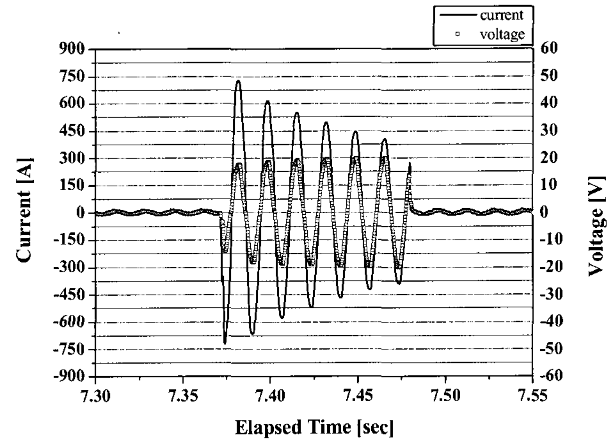

Fig. 8. Short-circuit test result of pancake bifilar coil.

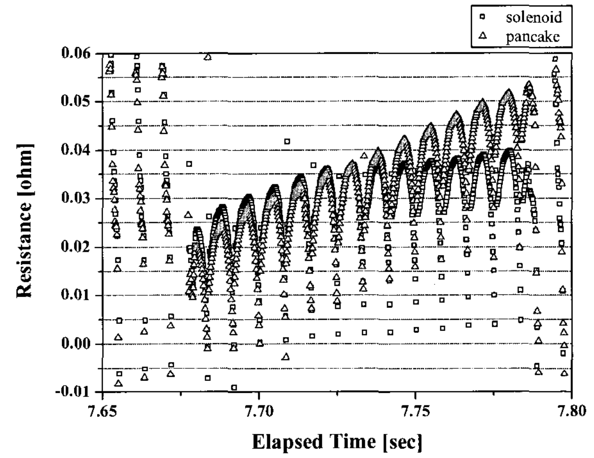

Fig. 9. Resistances of solenoid and pancake.

4. COMPARISON BETWEEN SOLENOID AND PANCAKE TYPE BIFILAR COILS

It is very important to choose the winding type in bifilar winding type SFCL. Comparison of winding types should be mainly focused on current limiting, thermal stability, system size, AC loss, electrical insulation and impedance during normal operation.

The inductance of pancake is smaller than solenoid because of winding structure as shown in Table II. It is important to bifilar winding type SFCL to minimize impedance because ideal SFCL has zero impedance in normal operation. In most case, the smaller inductance is, the smaller AC loss is. Pancake type has a merit in view of small impedance and AC loss in normal operation.

In solenoid type, there are grooves for winding. The groove can help electrical insulation between turns. On the other hand, pancake type has very closed terminals, and there can be a serious point in electrical insulation. Also, surface of wire are not in contact with liquid nitrogen in pancake type. Therefore, thermal stability is lower than solenoid.

5. FEASIBILITY STUDY ABOUT THE APPLICATION OF HTS WIRES TO SFCL

To apply Bi-2223 tape wire to the resistive SFCL, high resistance is required when a fault occurs. From the over-current tests, resistance of 7 mΩ/m is induced by applying electric field of 2.2V/m. From that result, we can design a resistive SFCL approximately. If we design the single-phase SFCL rated at 13.2 kV/630 A, wire of about 30 km length is needed. However, this design is not good in view of the cost because required amount of the wire is too large. This result is mainly caused by low resistance developed when an over-current is transported. The larger an electric field is applied, the shorter a length of required wire is. However, the optimal electric field is governed by stability of the wire and recovery time. For example, transportation current of 890 A may cause the recovery time of 1.4 sec or longer. In conclusion, Bi-2223 tape can be used for SFCL, but it is not good choice for optimized design because of the low resistance.

On the other hand, YBCO coated conductor (CC) may be an attractive choice for the SFCL. Because YBCO has high index number [2] and stabilizer of the conductor can be controlled. Bi-2223 is made by PIT (Power-In-Tube) process, so a matrix material is limited. It is very hard to enlarge the resistance of matrix part. However, CC is made by coating process, so it is relatively easy to control the material and thickness of stabilizer part. It is another merit that YBCO CC has very large critical current density and good cryo-stability[3].

To develop a resistive SFCL using HTS wire may have many advantages; short recovery time, possibility of various structure and low loss. In this research, it was shown that Bi-2223 wire can be used for resistive SFCL. However, YBCO CC has more attractive merits. Therefore, bifilar winding SFCL using YBCO CC should be investigated in the future.

6. CONCLUSION

In this research, the feasibility of an SFCL using HTS wire was confirmed. Over-current behavior of Bi-2223 short-sample was observed. In addition, two types of bifilar winding coils were fabricated and short-circuit tested. Both of them can limit fault current effectively. Comparing two coils, pancake type has advantages in view of current limiting performance, small inductance and AC loss. On the other hand, solenoid type has merits in view of electrical insulation and thermal stability.

A research on selecting the winding type should be performed for better design of resistive SFCL. In addition, bifilar winding type SFCL using YBCO CC can be an attractive model.

ACKNOWLEDGMENT

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