Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.10, No.2, (2008), pp.30~33

Experimental Analysis of Superconducting Fault Current Limiter Wound with Two Different HTS wires in Parallel

Ji Tae Kim[1,*], Jae Young Jang[2], Dong Keun Park[2], Ki Sung Chang[2], Young Jae Kim[2], and Tae Kuk Ko[2]

[1]Department of Electronic Engineering, Kyungwon University
[2]Department of Electrical and Electronic Engineering, Yonsei University

Abstract-- **Several kinds of superconducting fault current limiters (SFCLs), which reduces huge fault current, have been developing by many research groups. The SFCL has no impedance during normal operation, so it dose not give any influence to electric power system. The resistive type SFCL reduces the fault current with the impedance generated in the superconducting part of the SFCL when the fault current exceeds the critical current of SFCL. In this paper, a new type resistive SFCL made of bifilar coil wound with two different high-Tc superconducting (HTS) wires in parallel. Although a bifilar coil has theoretically no inductance, the bifilar coil made in this paper could generate inductance at fault. The specifications of the used two wires were considerably different, thus current distribution between the two HTS wire was different at fault. When the fault current exceeded the critical current of one wire in the bifilar coil, the momentary sharp increase of impedance was detected. Base on the results, a new resistive type SFCL can generate not only resistance but also inductance, which can be used to control a fault current in the future.**

1. INTRODUCTION

Recently, the demand for electric power is increasing rapidly. The electric power system is getting amazingly bigger and complicated, which can easily induce serious troubles from the potential of large fault problems and /or system failure. The application of Superconducting electric power will resolve the stability and efficiency problems which electric power industry has to overcome.

The superconducting fault current limiter (SFCL) can reduce huge fault current, and does not give any influence to electric power system during normal operation. To make an ideal SFCL, it is important to have zero impedance during normal operation, fast generation of impedance at fault, and fast recovery after clearing the fault.

The bifilar coil can be one of the solutions to make a resistive type SFCL. The magnetic fluxes generated in the bifilar coil by the clockwise winding and counterclockwise winding have same magnitude and opposite direction, which means magnetic fluxes cancel out and do not exist any inductance in the coil.

In the previous researches, the bifilar coils were wound with the same wire. A purpose of this paper was to make not only resistance but also inductance at fault.

To accomplish this purpose, a bifilar coil wound with two different high-Tc superconducting (HTS) wire was suggested. A double-pancake type HTS coil was also suggested to make high inductance at fault. The double-pancake type bifilar coil has an advantage in making high magnetic flux than solenoid type coil [1]- [3]. Because the specifications of the used two wires were different, unequal current distribution was occurred at fault. The unequal current distribution means that the generated magnetic flux of upper and lower layer of double-pancake type coil was not same.

In this paper, proposed bifilar coil was designed fabricated and tested. The magnetic flux of the coil also is calculated by using numerical simulation method. It is possible that the proposed concept can be applied to SFCL in the future

2. EXPERIMENTAL SETUP

2.1. HTS Wires

The used HTS wires were "High Strength Plus Wire" and "344S Superconductors" from American Superconductor Corporation (AMSC). The "High Strength Plus Wire" is 1G HTS wire made of BSCCO HTS material and the "344S Superconductors" is 2G HTS wire made of YBCO HTS material. The matrix of the BSCCO HTS wire is Ag alloy and the substrate of the YBCO HTS wire is Ni alloy and both wires were reinforced with stainless steel tapes. Table I shows the specifications of used two HTS wires.

Fig. 1 shows the V-I curves of the used two HTS wires. The critical current of BSCCO HTS wire and YBCO HTS wire, with 1μV/cm criterion, was 125 A and 98.1 A, respectively.

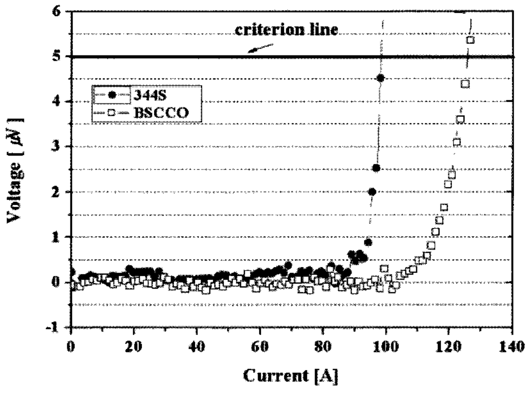

Fig. 1. V-I curves of used HTS wires.

---

* Corresponding author: nan99ma@yahoo.co.kr

TABLE I
SPECIFICATIONS OF USED WIRES

	YBCO HTS wire	BSCCO HTS wire
Width	4.32 mm	4.22 mm
Thickness	0.18 mm	0.28 mm
Ic	98.1 A	125 A

TABLE II
SPECIFICATIONS OF DOUBLE- PANCAKE TYPE HTS BIFILAR COIL

	Top coil	Bottom coil
Wire	BSCCO	YBCO
Number of turns	6	6
Wire length	980 mm	960 mm
Inductance	5 μH	4 μH

Base on the results of the critical current measurements, it was expected that quench would occurs in YBCO HTS wire firstly, then most of the transport current would flow to BSCCO HTS wire, which means inductance component could be made by asymmetric magnetic flux between upper and lower coil at fault.

2.2. Double-Pancake Type HTS Bifilar Coil

Table II shows the specifications of the double-pancake type HTS bifilar coil. Both of wires were insulated with Kapton tape. Fig. 2 shows the manufactured bifilar coil. Top coil was wound with BSCCO HTS wire in a clockwise direction and bottom coil was wound with YBCO HTS wire in a counterclockwise direction. The direction of magnetic by top coil was against to the direction by bottom coil. If the top and bottom coils have symmetrical structure perfectly, the magnetic flux by top and bottom coil would cancel out. The HTS bifilar coil dose not has any impedance during normal operation. The HTS bifilar coil could have impedance including resistance and inductance at fault because the difference of the critical current and matrix material between top and bottom coil.

2.3. Short- Circuit Test

To investigate the characteristics of the manufactured double-pancake type HTS bifilar coil, short- circuit tests were performed in liquid nitrogen. The experimental system coil consisted of AC power supply, shunts for measurement of current distribution, resistive load, and fault controller using high voltage thyristor.

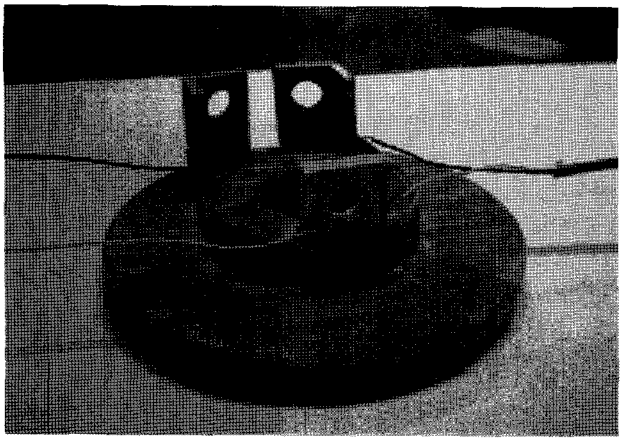

Fig. 2. Manufactured double-pancake type HTS bifilar.

All signals were acquired and processed in DAQ processor. Fig. 3 illustrates the schematic overview of the short-circuit test. The short-circuit condition was made by the fault switch. The fault duration was 0.1 sec. To measure the current in each winding, shunt resistors were connected in series. The experiment was implemented from 3 V to 35 V at the module.

3. RESULTS AND DISCUSSIONS

3.1. Current Distributions

In this research, because the resistance of the shunt resistor was very higher than that of SFCL, it affected the current distribution. It means currents through two kinds of wires were almost same during normal operation. Fig. 4 shows the distribution of current during normal operation. Although the resistance generated by the HTS wire was much higher than shunt resistor, shunt resistors do not influence the current distribution [4]. Fig. 5 shows a current distribution and line current after the fault. The normal operation line current was 75.12 A and the fault line current at the first peak and last peak were 1706 A and 771 A, respectively. The fault current in BSCCO HTS wire and YBCO HTS wire at the first peak were 1542 A and 184 A, respectively. And the fault current at the last peak were respectively 646 A and 125 A. There was significant difference between the current of two wires. After a quench, about 85 % of current flew through BSCCO wire.

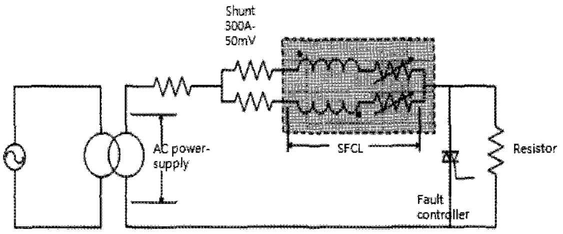

Fig. 3. Schematic overview of short-circuit test.

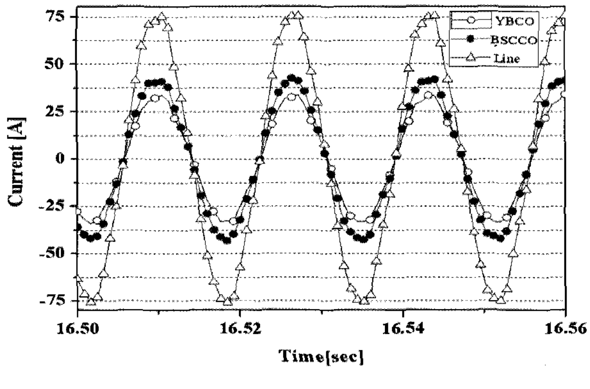

Fig. 4. Current distribution between top and bottom coil and line current during normal operation with applied voltage of 29 V.

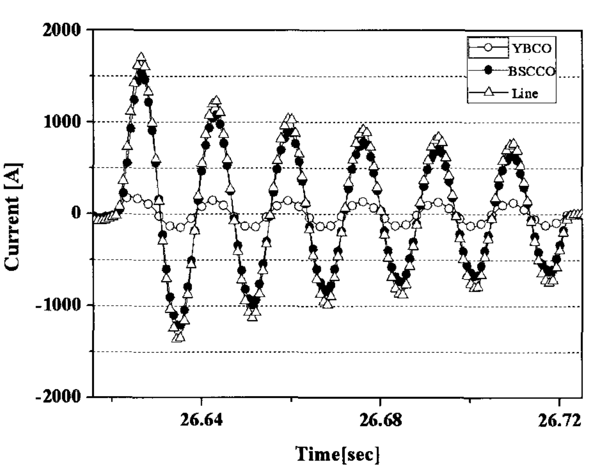

Fig. 5. Current distribution between top and bottom coil and line current at fault with applied voltage of 29 V.

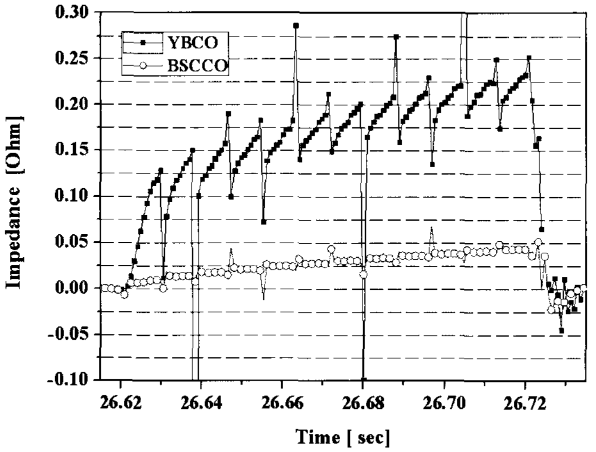

Fig. 6. Impedance curves of YBCO HTS wire and BSCCO HTS wire at fault with applied voltage of 29 V.

Unequal current distribution made different magnetic flux, and then magnetic flux by each top and bottom coil wound with opposite direction could not cancel out perfectly. Thus inductive component appeared in the HTS bifilar coil.

Fig. 6 shows the impedance curves of YBCO HTS wire and BSCCO HTS wire at fault. Impedance during normal operation was nearly zero. But when the fault occurred, impedance was suddenly increasing in YBCO HTS wire. The slope between two wires was different due to the different material of matrix. Resistance of YBCO HTS was much higher than BSCCO HTS wire. The current was distributed to each path following the difference of the total impedance.

Fig. 7 shows current and voltage waveform during normal operation with applied voltage of 29 V. Theoretically, the double-pancake bifilar coil has no inductance and current and voltage curves should be in phase, but the manufactured double-pancake type HTS coil was not perfect non-inductive coil as shown in Fig. 7 due to the difference of the thickness between used two HTS wires. The inductance of manufactured HTS bifilar coil was estimated to 1.49 μH by (1). Because the resistance of the HTS bifilar coil was nearly zero, waveform seemed like inductive type circuit.

$$V = I_m\sqrt{R^2+(wL)^2}\,\sin(wt+\theta) \tag{1}$$

Fig.8 shows the current and voltage waveform at fault. It seemed like that the current and voltage waveform was in the same phase, because the resistive component of coil generated at fault was too much higher than inductive component. Calculated phase difference was 1.58 degree which was exchanged into 73 μs by (2).

$$\theta = \tan^{-1}\frac{wL}{R} \tag{2}$$

Although inductance of the HTS coil was generated at fault, the phase difference was not distinguished due to the large resistance of the HTS coil.

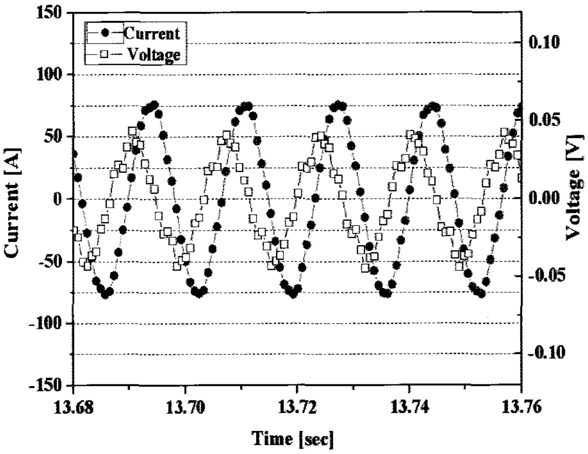

Fig. 7. Current and voltage during normal operation with applied voltage of 29 V.

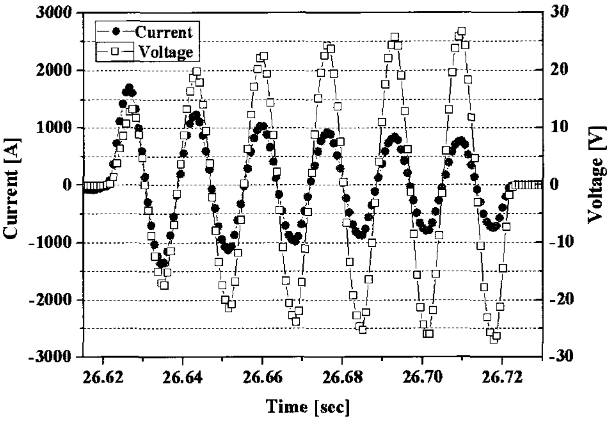

Fig. 8. Current and voltage at fault with applied voltage of 29 V.

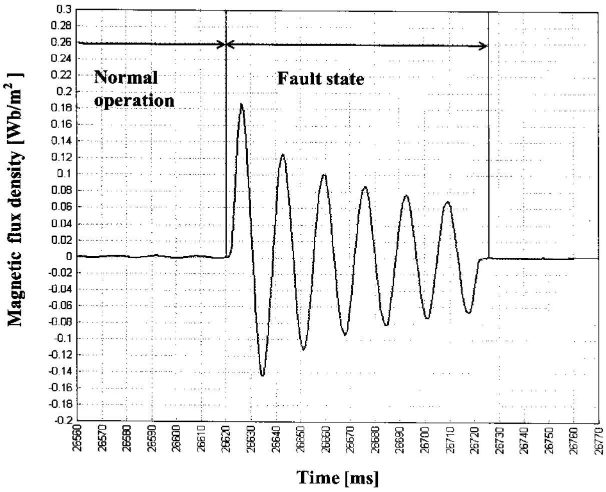

Fig. 9. Calculated magnetic flux density at the center of the coil.

Fig. 9 shows the result of simulation. It expresses a magnetic flux density at the center of the HTS bifilar coil. To simulate the result, the 'MagNet', which is made by 'Infolytica' was used. The simulation was performed with the parameters which are same to the real values. The result shows that the magnetic flux density was nearly zero during normal operation, but the magnetic flux densities at first peak and last peak were respectively 0.186 Wb/m^2 and 0.0731 Wb/m^2 at fault. Calculated inductive components were 0.84 μH during normal operation and 2.5 μH at fault. Generated magnetic flux can be applied to drive fast switch, which was inducing a inductive- repulsive force.

In this research, the HTS coils wound with opposite direction have symmetrical structure, the total impedance and current distribution in each coil were totally different at fault. Therefore, magnetic field was not completely canceled out and the proposed coil wound with two kinds of HTS wires made inductive component as well as resistance at fault.

3.2. General discussions

The general non-inductive type SFCLs make only resistance, but the double-pancake type bifilar coil wound with two kinds of HTS wires makes inductive component as well as resistive component at fault. Proposed HTS bifilar coil can be applied to a novel SFCL. Superconductor-Trigger Fault Current Limiters (STFCLs) have an additional copper sub-coil to generate the magnetic field to open fast switch. The proposed HTS bifilar coil makes the magnetic field which can drive the fast switch used in STFCL developed by LSIS and KEPRI [4]. In this research, feasibility to be a novel type SFCL was confirmed. The longer wire will be used to wind a coil, and then the inductive component should be remarkable.

4. CONCLUSION

This paper describes the characteristic of the double-pancake type HTS bifilar coil wound with two different HTS wires. Although the HTS coil did not manufactured non-inductive type perfectly, the coil using two kinds of wire was designed and tested successfully. Proposed HTS bifilar coil can make not only resistance but also inductive component at fault. We could find a development feasibility of a new SFCL with the proposed HTS bifilar coil instead of SFCL using a sub-coil which generates the magnetic field to open a circuit break switch. In the future, new combinations using other HTS coils will be investigated, and large scale coils will be made through series or parallel connection of coils.

ACKNOWLEDGMENT

This work was supported by MOCIE through EIRC program with Yonsei Electric Power Research Center (YEPRC) at Yonsei University, Seoul, Korea.

REFERENCES

[1] D. K Park, M. C. Ahn, S. E. Yang, Y.S. Yoon, B. -Y. Seok, C. Lee, .-M Chang, T. K. Ko, "development of 220V/ 300 A Class Non-inductive Wingding Type Fault Current Limiter Using 2G HTS Wire," *IEEE Trans. on Appl. supercon.*, vol.17, no.2, pp. 1863-1866, 2007.

[2] Wolfgang Schmidt, Hans-Peter Kraemer, Heinz-Werner Neumueller, Urs Schoop, Darren Verebelyi, and Alexis P. Malozemoff, "Investigation of YBCO Coated Conductor for Fault Current Limiter Application," *IEEE Trans. on Appl. Supercon*, vol.17, no.2, pp.3471-3474, 2007.

[3] D. K. Park, M. C. Ahn, S. Park, H. Kang, D. K. Bae, S. E. Yang, B, -Y. Seok, and T. K. Ko ,"An analysis and short circuit test of various types of Bi-2223 bifilar winding fault limiting module," *IEEE Trans. on Appl. Supercon*, vol. 16, no. 2, pp.703-706, 2006.

[4] M. C. Ahn, D. K. Park, S. E. Yang, B. -Y. Seok, and T. K. Ko, "Impedance Characteristics of Non-inductive Coil Wound with Two Kinds of HTS Wire in Parallel," *pesented at MT*, 2007.