Development of 220 V/300 A Class Non-Inductive Winding Type Fault Current Limiter Using 2G HTS Wire

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***Abstract*—As a part of the 21st Century Frontier R&D Program in Korea being performed from 2004, a non-inductive winding type superconducting fault current limiter (SFCL) is being developed. The target of the second year in phase II of the program is to develop a 220 V/300 A class non-inductive winding type SFCL as a prototype for a 13.2 kV/630 A class, the final goal of phase II. This SFCL has three solenoid type non-inductively wound coils in series using a 2G high temperature superconducting (HTS) wire and it was tested in sub-cooled nitrogen of 65 K, 1 atm. A coil which is composed of four parallel windings in a bobbin and winding directions are opposite to have non-inductive characteristics. Three coils were connected in series and the total length of 108 m of 2G HTS wire was used. Short-circuit tests were performed at applied voltage of 220 V and the SFCL limited the fault current to a few kA extents at the tests. Recovery time of the SFCL was measured after short-circuit tests.**

***Index Terms*—Non-inductive winding, recovery time short-circuit test, superconducting fault current limiter, 2G HTS wire.**

I. Introduction

IN ELECTRIC power transmission and distribution grid, it has been known that the SFCL is the most proper solution to reduce fault current levels. The fault current has been increasing with the growth and increasing interconnection of the power grid or adding new generation [1]. The problem of the fault current over-duty on the existing equipment can be solved by injecting the SFCL to the power grid [2], [3]. Various types of SFCL have been developed in many research groups and a non-inductive winding type SFCL using 2G HTS wire was developed in this research. DAPAS (Development of Advanced Power system by Applied Superconductivity) program which is one of the 21st Century Frontier R&D Program in Korea is going on the phase II with the goal of a single phase 13.2 kV/630 A SFCL development.

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This paper describes design, manufacture and short-circuit test of proto-type 220 V/300 A class, the target of second year in phase II, non-inductive winding type FCL using 2G HTS wire. 2G HTS wire has good characteristic for SFCL application such as high index number of YBCO and relatively easy fabrication with various material and thickness of stabilizer [4]. The SFCL has solenoid type non-inductively wound coils and each coil has four windings which cancel the whole magnetic field of the coil. In this type, exposed winding surface is larger than other resistive type SFCL when the same current flows through them so better recovery characteristic is expected. Recovery time was measured by inserting high resistance instead of load resistance.

II. Design and Manufacture of the FCL

A. Concept of the SFCL

SFCLs should have zero impedance during normal state to reduce the electric loss in power grid. There are many kinds of non-inductive winding methods with different characteristics [5]. The novel solenoid type non-inductively wound coil consists of even number of windings; the halves of total number of wires of inner windings and the other halves of outer windings, and they are connected in parallel [6]. The inner windings and the outer windings are wound downwards on the same bobbin in the opposite winding direction to each others and the distance between two windings is very close to have nearly perfect non-inductive characteristics. To enlarge the operating current of the SFCL, instead of a stack of wires, the number of parallel windings should be increased. Most of windings are exposed to the coolant and bobbin so that the recovery time after the fault would be reduced.

B. Design and Manufacture of the SFCL Using 2G HTS Wire

The 2G HTS wire used in this research is "344" coated conductor (CC) made by American Superconductor Corporation (AMSC). It consists of copper alloy (Cu155) stabilizers, YBCO, buffer layer and Ni-5 %W substrate. Table I shows properties of 2G HTS wire.

Temperature reached of the SFCL during fault state is designed in first. Generally, SFCL is designed maximum temperature reached of about 300 K because thermal shock can degrade the YBCO properties. CC has limited temperature reached up to about 450 K which is melting point of solder in it. In order

TABLE I
SPECIFICATION OF A 2G HTS WIRE, "344" CC

HTS Material	$YBa_2Cu_3O_y$ (T_C of 95 K)	
Stabilizer	Copper alloy (Cu155)	
	Resistivity	6 nΩ·m @ 77 K 20 nΩ·m @ 300 K
Dimension	Width	4.3 mm
	Thickness	0.15 mm
Critical current	69 A (@ 77 K, self-field) 170 A (@ 65 K, self-field)	

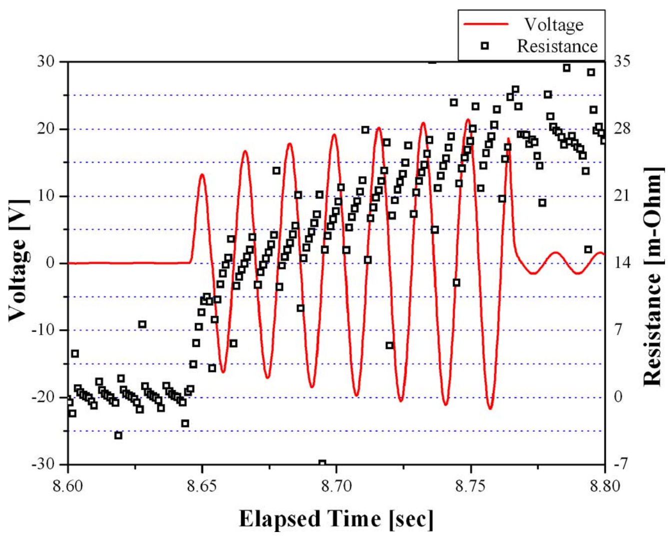


Fig. 1. Resistance and applied voltage waveform of small-scale non-inductively wound coil.

to make more thermally stable operation, the SFCL is designed 190 K [7]. Small-scale non-inductively wound coil was manufactured. Then, the short-circuit tests at various applied voltages were performed and temperature reached can be calculated by resistance of stabilizer of CC. Since the small-scale coil has similar heating and cooling condition with the SFCL, temperature reached at the last peak current during fault according to applied voltage per unit length, electric field, of CC is almost same with the SFCL. In case of temperature reached of 190 K, which is 28.85 $\mathrm{m}\Omega/\mathrm{m}$, applied voltage waveform of small-scale coil was shown in Fig. 1 and the applied voltage per unit length at the last peak current during fault was 8.25 V/m. Then, the SFCL needs about 26.7 m length CC in series to be subjected to 220 V. At last the number of parallel windings and bobbins are decided considering operating current of 300 A at 65 K and the length limit per reel of CC. Four parallel windings and three bobbins in series are needed. Table II shows detail specification. The SFCL and assembly with cryogenic cooling system are illustrated in Figs. 2(a) and (b), respectively.

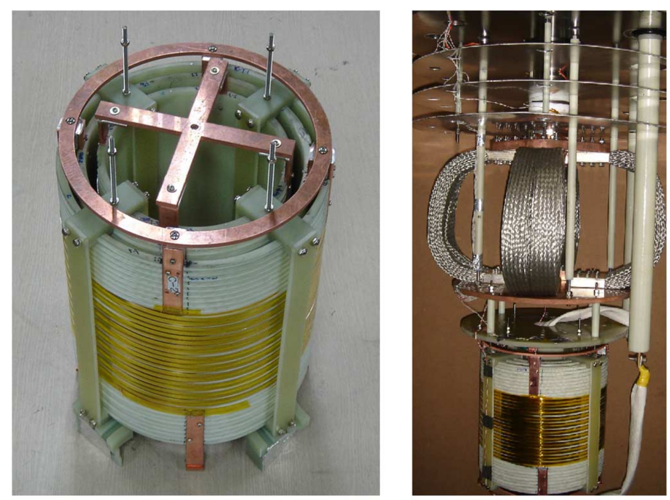
III. EXPERIMENTAL SETUP

The schematic overview of the SFCL short-circuit test is illustrated in Fig. 3. Short-circuit tests are performed in a real single phase 220 V distributing panel at laboratory of Hyundai

TABLE II
SPECIFICATION OF THE NON-INDUCTIVE WINDING TYPE SFCL

A Non-inductively Wound Coil				
Winding number	#1	#2	#3	#4
Layers on a bobbin	Inner	Inner	Outer	Outer
Winding direction	Clock	Clock	Counter	Counter
Inductance [μH]	30	30	31	31
Resistance* [mΩ]	456	456	465	465
Length of wire [m]	9	9	9	9
The SFCL				
Inductance	1.3 μH			
Resistance	328 mΩ			
Length of wire	108 m			
Critical current	225 A @ 77 K, self-field 533 A @ 65 K, self-field			

*Resistance at room temperature



(a) (b)

Fig. 2. (a) Non-inductive winding type SFCL using 2G HTS wire, (b) assembly with cryogenic cooling system.

Heavy Industries in Yong-in, Korea. It consists of electrical power, switch for circuit breaker (SW1), shunt for measurement of line current, resistive load, fault controller using high voltage thyristor, high resistance for measurement of recovery time and switch for measurement of recovery (SW2) which is closed during short-circuit tests. Line current hardly flows through high resistance for recovery. The fault duration time is set to be 0.1 s. After the fault, the thyristor is opened to reconnect the load with the source. Then, about 300 A line current flows through the SFCL again and it is not available to measure recovery time. In order to measure the recovery time, the SW2 is now opened and only high resistance is connected to power source so that very low current flows through the SFCL.

All tests in this research are performed in sub-cooled nitrogen cooling system at 65 K, 1 atm by injection of gas helium. Sub-cooled nitrogen cooling has benefits for SFCL application such as enhancement of the thermal stability at fault state and increase of critical current of the SFCL. Fig. 4 shows current-voltage curve of the SFCL. The critical current in sub-cooled

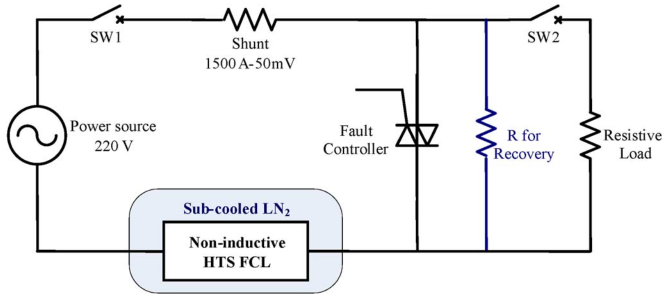


Fig. 3. Schematic overview of the SFCL short-circuit test.

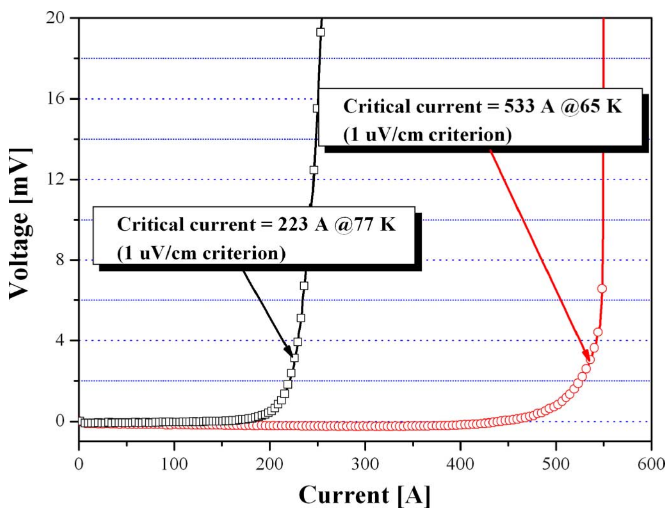


Fig. 4. Current-voltage curve of non-inductive winding type SFCL in saturated LN_2 of 77 K and sub-cooled LN_2 of 65 K.

nitrogen of 65 K is 2.4 times larger than the one in saturated nitrogen of 77 K. Total length of wire can be reduced in sub-cooled nitrogen cooling.

IV. Results and Discussion

Short-circuit tests were performed in sub-cooled nitrogen cooling system at the rated power of 220 V/300 A which was applied to the SFCL. Fig. 5 shows the line current and SFCL voltage waveforms under normal and fault condition at the applied voltage of 220 V. The line current is 300 A and the fault current at first peak and last peak is 3.4 kA and 1.5 kA, respectively. There is no voltage drop under normal condition but the end of the fault whole 220 V is applied to the SFCL. In the previous short-circuit test result of the small-scale coil, the generated resistance of the 220 V/300 A class SFCL could be expected to be 194.75 $m\Omega$ at the end of the fault, last peak of fault current was expected to be 1.59 kA. Fig. 6 shows the generated resistance and line current. Normal impedance was almost zero. Resistance of 0.1 Ω was generated right after the fault and about 0.2 Ω was generated at the end of the fault. Generated resistance and temperature reached of the SFCL is almost same with designed value. To design a 13.2 kV/630 A class same type SFCL with the same 2G HTS wire, total length of 9.6 km is needed and there are 6 parallel structures. Since it has complicate structure and so long length of wire is needed,

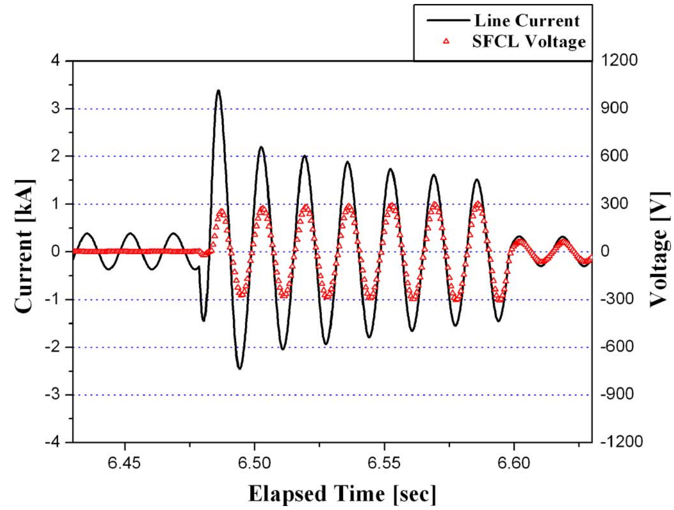


Fig. 5. Line current and SFCL voltage waveforms of short-circuit test at applied voltage of 220 V.

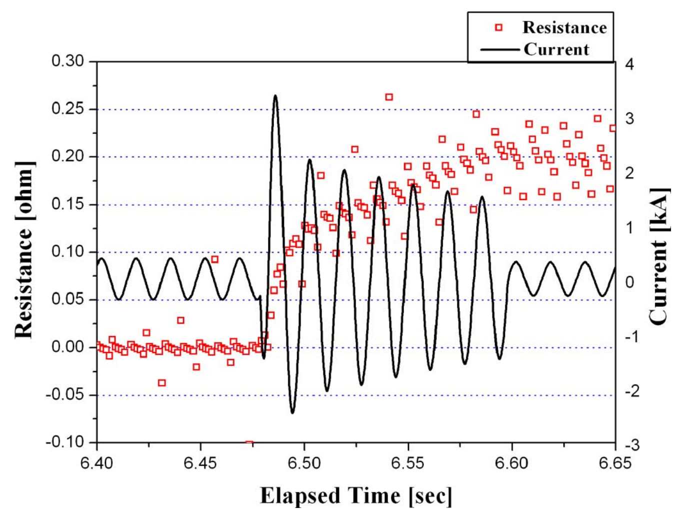


Fig. 6. Resistance and line current waveforms of short-circuit test at applied voltage of 220 V.

other 2G HTS wire which has stainless steel stabilizer, called "344S" will be used.

The SFCL in this research consists of three non-inductively wound coils connected in series and each coil has four parallel windings. In series connection of three coils, voltage distribution among three coils is very significant. Unless the voltage is equally distribute to each coil, whole voltage of 220 V is applied to one or two coils that is over-duty of the SFCL in the worst case. Fig. 7 shows voltage distribution of the SFCL. V_1 and V_2 are equally distributed and V_3 is also distributed within 20% of the peak voltage of V_1 and V_2 after fault occurrence so that there are no problems of voltage distribution.

After short-circuit tests, recovery time measurement was performed by open the SW2 in Fig. 3. Three 220 V-60 W bulbs connected in parallel were used as high resistance for recovery measurement and the line current was 0.8 A. The measured recovery time is 1.3 s as shown in Fig. 8. It is relatively short recovery time and it means good cooling characteristic of the SFCL compared with other type SFCL with various materials.

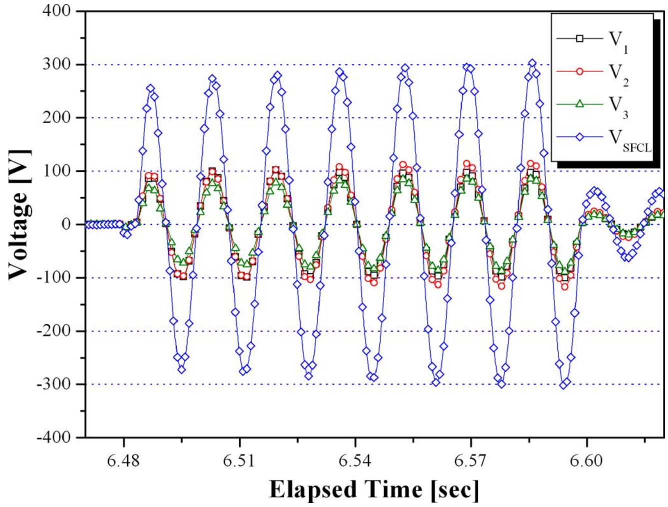


Fig. 7. Distributed voltage waveforms of each coils and whole voltage of the SFCL at applied voltage of 220 V.

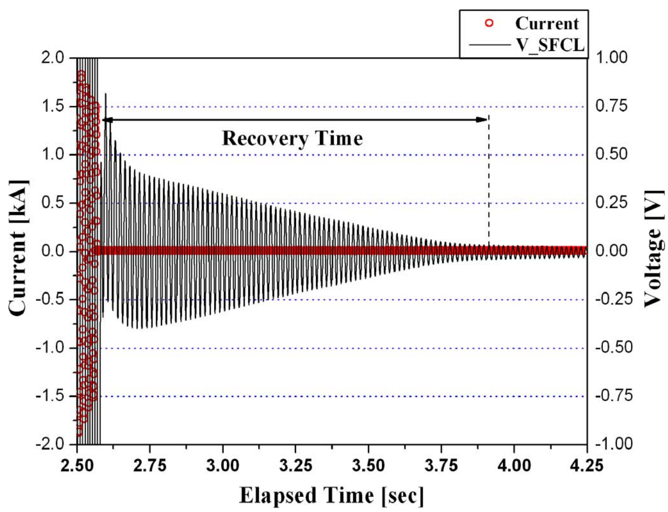


Fig. 8. Recovery time measurement after the fault at applied voltage of 220 V.

To reduce the recovery time more, a design with the temperature reached of lower than 190 K is needed or the bypass reactor for heat distribution must be connected in parallel to the SFCL.

V. Conclusion

The 220 V/300 A class non-inductive winding SFCL was designed and tested successfully. The main results of this study as follows:

(1) It is available to design the SFCL by relationships between the applied electric field and the temperature reached from the result of short-circuit test of the small-scale non- inductively wound coil.

(2) The SFCL has a good current limiting characteristic at a distribute power source of 220 V with operating current of 300 A.

(3) Cooling characteristic of non-inductive winding type SFCL is proved by measuring recovery time.

To design the SFCL using 2G HTS wire, it is useful method to test a small-scale coil in case of using the same wire. The SFCL developed in this research can be applied to the power of 220 V and also will be extended to a 13.2 kV/630 A SFCL.

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