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Short-circuit Analysis by the Application of Control Signal of Power Converter to the Inductive Fault Current Limiter

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Abstract-- **Three-phase inductive superconducting fault current limiter (SFCL) with DC reactor rated on 6.6 kV_{rms}/200 A_{rms} has been developed in Korea. This system consists of one DC reactor, AC/DC power converter, and a three-phase transformer, which is called magnetic core reactor (MCR). This paper deals with the short-circuit analysis of the SFCL. The DC reactor was the HTS solenoid coil whose inductance was 84mH. The power converter was performed as the dual-mode operation for dividing voltage between the rectifying devices. The short-term normal operation (1 sec) and short-circuit tests (2~3 cycles) of this SFCL were performed successfully. In regular short-circuit test, the fault current was limited as 30 % of rated short-circuit current at 2 cycles after the fault. The experimental results have a very similar tendency to the simulation results. Using the technique for the fault detection and SCR firing control, the fault current limiting rate of the SFCL was improved. From this research, the parameters for design and manufacture of large-scale SFCL were obtained.**

1. INTRODUCTION

Superconducting fault current limiter (SFCL) is one of promising power apparatuses. There are several kinds of SFCLs which have been developed by many research groups. Among them, the experimental result and analysis of DC reactor type SFCL is mainly described in this paper. DC reactor type SFCL is one of inductive SFCLs and have been developed by Los Alamos National Lab. and Toshiba Co. etc. In Republic of Korea, the development of this type SFCL have been going from 2001 as one of 21st Century Frontier R&D Program. In June 2002, 1.2 kV/80 A class SFCL using conduction-cooled DC coil was short-circuit tested successfully [1]. In June 2003, 6.6 kV/200 A class SFCL using sub-cooled nitrogen was manufactured and tested.

In this paper, 6.6kV/200A DC reactor type SFCL has been manufactured and short-circuit tested. And the short-circuit characteristics are analyzed.

2. DEVELOPMENT OF 3-PHASE 6.6 KV/200 A SFCL

Generally, the constitution of the three-phase DC reactor type SFCL has two methods. One is that three DC reactors and three AC/DC power converters are used for three-phase. The other is that a three-phase series transformer called magnetic core reactor (MCR), a three-phase power converter and just one DC reactor are used. The major merit of the latter is cost because the cost of high-T_C superconducting (HTS) DC reactor is dominant part among total system. This research used the latter constitution. Fig. 1 shows the schematic drawing of three-phase DC reactor type SFCL.

To connect three-phase power line to a three-phase power converter and an HTS DC reactor, a three-phase series transformer called magnetic core reactor is used. The secondary winding of MCR has center tap. Hence, the 6.6 kV voltage of primary winding is divided to two 3.3 kV on the secondary winding by center tap. This MCR is mold type for supporting electro-magnetic force when a fault occurs.

In order to convert AC power to DC, AC to DC power converter is used. The rectifying devices of converter are light triggered thyristors. Those thyristors are controlled gate signal by light signal generated light laser. The rated repetitive peak reverse voltage of used thyristor is 7 kV. On the other hand, voltages of thyristors are about 9 kV in fault condition of three-phase 6.6 kV power system. In general case, two thyristors are connected in series for taking a share voltage in common. However, the direct series connection of thyristors has some problems, which is uncertainty of dividing voltage. To solve this problem, this power converter is made of two thyristor modules, so

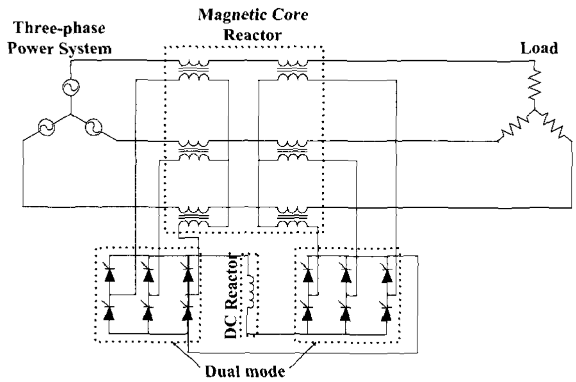

Fig. 1. Schematic drawing of 3-phase DC reactor type SFCL.

called dual-mode operation. In a dual-mode operation, each thyristor module is connected to one of secondary winding of MCR. Hence, the actual rated voltage of thyristor module is 3.3 kV. A thyristor module has 6 thyristors and a dump diode as shown Fig. 2. This power converter has a special function for application to the inductive fault current limiter. The function is about fault detection and control of the gate trigger signal of thyristor. The converter always measures current of DC reactor. When DC reactor current is above setting current level which is larger than normal current of DC reactor, fault detection circuit detects fault and controls gate signals of thyristors. In 6.6 kV/200 A system, normal current is about 283 A which is peak value of RMS 200 A.

Actually DC reactor plays a role of limiting fault current, so the manufacture of DC reactor is very important technology in the development of this type SFCL. According to some simulations and small-scale experiments, the proper inductance of the DC reactor is about 75~100 mH and required critical current is above 350 A at operating temperature [2]. Manufactured DC reactor has 5 layers that are separated by bobbins each other. Those five layers are coils with private bobbins. The bobbins are concentric tubes whose inner diameters are 600~760 mm. In each bobbin, there is the groove for winding several wires in same position. The bobbin is made of G10-FRP. In upper and lower side of the bobbin, there are several copper bars for fixing wire and one current terminal respectively. Using the private winding machine, five coils are wound. In each coil, 2 layers copper tapes whose thickness are 0.4 mm and 4 layers HTS tapes are wound. There is no insulation between stacked tapes. After winding a tape, another tape is overlapped. Used HTS tape was the high-strength reinforced Bi-2223 wire made by AMSC® and whose critical current is 115 A at 77 K, self-field. Five coils are connected in series. Because just DC current flows in the DC reactor for this type SFCL continuously, we didn't connect by a transposition. Nevertheless, because the current above critical current flows in the DC reactor, copper tapes are wound innermost. The purpose of copper tapes is sharing of current when a quench occurs. Because diameters of bobbins are different and turn pitches and wire lengths are same, the numbers of turns are different each other; i.e. 93, 88, 83, 78 and 73 turns. Winding length is 0.9 km and the number of stacks is four. Total length of used HTS tape is 3.6 km. The inductance of the completed DC reactor is 84 mH.

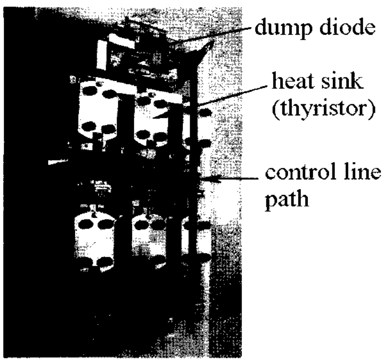

Fig. 2. Thyristor module of power converter

TABLE I.
SPECIFICATIONS OF DC REACTOR

Inner diameter	600 mm
Outer diameter	784 mm
Height	800 mm
Layers	5
Stack	6 ea (2 coppers + 4 HTS tapes)
Total turns	415
Winding length	0.9 km
Inductance	84 mH
Critical current	490 A @ 65 K, self field

Fig. 3 shows the fabricated DC reactor. The specifications are shown as table I.

The DC reactor was cooled down by sub-cooled nitrogen. Operating conditions are 65 K and 1 atm. The cooling system using sub-cooled nitrogen was to increase the critical current of the DC reactor and electrical insulation level. To make sub-cooled nitrogen, a single-stage cryocooler whose capacity is 120 W at 80 K was installed to cooling system. The cooling copper plate and copper bars are connected to the coldhead of cryocooler and cooled down. Fig. 4 shows the cryogenic system with DC reactor. The I-V characteristic of the DC reactor was

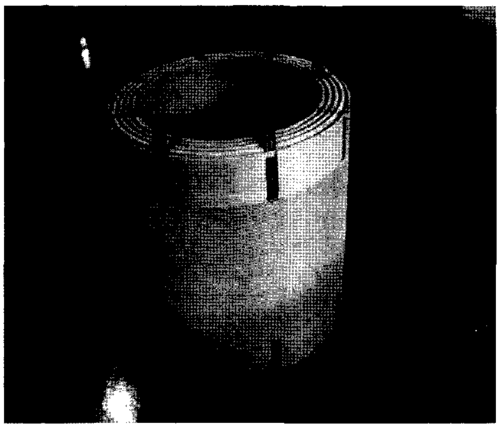

Fig. 3. Fabricated HTS DC reactor.

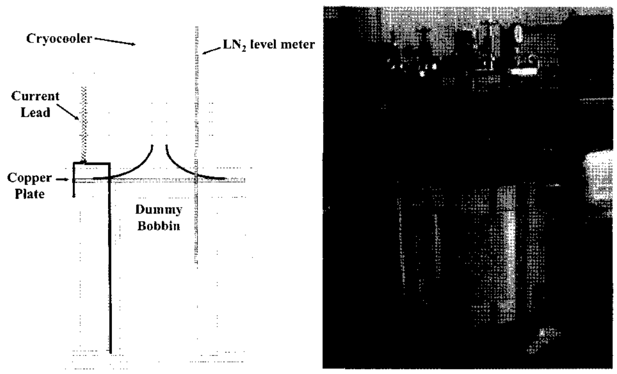

Fig. 4. Cryogenic system with DC reactor.

measured at 65 K using sub-cooled nitrogen. The measured critical current is about 490 A. In normal condition, the current through the DC reactor is about 283 A. Hence, the fabricated DC reactor has enough high critical current for application of 6.6 kV/200 A SFCL.

3. EXPERIMENT AND DISCUSSION

The completely manufactured elements of SFCL which are a MCR, a dual-mode power converter system and a superconducting DC reactor are assembled as shown Fig. 1. The short-term run operation and short-circuit test were performed at short-circuit test facility. The rated power, 6.6 kVrms/200 Arms, was applied to the SFCL system during 1 second, and then three-phase short-circuit test was executed. A maximum planned fault current is 4 kA_{rms} when the SFCL was not installed to power system. The fault duration is set to 3 cycles (50 ms).

Fig. 5 presents the experimental result of line currents when the fault duration is 2 cycles. This case did not use the fault detection function. In this graph, a fault is occurred at the timing of elapsed time 1.19 second. During short-term (1 sec) run operation, there are no problems in whole SFCL system. When a fault occurs, the line currents increase not rapidly but gradually. This result is general waveform of result of DC reactor type SFCL. There are no surge current using SFCL. For three-phase, maximum fault currents are different each other because fault angles of each phase are not same. In waveform of Fig. 5, maximum fault current during 2 cycles is about 1.70 kA_{peak} which are the line current of s-phase. Comparing fault current without SFCL, 5.66 kA_{peak}, the SFCL limits a fault current to the 30 % level of value without SFCL. A fault current is limited by the inductance of DC reactor coil. The larger the inductance of the coil is, the lower the fault current is but the higher the cost is [3]. Therefore, it is necessary to decide proper inductance considering the short-circuit current capacity of the circuit breaker. The simulation study was performed using spice program. The simulation result shows in Fig. 6. The simulation condition is same as that of Fig. 5. Comparing two results,

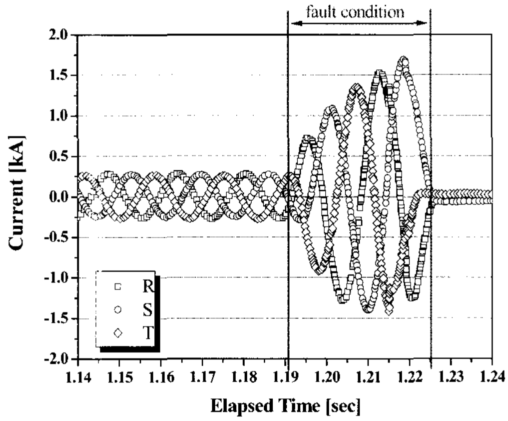

Fig. 5. Experimental result of the short-circuit test without fault detection.

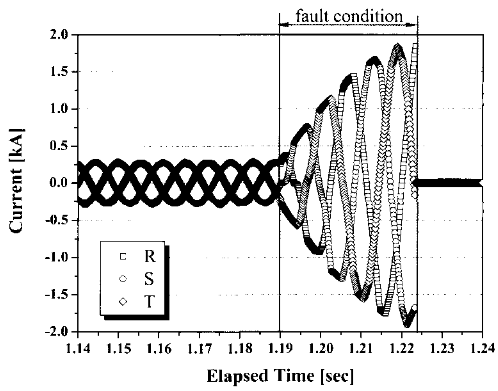

Fig. 6. Simulation result of the short-circuit test without fault detection.

the experimental result is very similar to the simulation result.

As mentioned in section II, the power converter has a function of fault detection. Fig. 7 shows the waveform of line currents with fault detection function. The fault duration is 3 cycles. The waveform of line current is different from Fig. 5. Line currents did not increase gradually but generate a peak and then reduce them. The reason for difference from general case is that fault detection and gate control of thyristors were acted. The maximum line current among three-phase line is 1.12 kA_{peak} which is about 20 % of value without SFCL. While a fault current increases until circuit breaker operates when a fault occurs in general DC reactor type SFCL, a fault current decreases in the SFCL using this technology. Hence, we can reduce the inductance of the DC reactor.

In order to analyze the waveform in case of the SFCL using fault detection, one waveform of line currents presents in Fig. 8. The region of Fig. 8 (a) is normal condition. At the elapsed time 1.175 sec, a fault occurred. A fault current was limited by inductance of DC reactor in the region of (b), and a fault is detected in this region. Then twelve gate control signals were eliminated by controller. In that case, the DC reactor was separated from a fault current, and the secondary of MCR is equivalently

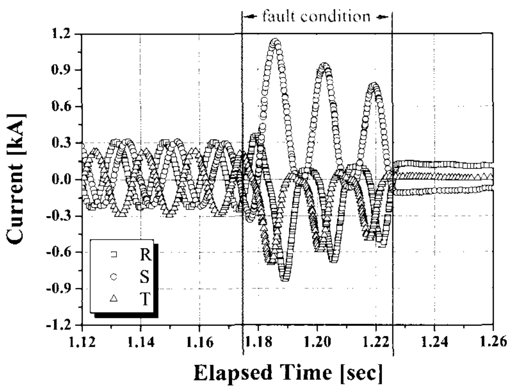

Fig. 7. Experimental result with fault detection and control of gate signal.

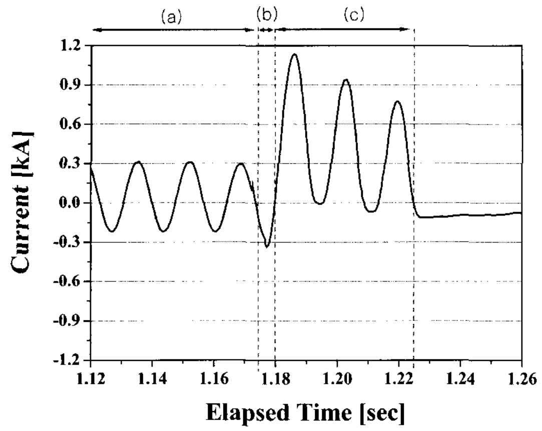

Fig. 8. Line current of short-circuit test using fault detection.

open. In the region of (c), the switching in-rush current of MCR was generated. The switching in-rush current is that the switching in a transformer on no-load that the ammeter registers an initial current rush greatly in excess of the normal no-load current and sometimes even greater than the normal full-load current of the transformer [4]. Hence, line current will reduce effectively according to design MCR properly. As a result, the three-phase DC reactor type SFCL using fault detection and control of gate trigger signals was short-circuit tested successfully and analyzed.

4. CONCLUSION

In this research, three-phase 6.6 kVrms/200 Arms DC reactor type SFCL has been manufactured. This system is made of a three-phase transformer, called MCR, a dual-mode power converter and a superconducting DC reactor. The short-run operation test during 1 second and three-phase short-circuit test were performed. For short-circuit test, the SFCL system limited a fault current effectively. Especially a fault detection and control of the gate signals of the thyristors were used for this SFCL. And analysis of this system was performed. Using the function of the fault detection, the fault current limited to 20 % of current without SFCL during 3 cycles. This result can be applied to the design and manufacture of the DC reactor type SFCL with the function of fault detection and the gate signal control function.

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