Vol. 7, No. 2, pp. 7-11, December 2008

INTERNATIONAL
JOURNAL OF SAFETY
www.kosos.or.kr

Magnetic Core Reactor for DC Reactor type Three-Phase Fault Current Limiter

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(Received July 2, 2008; Accepted December 10, 2008)

Abstract : In this paper, a Magnetic Core Reactor (MCR) which forms a part of the DC reactor type three-phase high-Tc superconducting fault current limiter (SFCL) has been developed. This SFCL is more economical than other types with three coils since it uses only one high-Tc superconducting (HTS) coil. When DC reactor type three-phase high-Tc SFCL is developed using just one coil, fewer power electronic devices and shorter HTS wire are needed. The SFCL proposed in this paper needs a power-linking device to connect the SFCL to the power system. The design concept for this device was sprang from the fact that the magnetic energy could be changed into the electrical energy and vice versa. Ferromagnetic material is used as a path of magnetic flux. When high-Tc superconducting DC reactor is separated from the power system by using SCRs, this device also limits fault current until the circuit breaker is opened. The device mentioned above was named Magnetic Core Reactor (MCR). MCR was designed to minimize the voltage drop and total losses. Majority of the design parameters was tuned through experiments with the design prototype. In the experiment, the current density of winding conductor was found to be 1.3 A/mm^2, voltage drop across MCR was 20 V and total losses on normal state was 1.3 kW.

Key words: SFCL, magnetic core reactor, fault current, high-tc superconducting dc reactor

1. Introduction

With the development of industrial society and the formation of metropolises, the demand of electric power have been increasing drastically. Fault current in the power systems have been increased because of the increased capacity of power systems. The fault current should be blocked to ensure providing highly reliable electric power and protecting electrical devices from damages. The steeper the demand of electric power increased, the more fault currents took place without any protection necessary to the existing electrical devices, which requires special measures. One of the measures will be SFCL which limits fault current in the system effectively maintaining the present-existing protection devices.

High-Tc SFCL is divided into three types of resistive type, inductive type, and hybrid type. Inductive type can be redivided into another three types of self-screening type, saturated reactor type and DC reactor type SFCL [1]. In case of certain fault, inductance of HTS DC reactor in DC reactor type SFCL imputed into the power system and so limits fault current. It uses two kinds of methods. One uses three high-Tc superconducting coils which play a role of DC reactor on each phase and the other uses only one coil which play a role of DC reactor on three-phase [2]. When the three-phase high-Tc SFCL is developed using one DC reactor, it is economical because the required amount of superconducting Bi-2223 wire and power electronic devices which play as a rectifier can be reduced. In addition, it has another advantage of reducing the space required for the SFCL. In the experiment of this paper, three-phase MCR which performs a role to transmit the energy of the power system to HTS DC reactor in DC reactor type three-phase SFCL and limits fault current has been developed.

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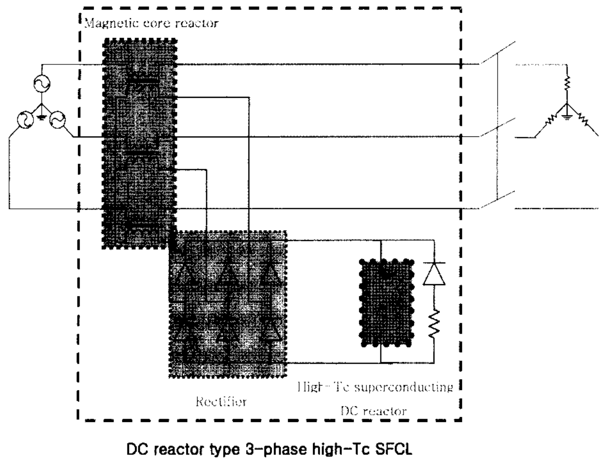

Fig. 1. Schematic of DC reactor type three-phase high-Tc superconducting fault current limiter

2. Design of Magnetic Core Reactor

2.1 Magnetic Core Reactor

Fig. 1 shows the position of MCR in DC reactor type three-phase high-Tc SFCL. This type of SFCL consists of three-phase MCR, a three-phase rectifier and a HTS DC reactor. High-Tc SFCL gives no influence on the system under the normal state but in case of certain fault, it has its inductance of HTS coil imputed into the system and so limits fault current. A device which can transmit the energy of the system to HTS DC reactor is necessary so this device has been designed based on the principle of interchangeability between electric energy and magnetic energy. The path of magnetic field has been made of ferromagnetic materials. When fault occurred in power systems, DC reactor type three-phase high-Tc SFCL with 1 DC reactor using SCRs can separate superconducting DC reactor from the power system. In this case, this device also plays a role of a reactor until circuit breaker opens. So, it was named Magnetic Core Reactor.

2.2 Aims of design

Fig. 2 shows the flow chart of MCR design, which was processed toward with the purpose of minimizing the loss and the volume of MCR reactor. Like other electrical devices, the Main losses of MCR are copper loss and core loss. Silicon steel sheets which have low loss of hysteresis were used in building the magnetic core to reduce core loss. The current density of conductor has been set low to reduce copper loss.

Because permeability of silicon steel is non-linear, the increase of current following the increase of voltage in

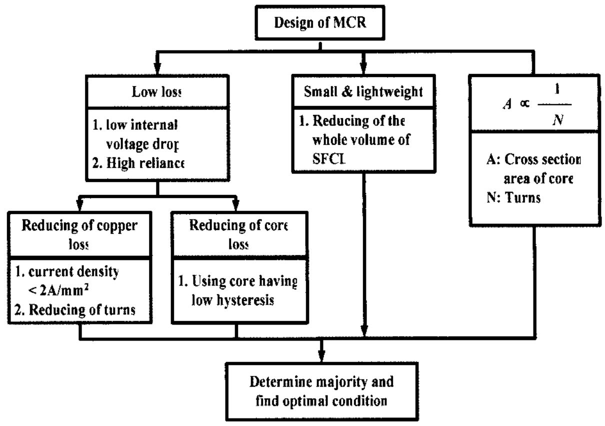

Fig. 2. Flow chart of magnetic core reactor design

MCR is non-linear.

The length of winding and the size of horizontal section of core are in inversely proportional to each another like the formula shown below [3].

$$A = \frac{E_{rms}}{4.44 N B_{\max} f} \tag{1}$$

Here, A means the size of horizontal section, E_{rms} means rms value of applied voltage, N means the number of turns, B_{max} means the maximum magnetic field density core and f means the frequency of source.

The number of turns is proportional to copper loss. Therefore, the % voltage drop across MCR and the maximum magnetic flux density of core have been determined first and then the size of horizontal section of magnetic core has been decided in the process of design. The goal of % voltage drop on the design was under 2 % and the current density of conductor of it was under 2 A/mm^2

Fig. 3. Experimental setup for the equivalent circuit test of SFCL with MCR

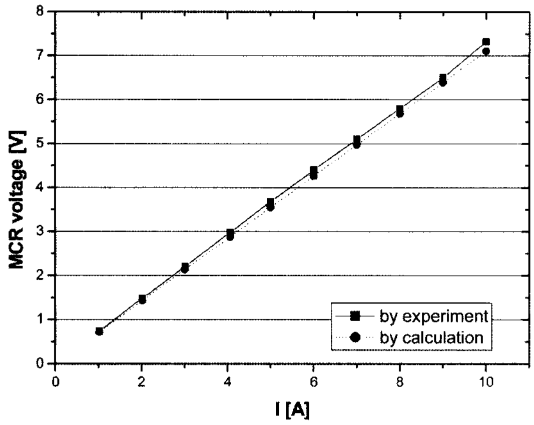

Fig. 4. Result of equivalent circuit experiment

2.3 Equivalent circuit test of SFCL with MCR

Fig. 3 shows the equivalent circuit experiment on SFCL with MCR. Because the secondary side of MCR is connected to parallel with rectifier and HTS DC reactor, the secondary side was shorted to make equivalent circuit. The specification for prototype MCR was 220 V of rated voltage and 4 A of rated current.

Fig. 4 shows the comparison result of this experiment with the calculated value based on the equivalent impedance through the equivalent experiment of MCR. The impedance corresponding to copper loss was based on the rated current and equivalent impedance corresponding to core loss was calculated with the % impedance voltage drop of designed MCR. Applied voltage was varied to change current in the condition of fixed load. There was not much difference between calculated value and experiment value. With this result, it can be recognized that the equivalent impedance could be calculated with the value from rated current and the % impedance voltage drop.

2.4 Design of Winding Conductor

Because the voltage drop across MCR is closely related to copper loss, the current density of winding conductor has to be set low. The density of conductor has been set at 1.3 A/mm^2 using two standard copper wire. The effective size of horizontal section of conductor was 60.98 mm^2. The insulation of the windings was done in dry method using insulation paper. When the level of voltage becomes higher afterwards, the mold type insulation using high performance insulating such as epoxy will be needed.

2.5 Design of Magnetic core

Fig. 5 shows the detailed size of designed magnetic core of three-phase MCR. The windings are coiled on

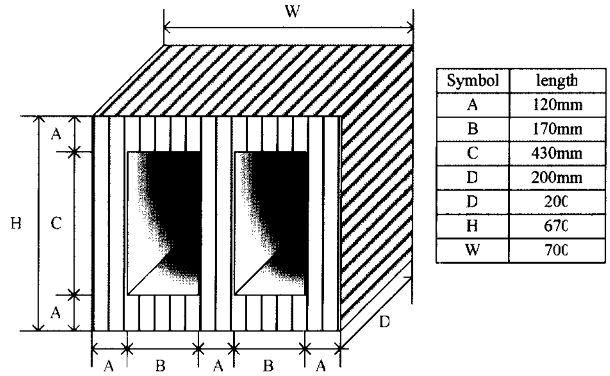

Fig. 5. Design of magnetic core

each leg of core. The size of horizontal section of magnetic core is inversely proportional to the number of windings and maximum magnetic flux density. It is ideal for reducing copper loss to minimize the number of windings. In this case, the volume and weight of magnetic core have to be increased considerably so the space and monetary difficulties are expected. For example, when there are 10 windings, the size of horizontal section becomes 1620 cm^2. In this design, the aim of % voltage dropping across MCR was 2 % and the number of windings was 75 turns. Therefore the size of horizontal section of magnetic core was 230.4 cm^2.

3. Specification for MCR

Table 1 and Fig. 6 show specification and overview of developed MCR, respectively. It was made for the 1.2kV-80 A class DC reactor type three-phase high-Tc SFCL. Measured total loss was 1.3 kW and core loss was 4 W. So, the majority of loss was copper loss.

Fault current limiting rate varies according to the turns ratio. Ratio of primary/secondary is proportional to DC reactor current but inversely proportional to the

Table 1. Specification for Developed MCR

Parameter	Specification
Rated voltage (V)	1200
Rated current (A)	80
Turns ratio (primary/secondary)	1/1.06, 1, 0.89, 0.81
Loss (kW)	1.3
Internal voltage drop (%/V)	1.7/20
Current density (A_{rms}/mm^2)	1.3
Reactance (mΩ)	145.3
Resistance (mΩ))	70.7
Maximum B (T)	1.5

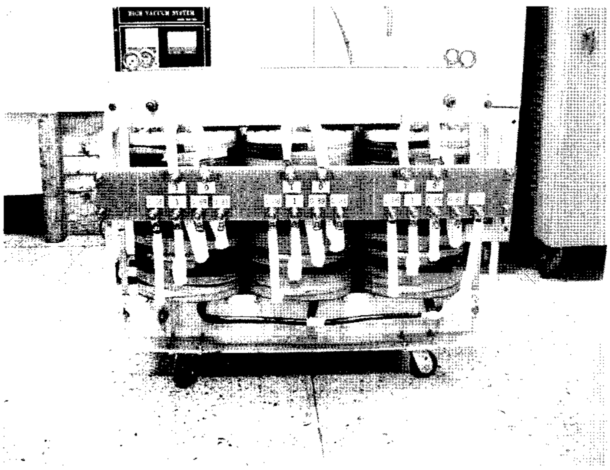

Fig. 6. Overview of developed MCR

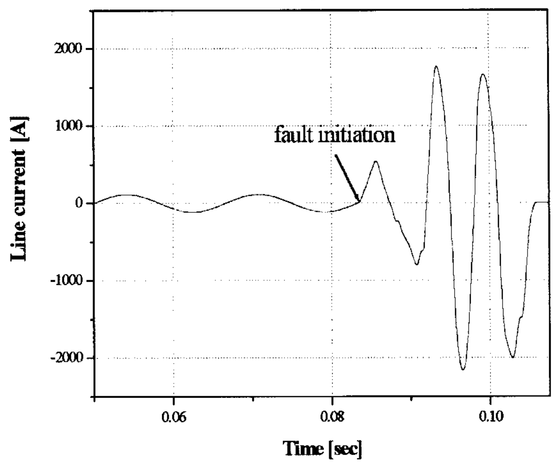

Fig. 8. Test result of SFCL with MCR

rate of increasing current [4]. 4 secondary taps were made and turns ratios are 1:1.06, 1:1, 1:0.89 and 1:0.81.

4. Experimental Result of SFCL with MCR and Discussion

Fig. 7 shows the whole system of DC reactor type three-phase high-Tc SFCL. HTS DC reactor was cooled down to 20 K by using a GM-cryocooler. It consists of 4 double-pancakes made of Bi-2223 wire and its inductance was 230 mH. Three-phase rectifier with 6 SCRs can separate HTS DC reactor from power system during fault condition.

Fig. 8 shows test results of developed DC reactor type high-Tc SFCL. Duration of fault was 3 cycles. Capacity of power system was 4.2 MVA and fault current without SFCL was 2 kA. Turns ratio of MCR was 1:1. The three-phase rectifier separated HTS DC reactor at 1 cycle after fault initiation. Fault current was reduced 80 % by HTS DC reactor at 1 cycle after fault initiation and 40 % at 3 cycles after fault initiation by MCR. After HTS DC reactor separated from power system, peak value of fault current became smaller as time passed by. This phenomenon looks like that of inductive SFCL using bulk HTS materials [5].

Though power electronic technology has been developed successfully, there can be something wrong in electronic devices. This result shows that developed SFCL can reduce fault current effectively in conditions of a trouble in control system of rectifier.

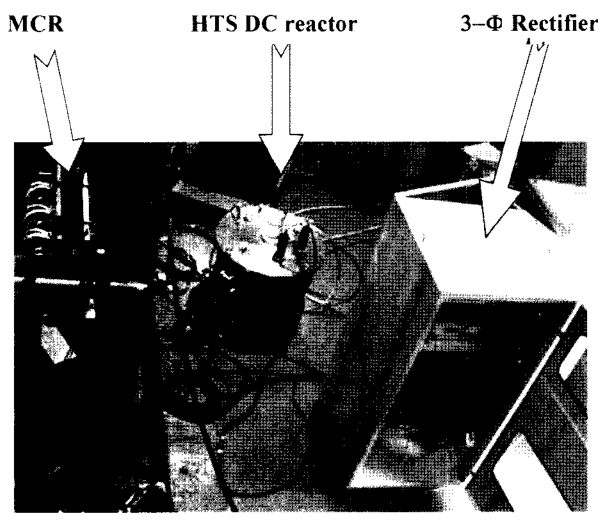

Fig. 7. Whole system of DC reactor type three-phase high-Tc SFCL in testing

5. Conclusion

In this paper, magnetic core reactor for the DC reactor type SFCL was developed and tested. The conclusions of the present work are as follows.

1) MCR can reduce the fault current after HTS DC reactor is separated from the power system in the fault duration. This shows that MCR can improve the reliance of SFCL.

2) Although the core loss of MCR is proportional to the volume of core, the core loss is negligible. The reason is that the length of the conductor is inversely proportional to the cross sectional area of the core and the total losses of MCR is mainly related to the copper loss, which in turn is inversely proportional to its volume.

3) For achieving efficiency and long-term reliance of MCR, it must be designed not to have small volume but low loss.

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