분리형과 일체형 리액터에 따른 매트릭스형 초전도 한류기의 외부자장 의존성 연구

논 문
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Dependence of External Magnetic Field in the Matrix-Type SFCL with the Separated or the Integrated Reactors

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Abstract - The matrix-type superconducting fault current limiter (MSFCL) consists of the trigger and current-limiting parts. The trigger part with reactors connected in parallel improves the quenching characteristics by applying the external magnetic field into the superconducting units. The current-limiting part with superconducting units connected in parallel and shunt reactors connected in series limit the fault current when the fault occurs. We developed the integrated reactor with the trigger and the current-limiting parts to apply high external magnetic field into the superconducting units. This was composed of a superconducting unit for the trigger part and two superconducting units for the current-limiting parts. We confirmed that the external magnetic field generated in the MSFCL with an integrated reactor was larger than that of the MSFCL with the separated reactors. So the differences of voltages generated between superconducting units were decreased in the difference according to the increment of the applied voltage. The whole magnitude of the SFCL was reduced because the volume of an integrated reactor could be reduced by one-third than that of the separated reactors. We confirmed that the critical behavior between the superconducting units in the MSFCL with an integrated reactor was more improved than that of the MSFCL with the separated reactors.

Key Words : Critical behavior, Magnetic field, Matrix-type SFCL, Separated and integrated reactors

1. Introduction

The superconducting fault current limiter (SFCL) is expected to be commercialized earlier than any other power equipment using the high-temperature superconducting units. When the fault occurred in the power grid system, the SFCLs limited the fault current. The SFCL uses the zero impedance behavior of superconducting units. If the fault current exceeded the critical current of the superconducting units, the units were quenched and the fault current was limited by the generated resistance [1-4].

We have studied the matrix-type SFCL (MSFCL) with a reactor for a superconducting unit. The MSFCL with the structure to apply the magnetic field into the superconducting unit has the characteristics as follows [2-4]:

1) The fault current was limited fast by the control of the critical current in the superconductor.

2) The trigger and the current-limiting parts for sensing and limiting of the fault could be made up as a module.

3) The shunt resistors and the shunt reactors performed the function to protect the superconducting units and to limit the fault current.

In this paper, we manufactured the MSFCL with an integrated reactor, which consisted of a superconducting unit for the trigger part and two superconducting units for the current-limiting parts. By the use of an integrated reactor, the whole volume of the MSFCL could be reduced as about one-third as that of the MSFCL with the separated reactors. In order to analyze the characteristics between the separated and the integrated reactors, we simulated the distributions of the magnetic field and experimented the characteristics of the MSFCL with the separated and the integrated reactors.

2. Experiment

2.1 The fundamental Principle of a MSFCL

The MSFCL consists of the trigger and the current-limiting parts. A reactor and a superconducting unit of

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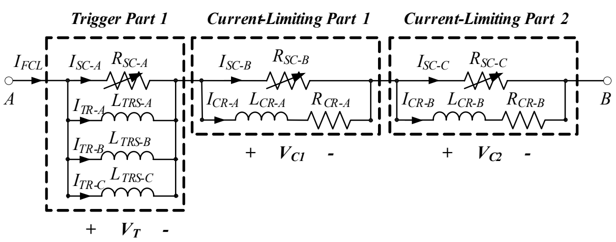
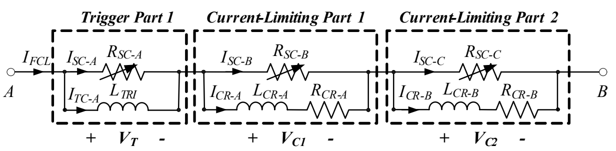
the trigger part were connected in parallel. The reactor could adjust the critical current through the supply of magnetic field into the superconducting unit. The current-limiting parts consist of the superconducting units connected in parallel and R-L units connected in series. They limit the fault current [2-4].

Figs. 1(a) and (b) show the equivalent circuits of the MSFCLs with 1×3 matrix structure using the separated and the integrated reactors. In the Fig. 1(a), three separated reactors (L_{TRS-A}, L_{TRS-B}, L_{TRS-C}) were connected with a superconducting unit in parallel to supply the magnetic field into the superconducting units. When the superconducting unit in the trigger part was quenched by occurrence of fault in the power grid system, the reactors could supply the magnetic field into the superconducting units by the distribution of the fault current through a superconducting unit and three separated reactors. In the meantime, in the Fig. 1(b), an integrated reactor could generate stronger magnetic fields. This is because the current (I_{TR}) flowing into the integrated reactor was three times larger than those (I_{TR-A}, I_{TR-B}, I_{TR-C}) flowing into the separated reactors.

The limited fault current (I_{FCL}) of the MSFCL with three separated and an integrated reactors can be expressed as the equations (1) and (2). We assumed that the resistances generated in the superconducting units of the trigger or the current-limiting parts were R_{SCT} and R_{SCC}, and the impedances (L_{TRS-A}, L_{TRS-B}, L_{TRS-C}) of three separated reactors were L_{TRS}, and the impedances (L_{CR-A}, L_{CR-B}, L_{CR-C}) of the shunt reactors were L_{CR}, and the resistances (R_{CR-A}, R_{CR-B}, R_{CR-C}) of the shunt resistors were R_{CR}, and the voltages (V_{C1}, V_{C2}) generated in the



(a) The MSFCL of 1×3 matrix structure with three separated reactors



(b) The MSFCL of 1×3 matrix structure with an integrated reactor

Fig. 1 Equivalent circuits of the MSFCL with three separated and a integrated reactors

current-limiting parts were V_C, respectively. In the equations, the current flowing into an integrated reactor was three times larger than those flowing into the separated reactors. Therefore, we expected that the external magnetic field generated in an integrated reactor was larger than those of the separated reactors.

1) The equation for an MSFCL of 1×3 matrix with the separated reactors (Fig. 1(a))

$$I_{FCL} = I_{SCT} + 3 \cdot I_{TRS} = \frac{(3R_{SCT} + jwL_{TRS})}{jwL_{TRS} \cdot R_{SCT}} \cdot V_T = \left(\frac{1}{R_{SCC}} + \frac{1}{R_{CR} + jwL_{CR}} \right) \cdot V_C \tag{1}$$

2) The equation for an MSFCL of 1×3 matrix with an integrated reactor (Fig. 1(b))

$$I_{FCL} = I_{SCT} + I_{TRI} = \frac{(R_{SCT} + jwL_{TRI})}{jwL_{TRI} \cdot R_{SCT}} \cdot V_T = \left(\frac{1}{R_{SCC}} + \frac{1}{R_{CR} + jwL_{CR}} \right) \cdot V_C \tag{2}$$

2.2 Experimental Procedure

The experimental circuit for the matrix-type SFCL with the separated and the integrated reactors was represented in the reference [4]. The table 1 shows the specifications of the separated and integrated reactors, shunt reactors and shunt resistors. The designed dimensions of the separated and the integrated reactors were expressed in table 2. The superconducting unit was fabricated using 300 [nm] thick $YBa_2Cu_3O_7$ films grown on 2 inch diameter Al_2O_3 substrates. To analyze the quenching characteristics of the MSFCL with the separated and the integrated reactors, we varied the

Table 1 Specifications on reactors, shunt reactors and resistors

Parameters		The Turn Numbers	Value of Impedance [mH]	Value of Resistance [Ω]
Separated Reactors	L_{TR-A}	570	10.86	1.72
	L_{TR-B}	570	10.09	1.69
	L_{TR-C}	570	10.17	1.7
Integrated Reactor	L_{TR}	570	12.57	3.58
Shunt Reactors	L_{CR-A}	100	1.08	0.24
	L_{CR-B}	100	1.07	0.24
Shunt Resistors	R_{CR-A} R_{CR-B}	None	None	20

Table 2 Designed dimensions of the separated and the integrated reactors

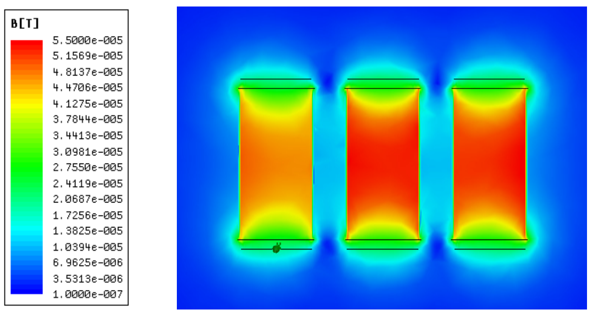
Parameters		Value	Unit
Separated Reactor	Horizontal length (ℓ)	160	mm
	Semidiameter (r)	40	mm
Integrated Reactors	Horizontal length (ℓ)	230	mm
	Semidiameter (r)	40	mm
	Gap of center part	10	mm

applied voltage (V_0) from $200/\sqrt{3}$ to $480/\sqrt{3}$ [V_{rms}]. The distribution of external magnetic field in the separated and the integrated reactors was simulated by using MAXWELL 3D program.

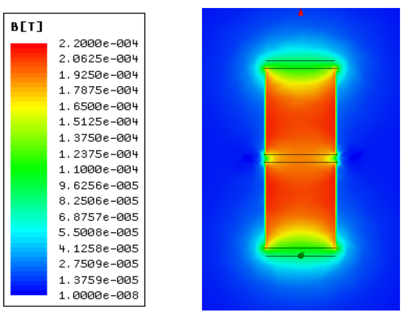
3. Simulation and Experimental Results

3.1 Simulation Results

We analyzed the distribution of external magnetic field in the separated and the integrated reactors by using the MAXWELL 3D program. Fig. 2 shows the external magnetic field distribution of the separated and the integrated reactors at $V_0=480/\sqrt{3}$ [V_{rms}]. In case of three separated reactors, we confirmed that the magnitudes of each external magnetic field were different. This is because the impedance of each reactor was different, so the current flowing into the reactor was different. In the meantime, the magnitude of external magnetic field generated in an integrated reactor was larger than those of the separated reactors. As a result, we found that the sum of external magnetic field generated in three separated reactors was nearly equal to the external magnetic field generated in an integrated reactor.



(a) The magnetic field generated in the separated reactors



(b) The magnetic field generated in an integrated reactor

Fig. 2 Distributions of the magnetic field generated in the separated and the integrated reactors ($V_0=480/\sqrt{3}$ [V_{rms}])

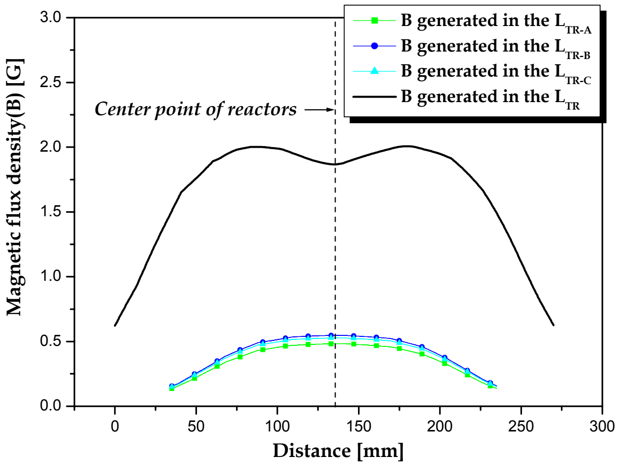


Fig. 3 Magnetic flux density generated in the center point of the separated and the integrated reactors

Fig. 3 shows the distributions of the external magnetic field generated in the center point of reactors. In case of an integrated reactor, the largest external magnetic field was generated at both sides 40 [mm] away from the center point. The external magnetic field was generated by quenching of superconducting units in the trigger part. By supplying the external magnetic field into the superconducting units of current-limiting parts, the difference of critical currents among superconducting units was reduced, and the fault current was limited effectively. Therefore, we arranged two superconducting units in the current-limiting parts at both sides about 40 [mm] away from the center point to supply the largest external magnetic field. Another superconducting unit in the trigger part was located at the center point.

3.2 Experimental Results

Fig. 4 expresses the current curves flowing into the separated and the integrated reactors. We confirmed that the sum of currents flowing into the separated reactors was nearly equal to the current flowing into an integrated reactor as shown in the equations (1), (2) and the simulation results. So the magnetic field generated in an integrated reactor was larger than that of the separated reactors.

Fig. 5 shows the voltage and the current curves of the MSFCLs of 1×3 matrix structures with the separated and the integrated reactors. The limited fault currents of the MSFCLs with the separated and the integrated reactors were 39.6 and 38.3 [A], respectively. This was because the total impedance of the MSFCLs was decreased by the parallel connection of three separated reactors.

The voltages generated in two superconducting units of the current-limiting parts, in case of the MSFCL with the separated reactors, were 186.6 and 173.1 [V], respectively. The voltages of the MSFCL with an integrated reactor were 176.7 and 166.2 [V], respectively. As a result, the differences of voltages among superconducting units were decreased by the reduction of the differences of critical currents among the superconducting units exposed to the external magnetic field. However, the voltages of two superconducting units at the quarter cycle from the fault occurrence were different. That is, the phase of the current was delayed by larger impedance value of an integrated reactor when it was compared to the impedance value of three separated reactors connected in parallel. The initial voltages generated at two superconducting units of the current-limiting parts were different.

Fig. 6 shows the differences of voltages generated in two superconducting units of the current-limiting parts according to the increase of applied voltage. The increase of the applied voltage means the increase of the fault current in the power grid system. In case of the MSFCL with the separated reactors, the voltages generated in two superconducting units according to the increase of applied voltage were nearly equal. However, in case of the MSFCL with an integrated reactor, the voltage difference was gradually reduced differently from the result in the MSFCL with the separated reactors. We found that the voltage difference was reduced more in the MSFCL with

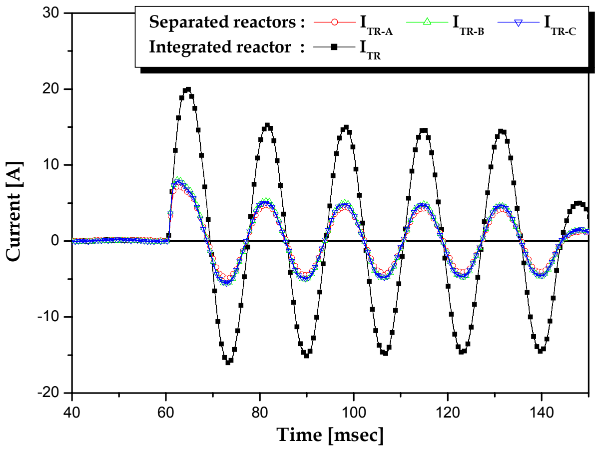
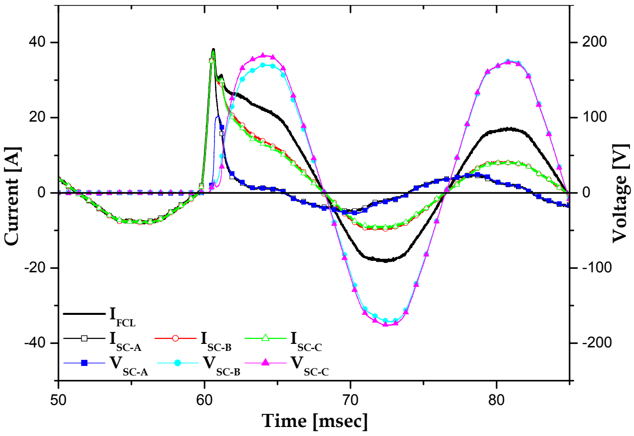
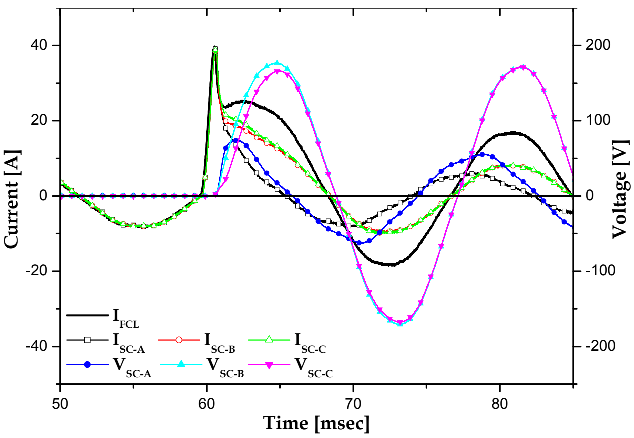


Fig. 4 Current curves flowing into the separated and the integrated reactors



(a) The MSFCL with separated reactors



(b) The MSFCL with an integrated reactor

Fig. 5 Current and voltage curves of the MSFCL with the separated and the integrated reactors (V_0=480/ $\sqrt{3}$ [V_{rms}])

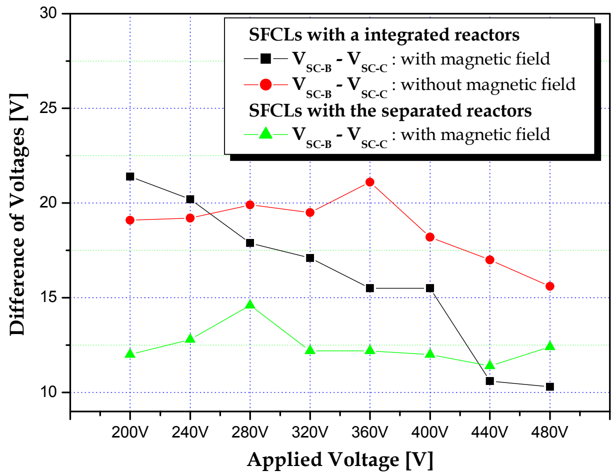


Fig. 6 Differences of voltages generated in two superconducting units of the current-limiting parts of the MSFCLs with the separated and the integrated reactors

an integrated reactor generating the external magnetic field. Consequently, we confirmed that the critical behaviors among the superconducting units were improved in the MSFCL with an integrated reactor because the external magnetic field generated in an integrated reactor was increased by the increment of the current flowing into the reactor.

4. Conclusion

We investigated the effects of the external magnetic field among superconducting units in the MSFCL, which consists of 1×3 matrix structure with the separated or the integrated reactors. The MSFCL with the trigger and the current-limiting parts could improve the critical behaviors of the superconducting units through the application of external magnetic field into the superconducting units. Because the current flowing into an integrated reactor was larger than those flowing into the separated reactors, the generated external magnetic field was increased. Because the largest external magnetic field was generated at both sides about 40 [mm] away from the center point of an integrated reactor through the electromagnetic simulation, we arranged two superconducting units of the current-limiting parts at that points and a superconducting unit of the trigger part at the center point. In case of the MSFCL with the separated reactors, the difference of voltages generated in two superconducting units of the current-limiting parts was nearly unchanged according to the increase of the applied voltage. However, the difference in the MSFCL with an integrated reactor was reduced remarkably. Consequently, we confirmed that the critical behavior among the superconducting units of the MSFCL with an integrated reactor was more improved than that of the MSFCL with the separated reactors because of the generation of the larger external magnetic field. In the meantime, the volume of the MSFCL with an integrated reactor could be reduced when it was compared to the MSFCL with the separated reactors.

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