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Computation of the Current Limiting Behavior of BSCCO-2212 High-Temperature Superconducting Tube with Shunt Coils

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Abstract-- **This paper deals with the computation of the current limiting behavior of high-temperature superconducting (HTS) modules for the superconducting fault current limiter (SFCL). The SFCL module consists of a monofilar type BSCCO -2212 tube and a shunt coil made of copper or brass. The shunt coil is connected to the monofilar superconducting tube in parallel. Through analysis of the quench behavior of the monofilar component with shunt coils, it is achieved to drive an equivalent circuit equation from the experimental circuit structure. In order to analyze the quench behavior of the SFCL module, we derived a partial differential equation technique. Inductance of the monofilar component and the impedance of the shunt coil are calculated by Bio-Savart and Ohm's formula, respectively. We computed the quench behavior using the calculated values, and compared the results with experimental results for the quench characteristics of a component. The results of computation and test agreed well each other, and it was concluded that the analytic result could be applied effectively to design of the distribution-level SFCL system.**

1. INTRODUCTION

The investigation of the quench behavior of high-temperature superconducting (HTS) components for the superconducting fault current limiter (SFCL) is very important because SFCL needs ~50 BSCCO2212 tubes per 1 phase. The SFCL system has 630 A_{rms} rated current and 3 phase 24 kV voltage, when the SFCL system is in the normal operation-mode [1-2].

If the power grid circuit was to face suddenly a large fault-energy, it would be subjected to a burden input or excitation in the form a voltage and a current provided by an independent source.

Recently, the 24 kV_{rms}/630 A_{rms}-SFCL is being developed by a collaborative research team including Korea Electric Power Research Institute (KEPRI) and LS Industrial Systems (LSIS), The Republic of Korea [1-3]. The total number of components, which are connected in series for one phase SFCL, is ~50 components. If we can predict the quench behavior and performance of the SFCL module, those results can be applied effectively to the development of a 3 phase system by design parameter.

In this paper, we present the quench behavior prediction and experimental results of the SFCL module, which consists of a BSCCO-2212 high-temperature superconducting (HTS) tube and a shunt coil using the copper alloy at the short circuit mode.

2. SFCL MODULE CONCEPT

2.1. Circuit Analysis

The equivalent circuit of the SFCL module which consists of the BSCCO-2212 tube and a shunt coil is shown in Fig. 1 [4-5]. For analysis of the electrical characteristic of the SFCL module according to various fault current, we suggest the differential equation for this equivalent circuit at the transient fault mode as follows [6]:

$$L_{tot}\frac{dI_{tot}}{dt} + R_{tot}\cdot I_{tot} = V_{input} \tag{1}$$

where $V_{tot} = V_{input} = V_m \sin(\omega t + \theta - \phi)$ is a periodic voltage , I_{tot} is a transport alternating current in the closed circuit at the normal and transient steady mode, $X_{tot}(=\omega L_{tot})$ and R_{tot} are the circuit reactance and resistance, respectively. Equation (1) is a standard differential equation. Deriving (1) with respect to *t* and dividing the resulting equation by L_{tot}, the solution of (1) is obtained as follows:

$$I_{tot}(t) = I_m \cdot \sin(\omega t + \theta - \varphi) - I_m \cdot \sin(\theta - \varphi)\cdot e^{-\frac{R}{L}t} \tag{2}$$

where $I_m = \frac{V_m}{Z_{tot}}$, $-\frac{\pi}{2} \le \theta \le +\frac{\pi}{2}$, $\varphi = \tan^{-1}\frac{\omega L}{R}$

As shown in Fig. 1, we can calculate the total impedance of the SFCL module as follows:

$$Z_{tot} = \frac{(Z_{hts} + Z_{coil})}{Z_{hts} \times Z_{coil}} \tag{3}$$

where $Z_{hts} = R_{hts} + j\omega L_{hts}$, $Z_{coil} = R_{coil} + j\omega L_{coil}$

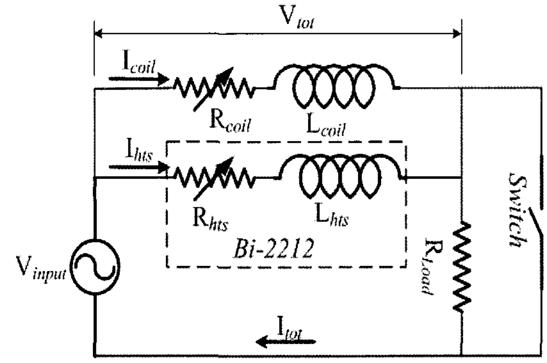

Fig. 1. Equivalent circuit of the system.

The current of each branch of the SFCL module can be obtained as follows:

$$I_{hts} = \frac{Z_{coil}}{Z_{tot}} \times I_{tot} \quad and \quad I_{coil} = \frac{Z_{hts}}{Z_{tot}} \times I_{tot} \qquad (4)$$

The circuit must satisfy both current and electric potential across the SFCL module by Kirchhoff Voltage Law (KVL) and we obtain as follows:

$$V_{hts} = Z_{hts} \times I_{hts} \quad and \quad V_{coil} = Z_{coil} \times I_{coil} \qquad (5)$$

We are also interested in determining the power delivered to the SFCL module. The instantaneous power absorbed by the SFCL module is given by

$$P_{tot} = V_{tot} \times (I_{hts} + I_{coil}) \qquad (6)$$

The energy absorbed by SFCL module as time becomes t1 is given by

$$W_{tot} = \int_0^{t1} P(t) \cdot dt = \int_0^{t1} (V_{tot} I_{tot}) \cdot dt \qquad (7)$$

2.2. SFCL Module Test

The configuration of short circuit test for the SFCL module is shown in Fig. 1. The short circuit test of the SFCL module according to various shunt coils tested at the PT&T (Power Testing and Technology) facilities in LS Industrial systems Co. Ltd. The various fault tests which have short circuit current with ~25 kArms at 200 Vrms voltage are applied to the modules [1-2].

Fig. 2 shows photograph of a SFCL module consisting of an HTS BSCCO-2212 tube and a shunt coil made of copper alloy which plays the role of the field assistance and the excessive energy dissipation of HTS tube to liquid cryogen like liquid nitrogen. The BSCCO-2212 HTS component is installed to the center of shunt coil and they are electrically connected in parallel. As indicated in the bottom photograph of the Fig. 2, for electrical insulation between an HTS component and shunt coil is covered by G-10 tubing. The specification of an SFCL module, which has an HTS component and shunt coil, is shown at the Table 1.

TABLE I
SPECIFICATION OF A SFCL MODULE.

	Parameters	Spec.
HTS component	Resistance	1.0 Ω @ 298K
	Inductance	1.13 μH
	Total length	21 cm
	# of turns	10.5
	Cross section area	0.232 cm^2
Shunt coil	Resistance	7.2 mΩ @ 77K 46.7 mΩ @ 298K
	Inductance	62.8 μH
	Total length	20 cm
	# of turns	60
	# of layer	1
	Cross section area	0.0531cm^2
	External resistance	50.0 mΩ @ 298K
	Material	Copper alloy

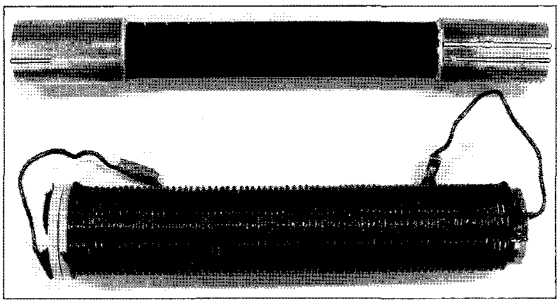

Fig. 2. Photograph for a shunt coil and BSCCO2212 tube.

The initial resistance at 77 K liquid nitrogen temperature of an HTS component and a shunt coil are almost zero and 7.2 mΩ , respectively. The room temperature values are around 1.0 and 46.7 mΩ , respectively. Because the inductance of an HTS component is very small, it can't be measured. So we used the calculated value for simulation.

2.3. Analysis of the Quench Behavior

The joule heating is zero in a SFCL module under normal operating conditions because all the transport currents in the SFCL module are subjected to an HTS component during the normal operation. Under fault circuit mode, the increasing fault current in the SFCL module will increase the electrical resistivity of the HTS component. As the resistance value of an HTS component is greater than that of a shunt coil, the fault current in the SFCL module is separated into both the HTS tube and the shunt coil paths. From (1) to (5), we may conclude that the quench pattern of each path in the SFCL module can be simulated.

Calculated values are voltage across the end of SFCL module, total limitation current of SFCL module and the currents of an HTS tube and a shunt coil.

The resistance variation as a function of temperature at the SFCL module can be calculated by the power density equation [7-8]. We used the resistance value of an HTS tube from an experimental result as shown in Fig. 3.

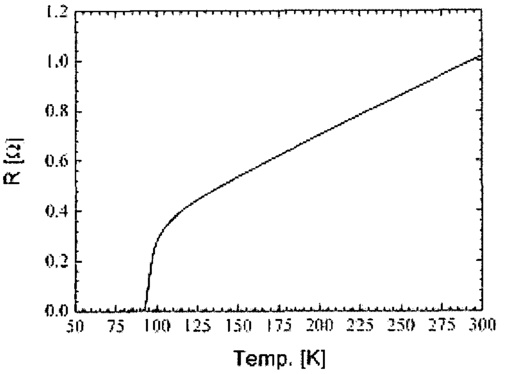

Fig. 3. Resistance vs. Temperature plot of the BSCCO -2212 tube.

The resistance with respect to the various fault currents in the HTS tube has the same value. But the increasing resistance slope as a function of time is only different.

Fig. 4 shows the calculated results which have voltage and current signals at short circuit test. The SFCL module has dramatically experienced a fault current of 25 kA_{rms} at 200 V_{rms} in 5 cycles, when the SFCL is in the fault-mode. The limitation currents of an HTS, shunt coil part and SFCL module due to an excessive current are 6.1 kA_{peak}, 0.6 kA_{peak}, and 6.7 kA_{peak} at the first cut-off point and 0.32 kA_{peak}, 3.0 kA_{peak}, and 3.32 kA_{peak} at the positive fifth peak position, respectively. Also the voltage across a SFCL module is 675 V_{peak} at the first cut-off point and 269 V_{peak} at the last peak point, respectively.

In this part we will consider power relationships for the SFCL module that are excited by limitation currents and voltages.

Fig. 5 shows instantaneous power plot of each part of a SFCL module having the fault current of 25 kA_{rms} at 200 V_{rms} in 5 cycles. The initial peak powers of the SFCL module, an HTS tube and a shunt coil are around 1145, 197 and 951 kW, respectively. After 5 cycles elapsed, the final peak powers are 840, 82.3 and 757.7 kW, respectively.

The energy absorbed by the SFCL module, HTS component and shunt coil during 5 cycles is calculated to be about 39.6, 5.16 and 34.5 kJ, respectively, as shown in Fig. 6.

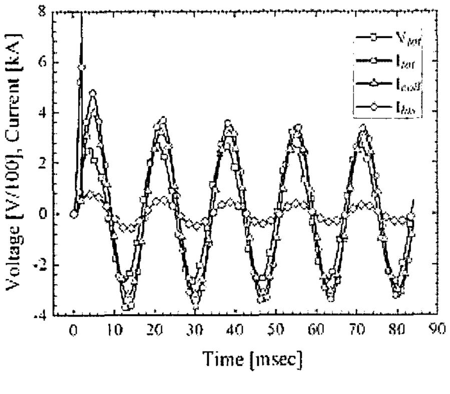

Fig. 4. Computational results of a SFCL component at short circuit test with a 200 V_{rms} and 25 kA_{rms}.

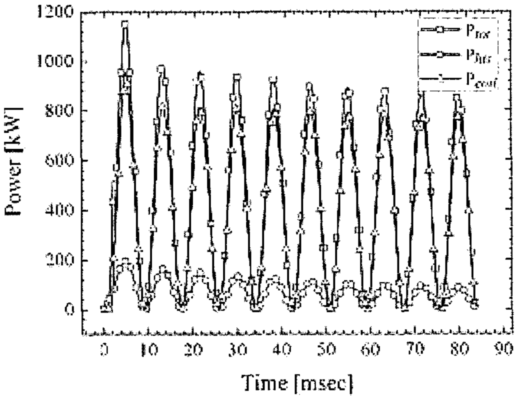

Fig. 5. Periodic instantaneous power plot of a SFCL component at the computational mode (200 V_{rms}/25 kA_{rms}).

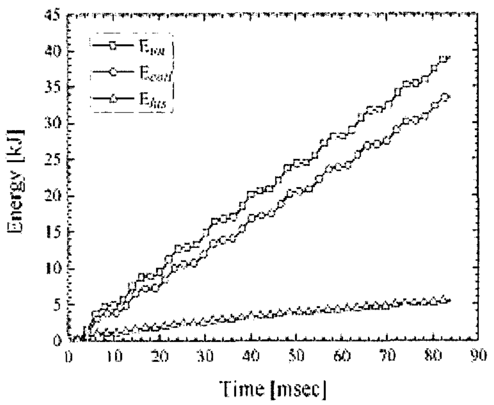

Fig. 6. Energy plot simulation of the SFCL module, HTS component and shunt coil.

3. RESULTS AND DISCUSSION

Fig. 7 shows the experimental results of a SFCL module at short circuit test with a voltage of 200 V_{rms} and current of 25 kA_{rms}. The limitation currents of an HTS, a shunt coil part and a SFCL module are 5.9 kA_{peak}, 0.5 kA_{peak}, and 6.4 kA_{peak} at the first cut-off point and 0.31 kA_{peak}, 2.95 kA_{peak}, and 3.26 kA_{peak} at the positive fifth peak position, respectively. Also the voltage across a SFCL module is 640 V_{peak} at the first cut-off point and 262 V_{peak} at the last point, respectively.

Fig. 8 shows instantaneous power plot of each part of a SFCL module having the fault current of 25 kA_{rms} at 200 V_{rms} in 5 cycles. The pattern of power absorbed on the SFCL module has been gradually reduced during 5 cycle fault current mode.

The initial peak powers of the SFCL module, HTS component and shunt coil are around 1180, 226 and 967 kW, respectively. After 5 cycles, the final peak powers are 855.2, 83.8 and 772.4 kJ, respectively. The energy absorbed by the SFCL module, HTS component and shunt coil during 5 cycles are about 38.9, 5.4 and 33.5 kW, respectively, as shown in Fig. 9.

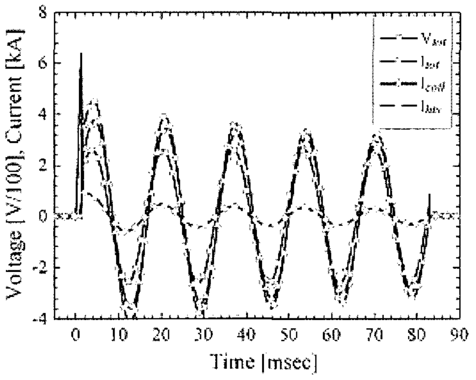

Fig. 7. Periodic instantaneous power plot of a SFCL component at the fault mode (200 V_{rms}/25 kA_{rms}) in experiment.

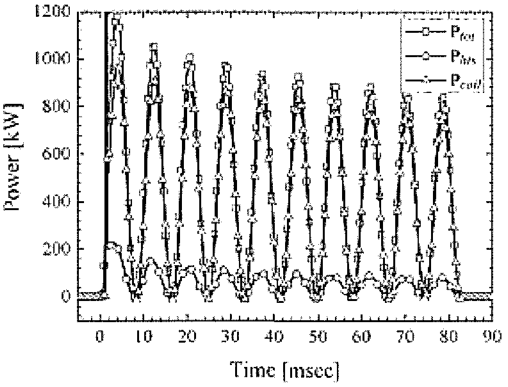

Fig. 8. Periodic instantaneous power plot of a SFCL component at the fault mode (200 V_{rms}/25 kA_{rms}) in experiment.

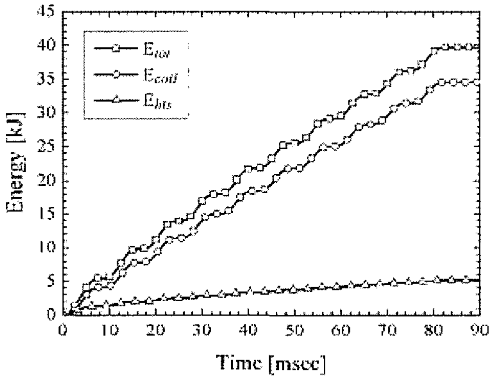

Fig. 9. Energy plot of the SFCL module, HTS component and shunt coil in experiment.

4. CONCLUSION

It is concluded that the quench behavior and the performance of SFCL module were investigated for development of a 3 phase 24 kV_{rms}/630 A_{rms} SFCL system. The results indicate that:

1) The simulation results of the SFCL module during 5 cycle short-circuit agree well with the experimental values.

2) The result of energy absorbed at 77 K liquid nitrogen cooling condition by the SFCL module is a good parameter for the development of a cryogenic system for the SFCL.

3) We can also extend the analytic method to a 3 phase 24 kVrms/630 Arms SFCL to analyze the electrical characteristics of it. Since the total SFCL modules are connected in series, in this circuit, it is obvious from the Kirchhoff Current Law (KCL) that all SFCL modules carry the same current, the only difference being that the 24 kVrms potential source divides between each impedance of SFCL module in direct proportion to their impedances.

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