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論 文

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Characteristics of Transformer-Type SFCL according to the Connecting Methods of Secondary Coils

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Abstract – We have analyzed operating characteristics of transformer-type superconducting fault current limiter (SFCL) according to the serial or parallel connections of secondary coils with $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) thin films. The turn ratio between the primary and secondary coils was 63:21. Transformer-type SFCL using a transformer with secondary winding of serial or parallel coils could reduce the unbalanced quench caused by differences of the critical current density between YBCO thin films. We found that transformer-type SFCL having serial or parallel connections induced simultaneous quench between the superconducting units. The limiting current in the transformer-type SFCL with a parallel connection was lowered to 30 % compared to the SFCL with a serial connection. In the meantime, when the currents generated in the superconducting units were similar, the voltage value in the parallel connection was 60 % as low as that in the serial connection. However, the voltage generated in the primary winding was some higher. In conclusion, we found that transformer-type SFCL with parallel connection of secondary coils was more effective in fault current limiting characteristics and in the reduction of the consumption power for superconducting units compared to those of the transformer-type SFCL with serial connection of secondary coils.

Key Words : transformer-type SFCL, serial or parallel connections, fault current limiting characteristics.

1. INTRODUCTION

The superconducting fault current limiter (SFCL) among power devices using superconducting materials is actively studying around the world. It is very important that the capacity of the SFCL should be increased to apply to power system. Consequently, the superconducting unit with high breaking capacity is widely studying. However, even if such units were developed, the serial and the parallel connections between units are still necessary for the increase of the capacity in the SFCL [1]–[3].

We have been studied the characteristics of a transformer-type SFCL with serial connection of superconducting units. The transformer-type SFCL using a transformer with the primary and secondary coils showed the simultaneous quenching between superconducting units with slight differences of their critical current densities [4]–[5].

In this paper, we tested the operating characteristics of

the transformer-type SFCL with a transformer. It has a primary coil and several secondary coils with three YBCO films connected in parallel. The parallel connection methods of secondary circuits are: the serial or the parallel connections of three secondary coils from the parallel connection of three superconducting units. We investigated the fault current limiting characteristics, power burden of superconducting units, and quench time compared to the resistive-type SFCL.

2. EXPERIMENTAL

2.1 Structure of transformer-type SFCL

The fundamental structure of a transformer-type SFCL consists of a transformer including the primary and secondary coils connected to the superconducting units. In case of a transformer-type SFCL, the parallel connection of secondary circuits has two options as shown in Fig. 1:

- 1) The combination between secondary coils connected in series and superconducting units connected in parallel (Fig. 1 (a)).
- 2) The combination between secondary coils connected in parallel and superconducting units connected in parallel (Fig. 1 (b)).

Fig. 1 shows the equivalent circuits of the transformer-

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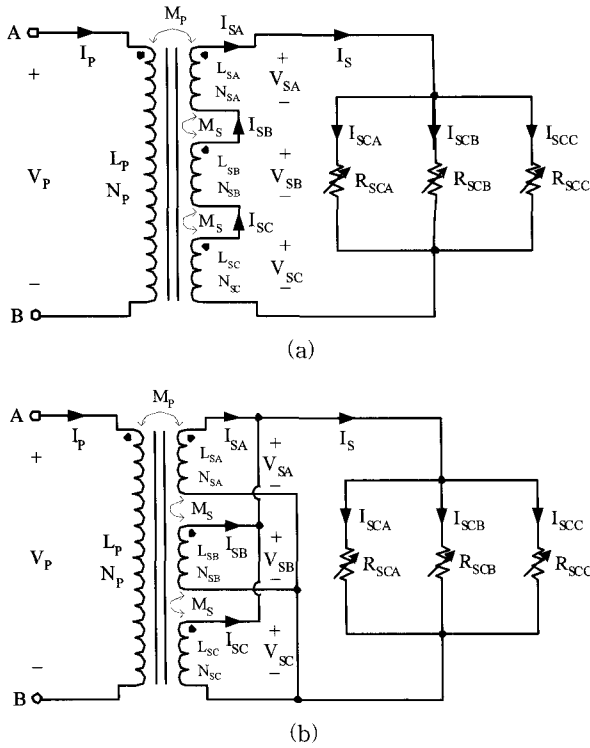


Fig. 1 Equivalent circuits of the transformer-type SFCL according to the serial and parallel connections of three secondary coils: (a) Equivalent circuit of the transformer-type SFCL with serial connections of three secondary coils, (b) Equivalent circuit of the transformer-type SFCL with parallel connections of three secondary coils

type SFCLs connected in the two options. Because the resistance of the superconducting units connected to the secondary coils is zero under no fault condition in power system, the line current (I_p) of the power system flows without I^2R losses. When the fault occurred in the power line, the superconducting units were quenched, and the fault current (I_p) was limited by the resistance generated in the superconducting units.

In the Fig. 1, I_p , I_{sa} , I_{sb} , I_{sc} , V_p , V_{sa} , V_{sb} and V_{sc} are currents and voltages flowing into a primary and three secondary coils, respectively. I_{sca} , I_{scb} and I_{sc} are currents flowing into three superconducting units. R_{sca} , R_{scb} and R_{sc} are the resistances generated in superconducting units after their quenching. L_p is the inductance of a primary coil, and L_{sa} , L_{sb} , L_{sc} are the inductances of three secondary coils, respectively. M_p is the mutual inductance between the primary and secondary coils, respectively.

If we assume that the coupling coefficients (k) between the coils is 1, and the resistances (R_{sca} , R_{scb} , R_{sc}) generated in each superconducting unit are the same value as R_{sc} , and the inductances (L_{sa} , L_{sb} , L_{sc}) of three secondary coils are identical as L_s , the limited fault

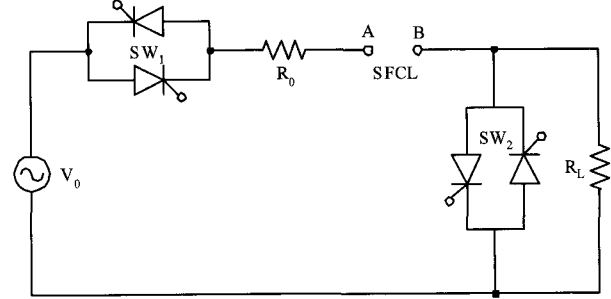


Fig. 2 Experimental circuit of transformer-type SFCL

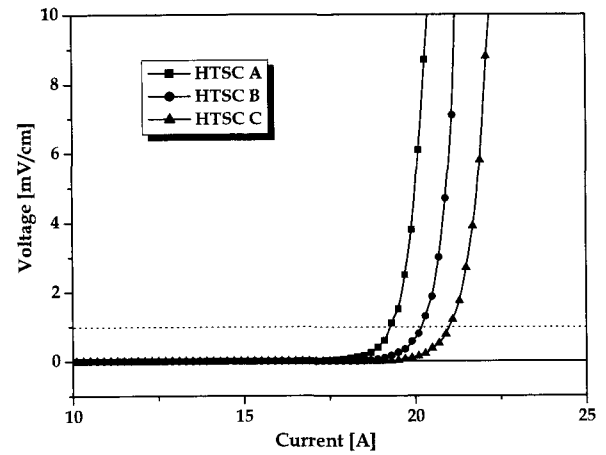


Fig. 3 I - V curves of three superconducting units

Table I The Design Parameters for Iron Core and Coils

Iron Core		Size	Unit
Outer Horizontal Length		340	mm
Outer Vertical Length		340	mm
Inner Horizontal Length		210	mm
Inner Vertical Length		210	mm
Thickness		155	mm
Turn Number of Coils		Value	Unit
Primary Coil	(N_p)	126	Turns
	(N_{sa})	21	Turns
	(N_{sb})	21	Turns
Secondary Coils		21	Turns
		21	Turns

current (I_p), the limiting impedance (Z_{lim}) and the initial limiting current (I_{ini}) from the equivalent circuits of Fig. 1 can be expressed as follows:

1) The transformer-type SFCL with secondary coils connected in series (Fig. 1 (a)).

$$I_p = \frac{j\omega(L_s + 2M_s) + Z_{ss}}{-j\omega M_p} \cdot I_s \quad (Z_{ss} = \frac{R_{sc}}{3} + 2j\omega L_s) \quad (1)$$

$$Z_{lim} = \frac{V_p}{I_p} = \frac{j\omega L_p (2j\omega M_s - 2j\omega L_s + Z_{ss})}{j\omega(L_s + 2M_s) + Z_{ss}} \quad (2)$$

$$I_{ini} = \frac{3(3L_s + 2M_s)}{-M_p} \cdot I_c \quad (3)$$

Where, Z_{ss} is the total impedance of secondary circuit about a coil in case that three secondary coils were connected in series. The current (I_s) flowing into the secondary circuit is equal to the currents (I_{SA} , I_{SB} , I_{SC}) flowing into each secondary coils, and is equal to the total sum of currents (I_{SCA} , I_{SCB} , I_{SCC}) flowing into each superconducting unit.

2) The transformer-type SFCL with secondary coils connected in parallel (Fig. 1 (b)).

$$I_p = \frac{j\omega(L_s + 2M_s) + Z_{SB}}{-3j\omega M_p} \cdot I_s \quad (Z_{SB} = \frac{L_s \cdot R_{SC}}{2R_{SC} + 3j\omega L_s}) \quad (4)$$

$$Z_{lim} = \frac{V_p}{I_p} = \frac{j\omega L_p(2j\omega M_s - 2j\omega L_s + Z_{SB})}{j\omega L_s + 2j\omega M_s + Z_{SB}} \quad (5)$$

$$I_{ini} = \frac{L_s + 2M_s}{-3M_p} \cdot I_c \quad (6)$$

Where, Z_{SB} is the total impedance of secondary circuit about a coil in case that three secondary coils were connected in parallel. The current (I_s) flowing into the secondary circuit is equal to the total sum of currents (I_{SA} , I_{SB} , I_{SC}) flowing into each secondary coils, and is equal to the total sum of currents (I_{SCA} , I_{SCB} , I_{SCC}) flowing into each superconducting unit.

In the transformer-type SFCL with the serial connection of three secondary coils, we confirmed that the current (I_p) flowing into the primary coil was higher than in the SFCL with the parallel connection of secondary coils from equations (1), (4) because of the large impedance (Z_{ss}) in the serial connection of secondary coils. It is also certified that the limiting impedance (Z_{lim}) at serial connection of secondary coils was smaller than those of the parallel connection from equations (2), (5). In other words, the limiting fault current (I_p) in a transformer-type SFCL with serial connection of secondary coils was about 3 times as high as those of the parallel connection.

The initial limiting current (I_{ini}) of the transformer-type SFCL according to the connecting options of the secondary coils, when the currents (I_{SA} , I_{SB} , I_{SC}) of the secondary coils reach the critical current of the superconducting units, can be obtained from the equations (1) and (4) by inserting $R_{SC}=0$, $I_s=3I_c$, and $I_p=I_{ini}$ as shown in equations (3) and (6). From these equations, the initial limiting current could be controlled by the inductance (L_p) of the primary coil and the inductance (L_s) of the secondary coils. We expected that the fault

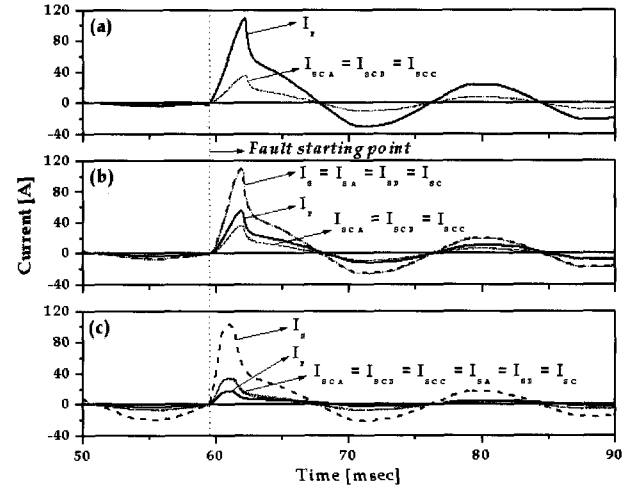


Fig. 4 Current waveforms of the resistive and transformer-type SFCLs: (a) A resistive-type SFCL, (b) A transformer-type SFCL with serial connection of secondary coils, (c) A transformer-type SFCL with parallel connection of secondary coils

current of a transformer-type SFCL could be controlled flexibly by these factors.

2.2 Experimental procedure of transformer-type SFCL

Fig. 2 shows the experimental circuit of a transformer-type SFCL. V_o is a source voltage of $200/\sqrt{3}$ V_{rms}. The resistance (R_0) for power line and the resistance (R_L) for the load are 1 and 50 Ω , respectively. The short circuit accidents were simulated for five periods by SW_2 , which is switch for fault condition, after switch SW_1 for normal condition was closed at 0° of fault angle. The superconducting units were fabricated in the form of meander-line and it was 300 nm thick YBCO thin films grown on 2 inch diameter Al_2O_3 substrates.

Fig. 3 displays the individual I - V curves of three superconducting units used in the experiment. The quench current (I_q) was drawn at 1 mV/cm criterion as shown in dotted line of Fig. 3. The quench current (I_q) of each superconducting unit were slightly different as 19.3, 20.2 and 21 A, respectively.

The design parameters for the iron core and the primary and secondary coils used in the transformer-type SFCL were shown in Table I. The inductance (L_p) of primary coil was 221 mH, and the inductance (L_s) of secondary coils with the turn number of 21 was 2.9 mH, respectively.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figs. 4 and 5 are current and voltage waveforms of resistive and transformer-type SFCLs with the serial or

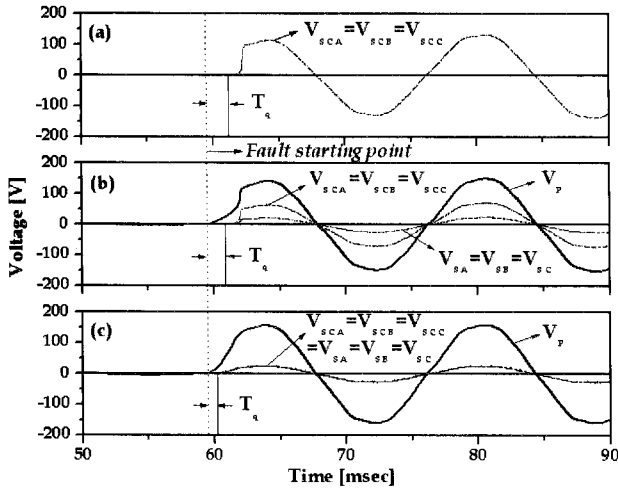


Fig. 5 Voltage waveforms of the resistive and transformer-type SFCLs: (a) A resistive-type SFCL, (b) A transformer-type SFCL with serial connection of secondary coils, (c) A transformer-type SFCL with parallel connection of secondary coils

parallel connections of secondary coils in case that three superconducting units are connected in parallel. The turn numbers (L_P , L_S) in the primary and secondary coils of transformer-type SFCL are 126 and 21, respectively.

The fault currents (I_P) of the resistive and transformer-type SFCLs with the serial or parallel connection of secondary coils as shown in the Fig. 4 were 109, 55 and 17.3 A, respectively. The current (I_S) flowing into the secondary coil of transformer-type SFCL was limited by quenching of superconducting unit connected in secondary coil during the fault duration. At this time, the current (I_P) flowing into the primary coil was induced in proportion to turn ratio (N_S/N_P) by the limited current (I_S) of the secondary coil. In case of the transformer-type SFCL with serial connection of secondary coils, I_S was 109 A, and I_P was 55.4 A because of turn number ($N_P:N_S=126:63$). We confirmed that I_S was 102.9 A, and I_P of transformer-type SFCL with parallel connection of secondary coils was 34.3 A because of turn number ($N_P:N_S=126:21$).

The currents (I_{SCA} , I_{SCB} , and I_{SCC}) flowing into each superconducting unit are the same because the resistance of the superconducting unit are same. Therefore, the $I_{SCA}=I_{SCB}=I_{SCC}$ flowing into the each superconducting unit was 36.6 A for serial connection of secondary coils, 34.5 A for parallel connection of secondary coils, respectively. In the Fig. 5, the voltages ($V_{SCA}=V_{SCB}=V_{SCC}$) of each superconducting unit with serial connection of three secondary coils are equal to the total sum of voltages (V_{SA} , V_{SB} , V_{SC}) by each coil. However, in case of transformer-type SFCL with parallel connection of

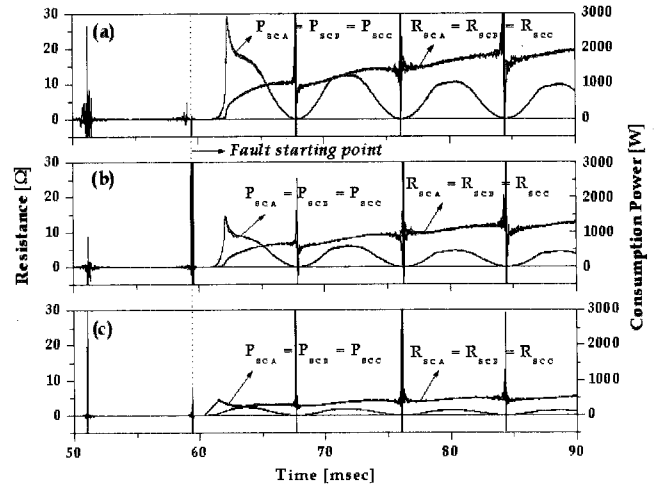


Fig. 6 Resistances and consumption powers of the resistive and transformer-type SFCLs: (a) A resistive-type SFCL, (b) A transformer-type SFCL with serial connection of secondary coils, (c) A transformer-type SFCL with parallel connection of secondary coils.

three secondary coils, voltages ($V_{SCA}=V_{SCB}=V_{SCC}$) of each superconducting unit are equal to the voltages (V_{SA} , V_{SB} , V_{SC}) by each coil. We confirmed that the voltage of superconducting units at serial connection of coils was 3 times as high as those of the parallel connection.

In the Fig. 5, the quenching times (T_q), which is defined as the time interval from fault starting point to the critical current value, were 1.71, 1.51 and 0.72 msec for the resistive-type, and the transformer-type SFCL with serial, or parallel connections of secondary coils, respectively. The more T_q is shortened, the better quick limitation of fault current is achieved. As a result, we estimated that the transformer-type SFCL with parallel connection of secondary coils could achieve faster limitation of fault current with the reduction of power consumed in the superconducting units.

The voltage generated in the superconducting unit causes on the resistance behavior of the superconducting unit during the quenching duration. Fig. 6 shows the waveforms of the resistances and the consumption powers generated in the three superconducting units connected in each SFCLs. In case of the resistive-type SFCL, the voltage ($V_{SCA}=V_{SCB}=V_{SCC}$) presented in superconducting units were 116V, and the resistances ($R_{SCA}=R_{SCB}=R_{SCC}$) in the units were about 20Ω after 0.03 seconds from the fault. The resistances in the units in case of the transformer-type SFCL were 12 Ω for serial connection of secondary coils, 5Ω for parallel connection of secondary coils. We found that the resistance generated in serial connection of secondary coils was about 2 times as high as that of parallel connection of secondary coils.

The consumption power was calculated by the voltage and the current flowing into the units during the half cycle as shown in Fig. 6. The consumption power of resistive-type SFCL was 2,885 W, and those of the transformer-type SFCL with serial or parallel connections of secondary coils were 1,458 and 460 W, respectively. Consequently, in case of the transformer-type SFCL with parallel connection of secondary coils, the power consumed in the units was diminished because the current ($I_{SCA}=I_{SCB}=I_{SCC}$) flowing into the units was lower than that of each unit and the voltage (V_s) presented in secondary circuit was also decreased.

4. CONCLUSIONS

We investigated and compared the characteristics of the transformer-type SFCLs with the serial or the parallel connection of secondary coils after three superconducting units were connected in parallel compared to a resistive-type SFCL. The turn numbers of the primary and secondary coils were 126 and 21. In case of the transformer-type SFCL with the parallel connection of secondary coils, the fault current was reduced to about 80 % of resistive-type SFCL, and to about 30 % of transformer-type SFCL with the serial connection of secondary coils because the current flowing into the primary coil was occurred in inverse proportion to turn ratio (N_s/N_p) of the primary and secondary coils by the quenching of the superconducting units. The current and the voltage in the secondary coils were reduced than other two SFCLs because the structural advantage from the parallel connection of secondary coils. As a result, the calculated resistance and the consumption power in superconducting units with the parallel connection of secondary coils were also less than those of the resistive-type SFCL or those of the transformer-type SFCL with serial connection of secondary coils. The quenching time of a transformer-type SFCL with the parallel connection of secondary coils was faster than other two SFCLs. In conclusion, we estimated that the transformer-type SFCL with parallel connection of secondary coils and three superconducting units was more effective in the limitation of the fault current and the consumption power and the quenching time of the superconducting units compared to the resistive and a transformer-type SFCLs with the serial connection of secondary coils.

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