A Study on Required Volume of Superconducting Element for Flux Flow Resistance Type Fault Current Limiter

H. Shimizu, Y. Yokomizu, M. Goto, T. Matsumura, and N. Murayama

***Abstract*—We have proposed a fault current limiter (FCL) suppressing an overcurrent only by a flux flow resistance of a high temperature superconductor (HTS). If the fault current is interrupted within an allowable time t_a after the fault occurs, the flux flow resistance type FCL can instantly recover to the superconducting state and pass a load current. In this paper, the volume V_r of the HTS in the FCL required to satisfy the specified limiting effect and t_a was investigated theoretically. The volume V_r depends on the critical current density and the flux flow resistivity of the HTS. As the flow resistivity and/or critical current density increase, V_r can be reduced to obtain a certain current limiting effect. When t_a is specified, V_r has a maximum value at a certain flux flow resistance. If both the limiting effect and t_a are given, the required volume is constant and independent of critical current density or flux flow resistance.**

***Index Terms*—Critical current, element volume, fault current limiter, flux flow resistance.**

I. Introduction

As a promising candidate to suppress a short-circuit current induced in an electric power system, a fault current limiter (FCL) with a high temperature superconductor (HTS) is anticipated [1]–[4]. We have proposed a concept that uses the flux flow resistance of HTS as a limiting resistance of FCL [5]. The flux flow resistance appears in the HTS when the transport current exceeds the critical current level I_c under the condition that the temperature of the HTS is less than the critical temperature T_c. If the HTS temperature is maintained below T_c, the flux flow resistance disappears again at the moment that the transport current decreases to lower value than I_c. Hence, the FCL using flux flow resistance (*Flux Flow Resistance Type FCL*) may be able to pass a load current immediately after the fault clearing if the fault current is interrupted within a proper time. We have called that time *the allowable operating time*.

To realize the recovery characteristics mentioned above, the HTS must have relatively large heat capacity. On the other hand, the flux flow resistance is about a hundredth as large as normal resistance. This means that a larger volume of the HTS may be required for the flux flow resistance type FCL to satisfy the requirements of an FCL than that for typical type of FCL using the normal resistance. Thus, it is important to understand the conditions where the required HTS volume is minimized.

In this paper, we theoretically investigate the relationship between the properties of the HTS and the volume required to satisfy the specifications as the FCL. We consider that the flux flow resistance type FCL is installed into a 6.6 kV distribution system. The computer simulation of fault current limiting performance is carried out for the FCL with the HTS having different characteristics of the critical current density and flux flow resistance. In the discussion, the current limiting effect and/or the allowable operating time are considered as fixed parameters of the FCL.

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II. Fundamental Properties of HTS

The critical current density and generating characteristics of flux flow resistance in the HTS depend on the HTS temperature T and applied magnetic flux density B. The flux flow resistance also changes with the instantaneous value of transport current density j. Such temperature and flux density dependences have to be taken into the consideration in the simulation of the limiting performance of the FCL. We made assumptions about those characteristics as described below.

The critical current density J_c degrades with the temperature rise of the HTS. The critical current density J_c linearly decreases with an increase in T as shown in Fig. 1(a). In this figure, T_c is the critical temperature of the HTS, T_b is the liquid nitrogen temperature, J_{c0} is the critical current density at $T = T_b$. From Fig. 1(a), J_c can be expressed as a function of T as follows:

$$J_c = -\frac{J_{c0}}{T_c - T_b}(T - T_b) + J_{c0}. \tag{1}$$

The case where $T > T_c$ was omitted from the consideration in this estimation because the normal resistance appears in the HTS instead of the flux flow resistance.

In Fig. 1(b), the relation between the voltage v generated per unit length of the HTS and current density j (v–j characteristic) at $T = T_b$ is indicated by solid line. The voltage v is zero for $|j| < J_{c0}$ and linearly increases with $|j|$ in the region of $|j| \geq J_{c0}$. The current density at the intersection of the v–j characteristic line and horizontal axis corresponds to critical current density J_{c0}. The intercept moves along the horizontal axis in

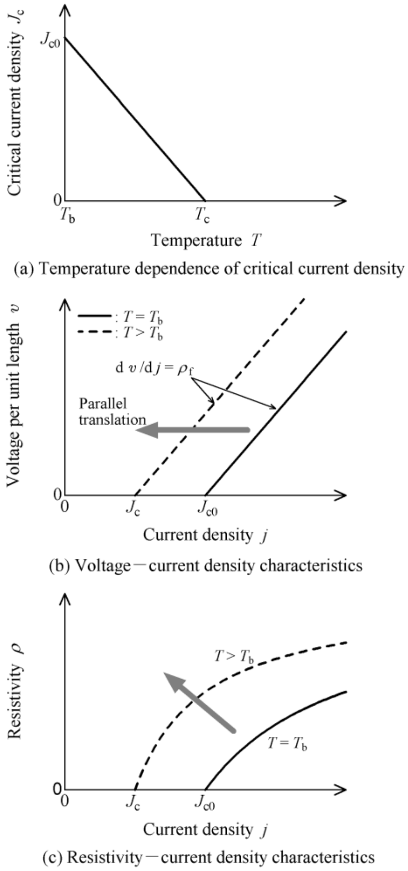

Fig. 1. Fundamental properties assumed in calculation. (a) Temperature dependence of critical current density. (b) Voltage-current density characteristics. (c) Resistivity-current density characteristics.

the direction toward the origin of Fig. 1(b) owing to the reduction of the critical current density J_c as the temperature of the HTS rises. It is also assumed that the slope of v–j characteristic does not change as the HTS temperature increases. This means that the v–j characteristic translates in the negative direction of the horizontal axis as shown by broken line in Fig. 1(b). From Fig. 1(b), v for $|j| \geq J_{c0}$ is expressed as follows:

$$v = \rho_f (j \mp J_c) \tag{2}$$

where ρ_f, which is called *flux flow resistivity* in this paper, is the slope of v–j characteristic. The minus and plus signs in (2) are correspond to positive and negative current density, respectively.

The resistivity ρ of the HTS is obtained by division of v by j. Substituting (1) into (2) and dividing by j, we can get the following expression for ρ under the condition of $|j| \geq J_c$:

$$\rho = \left\{ \frac{J_{c0}}{|j|} \left(\frac{T - T_b}{T_c - T_b} - 1 \right) + 1 \right\} \rho_f. \tag{3}$$

Fig. 1(c) shows the relationships between ρ and j in the cases of $T = T_b$ and $T > T_b$. The resistivity ρ goes up with T, as well as j.

In the above description, we ignored the influence of B because B applied to the HTS in the FCL may be not very high unless an external magnetic field is applied.

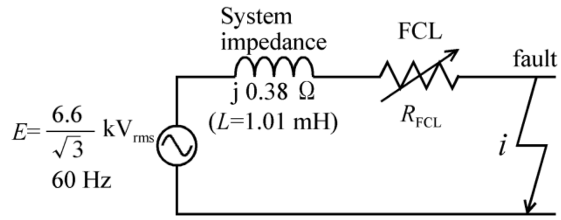

Fig. 2. Model of 6.6 kV class distribution system.

III. Limiting Performance of Fault Current Limiter in Distribution System

A. Calculation Conditions

We analyzed a flux flow resistance type FCL with the HTS having the properties mentioned and installed at an outgoing feeder in a distribution substation. We considered the situation that a three-phase short-circuit fault occurs near the substation. Fig. 2 illustrates the single-phase equivalent circuit. The system voltage and frequency are 6.6 kV and 60 Hz, respectively. The system impedance has only inductive component of $j0.38\ \Omega$ (1.01 mH). In this case, the maximum value of the short-circuit current I_{m0} with no fault current limiter is 14.1 kA$_{\mathrm{peak}}$. From Fig. 2, following equation is written:

$$L\frac{di}{dt} + R_{\mathrm{FCL}} i = \sqrt{2} E \sin(2\pi f t + \theta) \tag{4}$$

where t is the elapsed time from the fault occurrence, i is the instantaneous value of fault current, L is the inductance of the system, R_{FCL} is the limiting resistance of the FCL, E is the root mean square value of phase voltage, θ is the phase angle of the system voltage at $t = 0$. In the case of resistive type fault current limiter, the limiting resistance starts to be generated at the moment that i reaches the critical current I_{c0} at $T = T_b$, i.e., the initial current of limiting action I_{ini} is equal to I_{c0}. Hence, the cross section A_{sc} of the HTS is I_{ini}/J_{c0} because $I_{c0} = A_{sc} J_{c0}$. Furthermore, let l_{sc} denote the length of the HTS, then the element volume V_{sc} equals $l_{sc} A_{sc}$. Using these relations and (3), we can express R_{FCL} as follows:

$$R_{\mathrm{FCL}} = \rho \frac{l_{sc}}{A_{sc}} = \left\{ \frac{J_{c0}}{|j|} \left(\frac{T - T_b}{T_c - T_b} - 1 \right) + 1 \right\} \frac{\rho_f J_{c0}^2 V_{sc}}{I_{ini}^2}. \tag{5}$$

Solving (4) numerically, we can get the time variation in i. In this computation, the HTS temperature T must be given. Assuming that the HTS is under an adiabatic condition, we can obtain T from the accumulated joule heat W generated per unit volume of the HTS. Because the temperature rise $T - T_b$ is equal to W/C where C is specific heat per unit volume of the HTS. For simplicity, the temperature dependence of C is ignored because of the small temperature rise under the flux flow resistive condition. The accumulated joule heat W can be calculated by the integration of $i^2 R_{\mathrm{FCL}}/V_{sc}$. Table I summarizes the parameters used in the calculation. For values of T_c and C, we referred to those of Bi2223 bulk made by us [6]. The calculations were carried out for various values of V_{sc}, ρ_f and J_{c0}.

TABLE I
PARAMETERS USED IN CALCULATION

Critical temperature	T_c	107 K
Liquid nitrogen temperature	T_b	77 K
Initial current of limiting operation	I_{ini}	1 kA
System voltage (phase voltage)	E	$6.6/\sqrt{3}$ kV
System frequency	f	60 Hz
Phase angle of system voltage	θ	90°
System inductance	L	1.01 mH
Specific heat	C	1.0 MJ/m^3

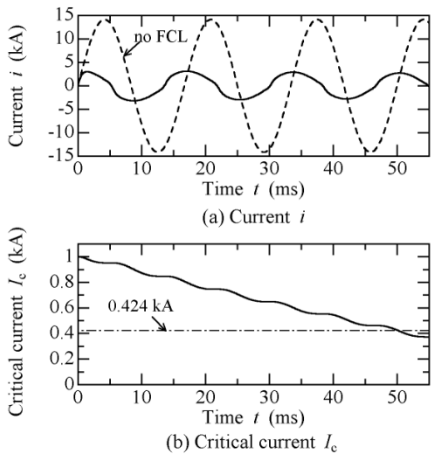

Fig. 3. Typical example of calculated waveforms ($\rho = 10^{-6}$ Ωm, $J_{c0} = 10^7$ A/m^2, and $V_{sc} = 2.32 \times 10^{-2}$ m^3).

B. Calculated Waveforms

Fig. 3 shows an example of typical waveforms. This figure was obtained under the conditions of $\rho = 10^{-6}$ Ωm, $J_{c0} = 10^7$ A/m^2 and $V_{sc} = 2.32 \times 10^{-2}$ m^3 ($A_{sc} = 10^{-4}$ m^2 and $l_{sc} =$ 232 m). Fig. 3(a) and (b) indicate the time variations in i and critical current I_c, respectively. In Fig. 3(a), the waveform of the prospective fault current without the fault current limiter is also shown with broken line. The maximum value of the limited fault current I_m is 3.20 kA which is 22.7% of that of the prospective fault current I_{m0}. The crest value of i slightly decreases with time. That is because $R_{\rm FCL}$ grows with the temperature rise of the HTS due to the joule heat generated in flux flow resistance.

As shown in Fig. 3(b), I_c decreases with time because of the temperature rise of the HTS. We now assume that the load current in a distribution feeder is 0.424 kA$_{\rm peak}$ (0.300 kA$_{\rm rms}$ in root mean square value). From Fig. 3(b), I_c declines to 0.424 kA at $t = 50.0$ ms. If the fault current is interrupted before $t =$ 50.0 ms, the FCL can pass the load current of 0.424 kA$_{\rm peak}$ without any resistance immediately after the current interruption. We have defined the time until the critical current is equal to the peak value of the load current from the fault occurrence as *the allowable operating time* t_a.

IV. REQUIRED VOLUME OF HTS

To estimate the limiting effect of the FCL quantitatively, we defined I_m/I_{m0} as the limiting factor α. A small α means that the FCL has a high limiting effect. We estimated the HTS volume V_r required to satisfy a specified α for different ρ_g and J_{c0}. Fig. 4 shows the relations between V_r and ρ_g for $\alpha = 0.2$ by broken lines. This figure indicates the results for various values of J_{c0}. Note that each broken line is interpreted to show V_r for the HTS with A_{sc} determined by I_{ini}/J_{c0}. This also means that the characteristics of V_r in Fig. 4 equivalently indicate relations between the required length of the HTS and ρ_f. The required volume V_r decreases with an increase in ρ_f under the condition of same J_{c0}. The limiting factor α depends on only $R_{\rm FCL}$ and is independent of the other parameter because of the fixed distribution system condition. There is no great difference in the value between the curly brackets of (5) due to ρ_f and J_{c0} at the time when i reaches its maximum value.[1] From (5), it is found that V_r for same $R_{\rm FCL}$ is in inverse proportion to ρ_f. The required volume V_r also decreases as J_{c0} goes up because V_r is also inversely proportional to J_{c0}^2 as seen from (5).

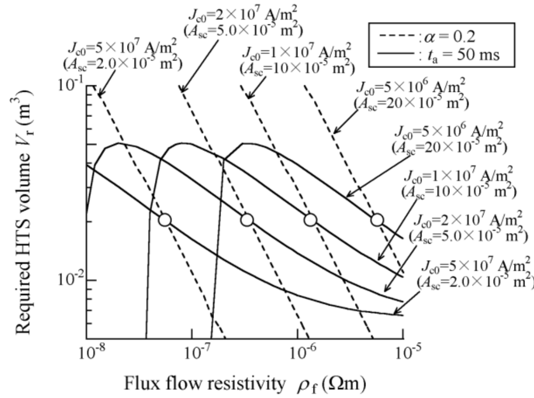

Fig. 4. Required volume of HTS as a function of flux flow resistivity.

Fig. 4 also indicates the relations between V_r and ρ_f for the condition of $t_a = 50$ ms by solid lines. The volume V_r takes a peak value at a certain $\rho_f = \rho_{fc}$ if J_{c0} is constant. This characteristic is understood as follows. The joule heat P generated per unit volume of the HTS is uniquely determined for given t_a. Thus, each solid line in Fig. 4 is understood to be the equi-joule-heat line (equi-P line). Let J denote the equivalent root mean square value of j, P is approximately expressed by

$$P \cong \rho_f J^2 = \frac{E^2 \rho_f}{A_{sc}^2 \left\{ \left(\rho_f V_{sc}/A_{sc}^2\right)^2 + (2\pi f L)^2 \right\}}. \qquad (6)$$

Since the numerator in (6) increases with ρ_f, the denominator must also rise at the same rate to maintain a constant P. When approximated $R_{\rm FCL} \cong R'_{\rm FCL} = \rho_f V_{sc}/A_{sc}^2$ is smaller than the system impedance $2\pi f L$, i.e., for $\rho_f < \rho_{fc}$, the increasing rate of the denominator for ρ_f is lower than that of the numerator. Thus, the large increment in $R'_{\rm FCL}$ or V_{sc} is required to keep a constant P even if ρ_f increases. On the other hand, in the case of $\rho_f > \rho_{fc}$, P is nearly equal to $E^2 A_{sc}^2/(\rho_f V_{sc}^2)$ because $R'_{\rm FCL} = \rho_f V_{sc}/A_{sc}^2$ is larger than $2\pi f L$. To obtain a constant

[1] Under the conditions that α is a certain specified value, $J_{c0}/|j|$ is same. Furthermore, T is nearly equal to T_b {when the fault current is maximum. That is because the fault current takes the maximum value for first or second half cycle when the temperature rise is small.

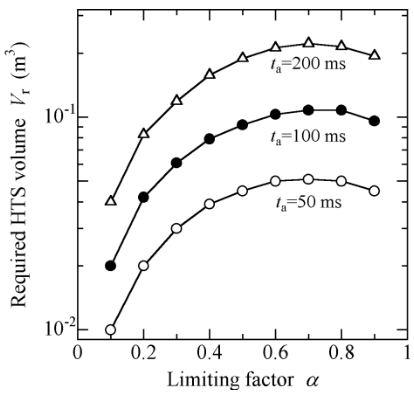

Fig. 5. Required volume of HTS as a function of limiting factor.

P under this condition, V_{sc} must decrease with an increase in ρ_f. As a result, the maximum of V_r exists at the medium point where $\rho_f = \rho_{fc}$.

When J_{c0} increases, the relation between V_r and ρ_f under the condition of constant t_a moves parallel in the negative direction of the horizontal axis. In order to understand this phenomenon, we consider the case where the HTS with same volume but different J_{c0} is used. Under this condition, since R_{FCL} is constant, $J_{c0}/|j|$ in (5) is also identical as mentioned above and the temperature rise per second is also constant. It is, therefore, found from (5) that J_{c0}^2 is inversely proportional to ρ_f.

The volume V_r at the intersection of broken and solid lines for the same J_{c0} corresponds to the volume required to satisfy both specifications of $\alpha = 0.2$ and $t_a = 50$ ms. The intersection is indicated by "◯" in Fig. 4. As seen from this figure, such V_r is constant and independent of J_{c0}. In the case of $\alpha = 0.2$ and $t_a = 50$ ms, the required volume is 0.02 m^3.

Fig. 5 shows V_r required to satisfy both of specified α and t_a. In this figure, the magnitude of V_r is indicated for the case that t_a is specified to be 50 ms, 100 ms and 200 ms. For all t_a, V_r takes a maximum value at α of about 0.7 where R_{FCL} is almost equal to system impedance and the joule heat generated in the whole of the HTS is the largest. It is found that V_r increases with t_a linearly. That is because the decreasing ratio of I_c must be reduced by using an HTS with a large volume to get a long t_a.

V. Conclusion

The HTS volume required to satisfy the specifications of the flux flow resistance type FCL is theoretically investigated. Considering the limiting effect and allowable operating time as the given parameters, we calculated the required volume for the FCL with the HTS having different characteristics of critical current density and flux flow resistivity. The results obtained in this paper are concluded as follows:

- As far as only the limiting effect is kept constant, we can reduce the element volume using an HTS with a high critical current density and/or flux flow resistivity.
- Under the condition that a certain allowable operating time is specified, the required volume has a maximum value at a certain flux flow resistivity which increases as the critical current density increases.
- In the case that both the limiting effect and allowable operating time are determined, the required volume is constant regardless of the critical current density or flux flow resistivity of the HTS.

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