Dependence of Quench Current Level on Current Ramp Rate in AC Superconducting Windings under Different Fixing Conditions

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Abstract—**Mechanical instabilities in a.c. Nb-Ti superconducting wire are theoretically investigated. We derived the expressions for the temperature rise of the SC wire due to the friction between the wire and the bobbin to estimate the quench current degradation induced by mechanical disturbances. The quench current levels were calculated for different conditions of frictional force and current ramp rate. It is confirmed that a certain frictional force brings about the lowest quench current level. It is also found that the quench current degradation induced by mechanical disturbance may be hard to occur when the current increases rapidly.**

I. Introduction

In superconducting (SC) apparatus, mechanical disturbance may be cause of the behavior that the quench occurs at lower current level than the inherent current capacity of the SC winding[1][2]. The mechanical instabilities are brought about by the wire motion of the SC winding induced by the electromagnetic force in the apparatus. It is difficult to estimate the magnitude of the mechanical disturbance because it will depend on the surface condition of the SC winding and the bobbin, the fixing condition of the winding and so on. Hence, the mechanism of such instability has not yet been clarified sufficiently.

We have suggested that the quench current levels of superconducting windings depend on the current ramp rate as well as the fixing condition of the conductor from our experiments[3]. In this paper, dependence of quench current level on current ramp rate in ac superconducting wires wound on the bobbin was theoretically investigated for different fixing conditions or different frictional force between the wire and the bobbin. The temperature rise in the wire due to frictional heat induced by the wire motion was estimated. Supposing the application to the electric power system with the frequency of 50/60 Hz, the calculations were carried out for the current ramp rates of more than several tens kA/s (these corresponds to the currents having the peak value of more than several hundreds amperes). It is pointed out that there is a certain frictional force which causes the maximum degradation of quench current level. Furthermore it is found that the quench due to frictional heat may be hard to occur for high current ramp rate because the transport current attains to the inherent quench current level before the wire temperature reaches the level where the stability limit of the current decreases by the thermal effect.

II. Derivation of Basic Equation

A. Frictional Energy

Fig. 1 illustrates the model for calculation of mechanical instabilities. We assumed that the ramp current i with the ramp rate K begins to supply to the SC winding at time $t = 0$, i.e.,

$$i = Kt \tag{1}$$

As shown in Fig. 1, in the case that the SC wire is exposed to the magnetic flux density having the perpendicular direction to the surface of the bobbin, the electromagnetic force is applied to the SC wire in the direction along the

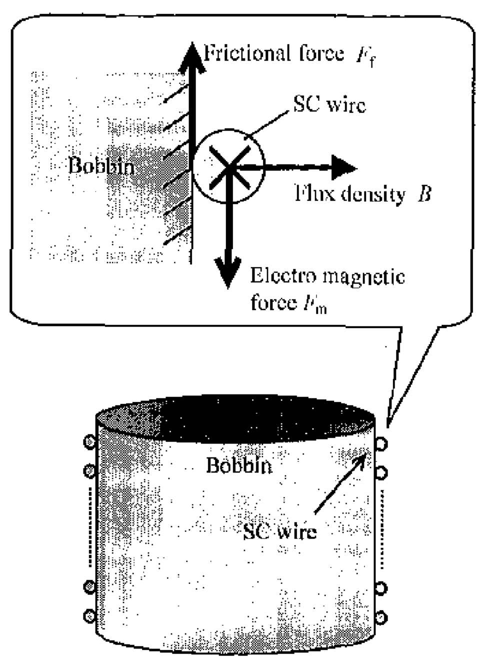

Fig. 1. Calculation model.

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bobbin surface. The electromagnetic force F_m applied to unit length of the SC wire is given by next equation.

$$F_m = B_0 i^2 = B_0 K^2 t^2 \tag{2}$$

where B_0 is the applied flux density for the unit current. When F_m exceeds the frictional force F_f per unit length between the wire and the bobbin, the wire begins to move. By using (2), the time t_s when the wire motion occurs is expressed as

$$t_s = \sqrt{\frac{F_f}{B_0 K^2}} \tag{3}$$

For $t \geq t_s$, following motion equation is applicable.

$$m\frac{d^2z}{dt^2} = F_m - F_f \tag{4}$$

where m is the mass of SC wire per unit length and z is the displacement from initial position of the SC wire along the bobbin surface.

For simplicity, it is assumed that B_0 and F_f are constant. Since $dz/dt = 0$ at $t = t_s$, we can obtain the moved distance dz of the SC wire for the very short period dt by substituting (2) and (3) for (4).

$$dz = \frac{F_f}{m}\left(\frac{1}{3t_s^2}t^3 - t + \frac{2t_s}{3}\right)dt \tag{5}$$

From (2), (3) and (5), the energy dW_m given to the SC wire by F_m for the period dt is expressed as

$$dW_m = F_m dz = \frac{F_f^2}{m}\left(\frac{1}{3t_s^4}t^5 - \frac{1}{t_s^2}t^3 + \frac{2}{3t_s}t^2\right)dt \tag{6}$$

The energy dW_m is divided into the kinetic energy dW_k and the frictional energy dW_f. The kinetic energy dW_k is written by

$$dW_k = \frac{d}{dt}\left\{\frac{1}{2}m\left(\frac{dz}{dt}\right)^2\right\}dt \tag{7}$$

From (5) and (7), the kinetic energy dW_k is obtained by

$$dW_k = \frac{F_f^2}{m}\left(\frac{1}{3t_s^4}t^5 - \frac{4}{3t_s^2}t^3 + \frac{2}{3t_s}t^2 + t - \frac{2t_s}{3}\right)dt \tag{8}$$

Hence, (6) and (8) yield dW_f

$$dW_f = dW_m - dW_k = \frac{F_f^2}{m}\left(\frac{1}{3t_s^2}t^3 - t + \frac{2t_s}{3}\right)dt \tag{9}$$

B. Wire Temperature

A part of dW_f is used for the temperature rise of SC wire and the remaining part flows out to the liquid helium. In this calculation, the heat conduction along the SC wire is ignored because a.c. Nb-Ti SC wire generally has low thermal conductivity. Furthermore, we assumed that the temperature is uniform over the wire. In such case, following equation is valid.

$$dW_f = Ac\,dT + hP(T - T_b)dt \tag{10}$$

where T, A and c are the temperature, cross-sectional area and specific heat of the SC wire, respectively. h is the heat transfer coefficient, P is cooling perimeter and T_b is the temperature of liquid helium. For simplicity, the temperature dependence of c and h is ignored. Substituting (9) into (10) and considering that $T = T_b$ at $t = t_s$, we can obtain the next equation.

$$T = \frac{F_f^2}{Acm}\left\{\frac{\Gamma}{3t_s^2}t^3 - \frac{\Gamma^2}{t_s^2}t^2 + \left(\frac{2\Gamma^3}{t_s^2} - \Gamma\right)t - \frac{2\Gamma^4}{t_s^2} + \Gamma^2 + \frac{2\Gamma t_s}{3} + \left(\frac{2\Gamma^4}{t_s^2} - \frac{2\Gamma^3}{t_s}\right)e^{-\frac{t-t_s}{\Gamma}}\right\} + T_b \tag{11}$$

where,

$$\Gamma = \frac{Ac}{hP} \tag{12}$$

Equation (11) gives the time variation of wire temperature for $t \geq t_s$. In the case of $t < t_s$, T is equal to T_b.

C. Stability Limit and Quench Current Level

The stability limit I_{sl} of transport current in SC wire decreases with an increase in T. In the discussion, we assumed that the I_{sl} is expressed for T as follows.

$$I_{sl} = -\frac{I_{q0}}{T_c - T_b}(T - T_b) + I_{q0} \tag{13}$$

where, T_c is the critical temperature and I_{q0} is the stability limit at $T = T_b$, i.e. the inherent quench current level without mechanical instabilities. By substituting (11) for (13), the change of I_{sl} due to the rise of T can be calculated. In this paper, we judged that the quench occurred when the i expressed by (1) agrees with I_{sl} and defined the instantaneous value of i at this time as the quench current level I_q.

III. Parameters Used for Calculation

The calculations were performed for a typical a.c. Nb-Ti superconducting wire. Table I summarizes the specifications of the SC wire adopted. The parameters for the calculations were determined on basis of the specifications of the wire as listed in Table II. The influence of transient heat transfer to liquid helium was neglected because we assumed the electrically insulated wire[4][5]. The inherent quench current level I_{q0} was obtained from our experiments carried out for the SC wire with same specifications listed in Table I. We measured I_{q0} of the SC wire completely fixed on the bobbin with epoxy resins. In general, I_{q0} decreases with an increase in current ramp rate as shown in Table II[6].

TABLE I
SPECIFICATIONS OF SC WIRE ADOPTED.

Diameter (bare)	0.205 (0.178) mm
Matrix	Cu-10%Ni
Nb-Ti : Cu : Cu-Ni	1 : 0 : 2
Electric insulation	PVF

TABLE II
PARAMETERS USED FOR CALCULATIONS.

Mass m	2.6×10^{-4} kg/m
Specific heat c	2.0×10^{3} J/m^{3}K
Cross-sectional area A	3.3×10^{-8} m^2
Heat transfer coefficient h	1000 W/m^{2}K
Perimeter P	3.2×10^{-4} m
Critical temperature T_c	9.4 K
LHe temperature T_b	4.2 K
Magnetic flux density B_0	2.0×10^{-4} T/A
Inherent quench current level I_{q0}	71.3 A ($K = 24$kA/s)
	65.6 A ($K = 37$kA/s)
	59.9 A ($K = 64$kA/s)
	56.9 A ($K = 92$kA/s)
	51.8 A ($K = 139$kA/s)

We calculated the quench current level I_q for frictional forces of 0.02, 0.2 and 0.5 N/m. Furthermore, supposing the use in electric power system with the frequency of 50/60 Hz, we estimated I_q for the current ramp rate of 24 kA/s to 139 kA/s. These increasing rates are corresponding to the sinusoidal (60 Hz) current of 74 A_{peak} to 370 A_{peak}, respectively.

IV. RESULTS AND DISCUSSION

A. Dependence of Quench Current Level on Current Ramp Rate

Fig. 2 indicates the time variations of i, I_{sl} and T obtained from the calculations. Fig. 2 (a) is the results for $K = 24$ kA/s and $F_f = 0.2$ N/m. At $t = 1.32$ ms, T begins to increase because F_m exceeds F_f. The stability limit I_{sl} is reduced as the temperature T increases. Since the transport current i is agreement with I_{sl} at $t = 2.64$ms, the quench occurs at this point. In this example, I_q was calculated to be 63.2 A. This quench current level corresponds to 89 % of $I_{q0} = 71.3$ A.

Fig. 2 (b) and (c) are calculation results for $F_f = 0.5$ N/m and $F_f = 0.02$ N/m and the same K as in the case of Fig. 2 (a). As shown in Fig. 2 (b), in the case of large F_f, the time t_s when the SC wire begins to move becomes later. Hence, the quench current degradation is lower than that for Fig. 2 (a). On the other hand, for small F_f like the case of Fig. 2 (c), the frictional energy dW_f is suppressed. Hence, the quench current level is also higher than the results in Fig. 2 (a) although the t_s is short. From Fig. 2 (a), (b) and (c), it is found that a certain frictional force may cause the lowest quench current level.

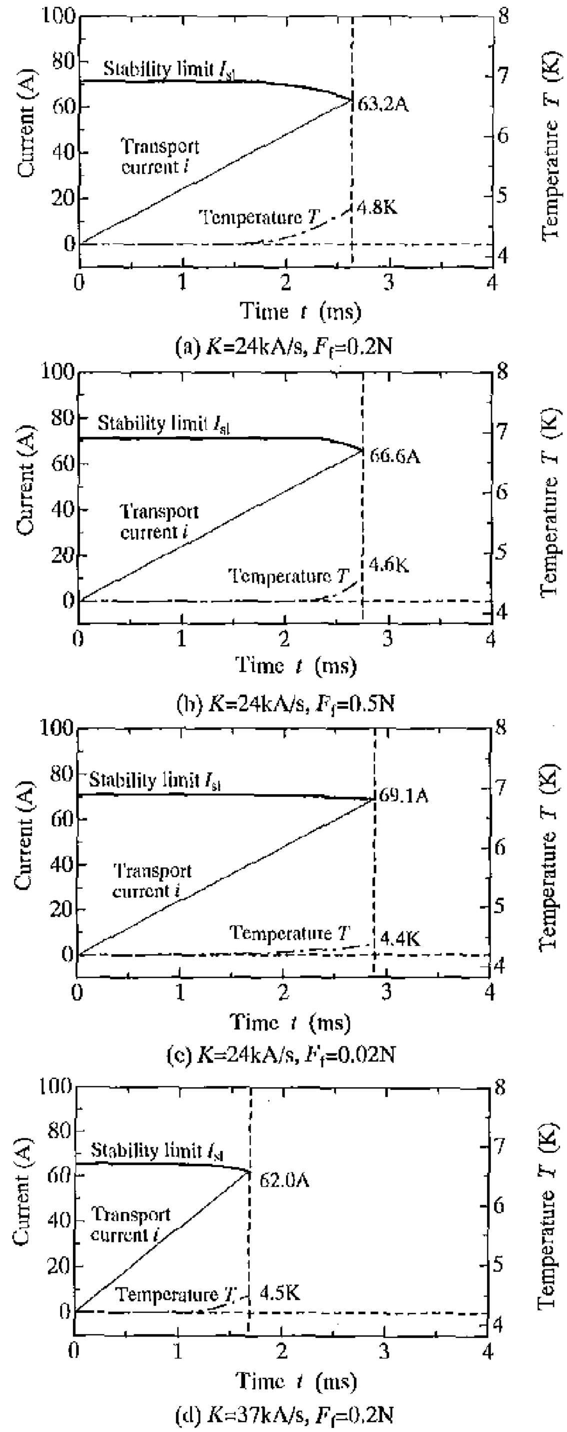

Fig. 2. Time variations of temperature and stability limit in SC wire.

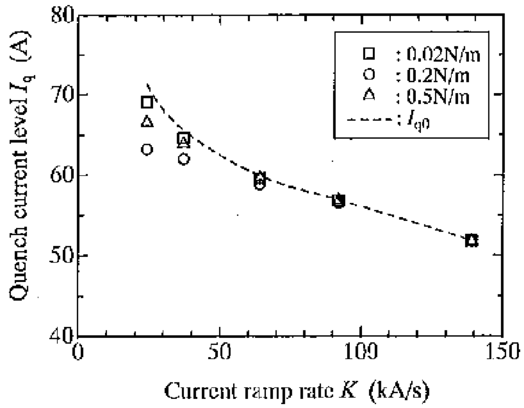

Fig. 3. Quench current level as a function of current ramp rate.

The results shown in Fig. 2 (d) corresponds to higher K of 37kA/s than that for Fig. 2 (a). For the case of higher K, since the i reaches the higher level at $t = t_s$, the quench current degradation is smaller than lower K. The quench current level in the case of Fig. 2 (d) is 62.0 A. This quench current level is 95 % of $I_{q0} = 65.6$ A.

Fig. 3 shows the dependence of the quench current level on the current ramp rate for F_f =0.02, 0.2 and 0.5 N/m. In this figure, the inherent quench current level I_{q0} is also indicated by dashed line. The quench current level is lowest at $F_f = 0.2$ N/m which is the intermediate frictional force. It is also found that the quench current degradation becomes smaller as K increases for all F_f.

It is pointed out that the quench current level of SC winding with the mechanical instabilities is determined by the correlation among t_s, K and increasing rate of T.

B. Energy Given to SC Wire

Fig. 4 shows the details of the energy given to the SC wire. The kinetic energy W_k was obtained by integration of (8) for the period until the quench. The energy W_e used for the temperature rise of the SC wire was calculated from the wire temperature at the quench occurrence. Subtracting W_e from the frictional energy W_f which was derived by integrating dW_f, we estimated the heat transfer W_h to the liquid helium.

In the case of $F_f = 0.02$ N/m, W_e is very small although the total energy W_m is the largest of the four conditions. This means that most of the energy applied to the SC wire is converted to the kinetic energy and the heat flow due to heat transfer for the small F_f. On the other hand, in the case of $F_f = 0.5$ N/m, whole of energy is suppressed because the period from the occurrence of wire motion to the quench is short. As a result, W_e becomes small. Owing to same reason, W_m and W_e are also small for the condition of $K = 37$ kA/s.

V. Conclusions

Dependence of quench current characteristics of a.c. superconducting wire on current ramp rate were discussed.

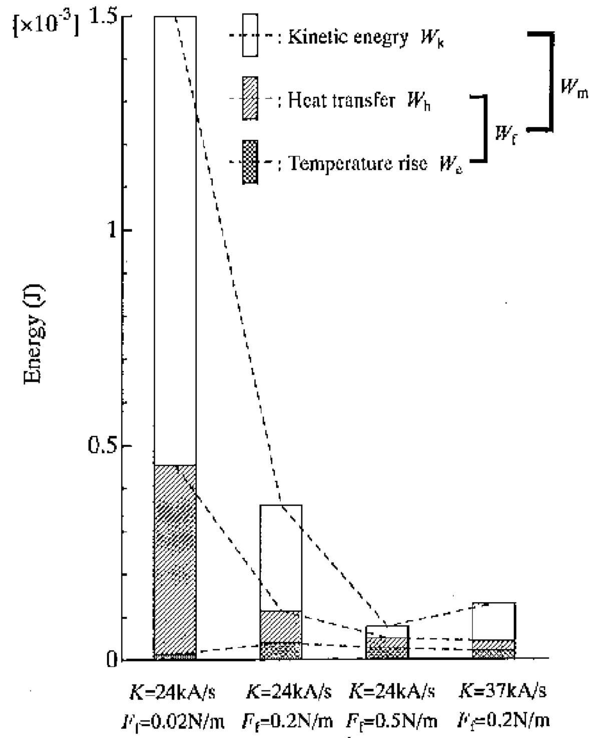

Fig. 4. Energy given to SC wire.

The basic equation for the wire temperature was derived and the mechanism of quench current degradation induced by mechanical disturbance is investigated using the equation. It is pointed out that the mechanical instabilities are influenced by the correlation between the increasing rate of the current and temperature as well as the time when the wire begin to move.

In the future, we should carry out the detailed investigation on the mechanical instabilities by comparing the calculated results with the measured ones.

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