Dependence of Quench Current Level of Superconducting Wire and Cable on the Winding Tension

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Abstract—**Mechanical instabilities in an a.c. Nb-Ti superconducting wire and cable are experimentally investigated. The quench current levels of the sample conductors were measured for different winding tensions and current increasing rates. We have developed a new type of experimental bobbin to apply the tension uniformly and to adjust it to the specified value from the outside of the cryostat. It is found that the influence of the mechanical instabilities on the quench current level decreases with an increase in the winding tension and/or the current increasing rate.**

I. Introduction

In superconducting (SC) apparatus, there are some cases that the quench occurs at lower current level than the inherent current capacity of the SC winding and the quench current level I_{q} changes at each flow of the overcurrent. Mechanical disturbance is one of the causes of such behavior[1][2]. The mechanical instabilities are brought about by the wire motion of the SC winding induced by the electromagnetic force in the apparatus. The quench current level I_{q} is considered to be reduced by the frictional heat produced by the winding-winding and/or winding-bobbin interactions. 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, it is important to fundamentally clarify the mechanical instabilities.

In this paper, the mechanical instabilities of SC winding were experimentally investigated. An a.c. Nb-Ti SC wire and cable were wound on the bobbin as the sample conductor and fixed only by application of the tension without epoxy resins. We have developed a new type of experimental bobbin to uniformly apply the winding tension to the sample and to adjust the tension to the specified value from the outside of the cryostat. The a.c. quench current level I_{q} of the sample was measured under different conditions of winding tension F_{T} and current increasing rate $\mathrm{d}i/\mathrm{d}t$. As a result, the faster $\mathrm{d}i/\mathrm{d}t$ as well as F_{T} became, the smaller the quench current degradation by the mechanical disturbance was. Thus, it is found that F_{T} may influence the dependence of I_{q} on $\mathrm{d}i/\mathrm{d}t$.

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II. Experimental Bobbin

In this paper, we attempt to measure the quench current level I_{q} of the sample conductor for different winding tensions under the condition that the sample is wound on a bobbin without epoxy resins. In such experiments, the sample is cooled down together with the bobbin after it is wound with a certain tension in room temperature. In this case, the specified tension may not be applied to the sample because of the different thermal contractions of materials at low temperature. As an idea to apply the tension after cooling, it is considered to pull the current lead from the outside of the cryostat. This method may be available for a short sample. However, the tension may not be applied uniformly for the relatively long sample wound on the bobbin because of the friction of the sample against the bobbin.

To avoid such problems, we have developed a new type of experimental bobbin. Fig. 1 (a) and (b) illustrate the external and cross-sectional view of the bobbin, respectively. The diameter of the bobbin is 100 mm and can be slightly enlarged because the bobbin has many slits. The sample conductor is wound on the bobbin without the tension. A disk with a shaft is set in the bobbin. The edge of the disk is slantingly cut and the shaft extends to the outside of the cryostat. As shown in Fig. 1 (b), the radial force F_r is generated by the vertical force F_z from the upside. In this method, the tension is uniformly applied to the sample.

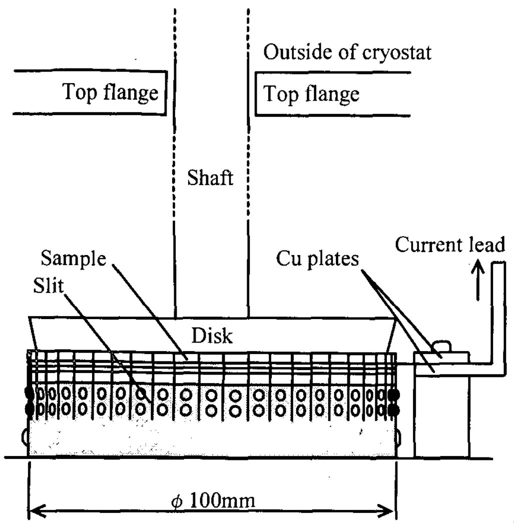
By neglecting the frictional force between the lateral face of the disk and the bobbin, we can calculate the tension F_{T} along the sample as follows.

$$F_{\mathrm{T}} = \frac{F_z}{2\pi n}\cot\theta \tag{1}$$

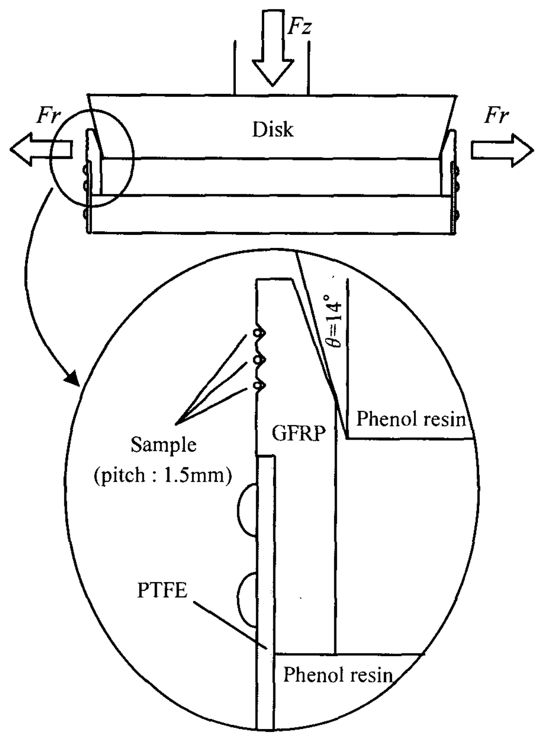
where θ is the angle at the edge of the disk shown in Fig. 1 (b) and n is the turn number of the sample. Since θ is 14° and n is 2.5 turns in the experiments, F_{T} is equal to $0.25F_z$ from (1). By changing F_z applied from outside of the cryostat, we can adjust F_{T} to the specified value.

We calculated the distribution of the magnetic field along the sample induced by the current i using the Biot-Savart's low and then estimated the electromagnetic force applied to the sample. As a result, the maximum value of the transverse magnetic field is 2.0×10^{-4} T per 1 A, i.e., the maximum electromagnetic force F_{m} is equal to

$$F_{\mathrm{m}} = 2.0 \times 10^{-4} \cdot i^2 \quad [\mathrm{N/m}]. \tag{2}$$



(a) External view.



(b) Cross-sectional view.

Fig. 1. Structure of experimental bobbin.

III. Experimental Procedure

Table I summarizes the specifications of the a.c. Nb-Ti SC wire and cable adopted. The SC wire has no stabilizing copper and is coated by PVF for electric insulation.

TABLE I
SPECIFICATIONS OF SC WIRE AND CABLE ADOPTED.

Wire	Diameter (bare)	0.205 (0.178) mm
	Matrix	Cu-10%Ni
	Nb-Ti : Cu : Cu-Ni	1 : 0 : 2
	Filament diameter	0.67 μm
	Filament number	23 749
	Twist pitch	1.76 mm (S-twisted)
	Electric insulation	PVF
Cable	Diameter	0.615 mm
	Strand number	6 + 1
	Center strand	Cu-10%Ni
	Twist pitch	6.2 mm (S-twisted)

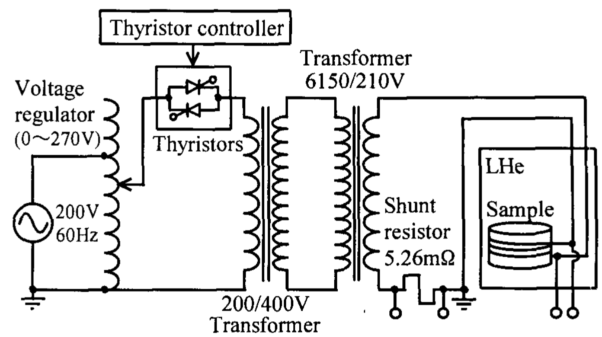


Fig. 2. Experimental circuit diagram.

The SC wire is used as the strand of the SC cable. Both samples are 905 mm in length.

Fig. 2 shows the experimental circuit diagram. The power source supplies the a.c. current of 60 Hz. The output of the voltage regulator was adjusted to a particular magnitude and a half cycle of the sinusoidal current was carried to the sample by turn-on of a pair of thyristors. The turn-on phase angle was controlled to contain no DC transient component in the current. In this paper, we define the prospective current $I_{\rm p}$ as the peak value of the current expected to flow if the quench dose not occur in the sample. By controlling the output of the voltage regulator, we can adjust $I_{\rm p}$ or the current increasing rate $\mathrm{d}i/\mathrm{d}t$. We measured $I_{\rm q}$'s of the SC wire and the SC cable for different $F_{\rm T}$'s and $I_{\rm p}$'s. The measurements were carried out ten times under the same experimental condition. The prospective current $I_{\rm p}$ was changed within the ranges of 74 $\sim$ 370 $\mathrm{A_{peak}}$ and 300 $\sim$ 970 $\mathrm{A_{peak}}$ for the SC wire and cable, respectively. The winding tension $F_{\rm T}$ of 0 $\sim$ 48.8 N was applied to the samples.

IV. Results and Discussion

A. Measured Waveforms

Fig. 3 shows the waveforms of the current and voltage in the SC wire measured under the conditions of $I_{\rm p}$ = 74 $\mathrm{A_{peak}}$ and $F_{\rm T}$ = 26.6 N. It was judged that the quench occurred at t = 3.03 ms because the voltage appeared at this point. In this paper, we define the instantaneous value of the current at this point as the quench current

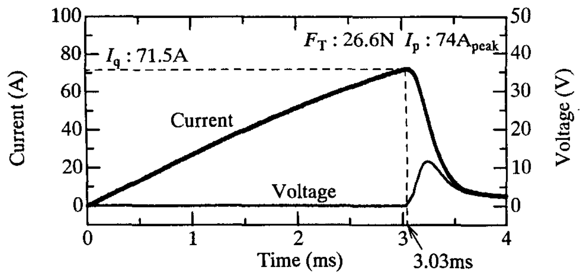


Fig. 3. Waveforms of current and voltage measured for SC wire.

level I_q. In this example, I_q was measured to be 71.5 A.

B. Results for SC Wire

Fig. 4 shows I_q of the SC wire as a function of F_T measured under the conditions of $I_p = 74$, 106, 173, 247 and 370 A_{peak}. The open circles in this figure indicate the averages for I_q measured for the same condition. In the case that F_T is high enough to suppress the wire motion induced by the electromagnetic force, the inherent quench current level of the sample has to be measured without the mechanical instabilities. Thus, measured I_q is constant for F_T. In the case of low F_T, since the mechanical instabilities occur, I_q may be lower than the inherent value. In the cases of $I_p = 74, 106$ and 173 A_{peak}, I_q is kept almost constant for $F_T \geq 9.4$ N. On the other hand, for lower F_T than 9.4 N, I_q is reduced with a decrease in F_T. These results mean that the mechanical instabilities are suppressed by F_T of more than 9.4 N. In the case of $I_p = 247$ A_{peak}, I_q is constant for F_T of more than 4.5 N, i.e., the mechanical instabilities are suppressed at lower winding tension. Furthermore, for $I_p = 370$ A_{peak}, I_q is independent of F_T and little dispersion of I_q appears.

It is found that high prospective current as well as high winding tension may have suppression effect on the mechanical instabilities. The quench due to mechanical instabilities may be hard to occur for high prospective current or fast current increasing rate since the current attains the inherent quench current level of the sample conductor before the mechanical disturbance causes the thermal effect on the quench initiation.

Fig. 5 shows dependence of I_q on I_p for $F_T = 0$, 7.0, 9.4 and 26.6 N. In this figure, average values are plotted. The dashed line in Fig. 5 indicates the characteristic measured for the sample completely fixed by epoxy resins and means the quench current level without mechanical disturbance. The inherent quench current level of SC wire essentially decreases with an increase in I_p or the rate of current rise[3]. At high F_T, such characteristics are observed and agree with the results for the sample completely fixed by epoxy resins. The quench current level I_q, however, increase with I_p for low F_T. That is because the influence of the mechanical disturbance producing the quench current degradation is large at low winding tension. It is found that the dependence of I_q on I_p may be affected by the winding tension.

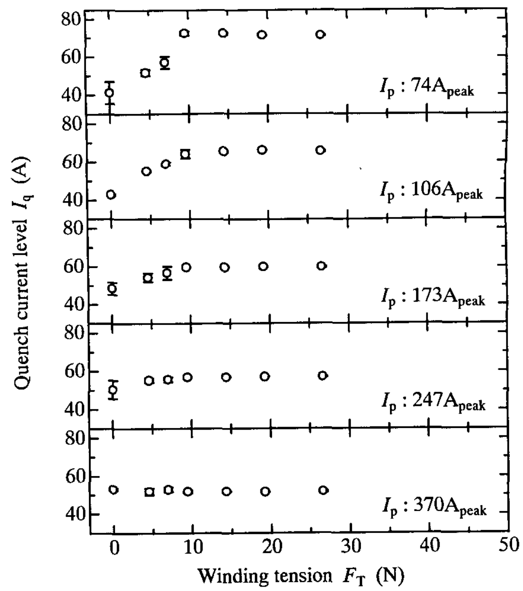


Fig. 4. Quench current level I_q as a function of winding tension F_T measured for SC wire.

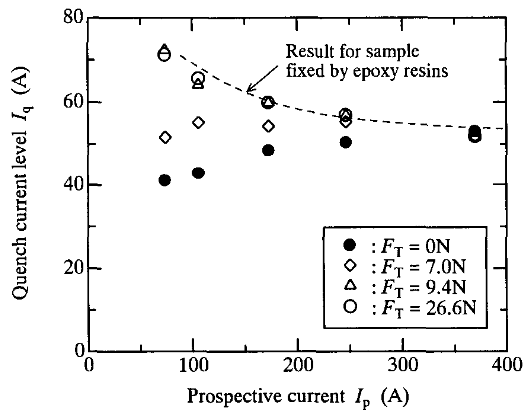


Fig. 5. Dependence of quench current level I_q on prospective current level I_p measured for SC wire.

C. Results for SC Cable

Fig. 6 shows I_q measured for the SC cable as a function of F_T. This figure illustrates the results for $I_p = 300$, 380, 600, 770 and 940 A_{peak} all together and the open circles also correspond to the averages for measured I_q. In the case of $I_p = 300$ A_{peak}, I_q increase with F_T. A little dispersion also exists at high F_T. This result suggests that the mechanical instabilities were not suppressed completely. Such characteristics are also observed in the results for $I_p = 380$, 600, 770 A_{peak}. In the case of $I_p = 940$ A_{peak}, I_q is almost constant at the tension of more than 19.2 N, i.e., the mechanical instabilities were

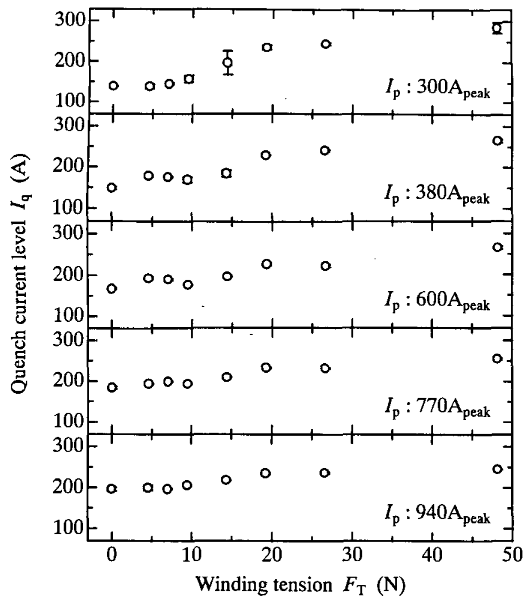


Fig. 6. Quench current level I_q as a function of winding tension F_T measured for SC cable.

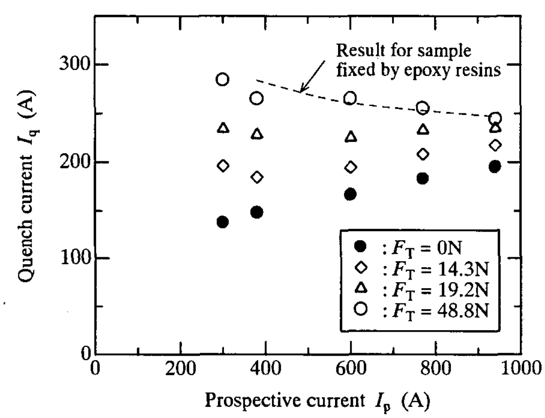


Fig. 7. Dependence of quench current level I_q on prospective current level I_p measured for SC cable.

suppressed by $F_T \geq 19.2$ N.

Fig. 7 indicates dependence of I_q on I_p measured under the conditions of $F_T = 0$, 14.3, 19.2 and 48.8 N together with the results for the sample completely fixed by epoxy resins. The results in this figure are similar to those for the SC wire, i.e., I_q rises with I_p for lower F_T, while I_q decrease with I_p for high F_T. Particularly, the results for $F_T = 48.8$ N almost agree with those for the sample completely fixed by epoxy resins. Therefore, in this case, the quench current degradation is almost suppressed.

The SC cable adopted is not long in length (905 mm) and has high resistive matrix. In such cable, the inherent I_q essentially decreases with I_p or the current increasing rate $\mathrm{d}i/\mathrm{d}t$ because the current commutation among the strands after the quench is completed for very short period[4].

D. Comparison between Winding Tension and Electromagnetic Force

It is experimentally found that the quench current degradation due to the mechanical disturbance was suppressed by F_T of 9.4 N at least for the SC wire. In the case of the SC cable, the mechanical instabilities were not suppressed by F_T of 48.8 N completely except the experimental condition of $I_p = 940$ A$_{peak}$. The winding tensions of 9.4 and 48.8 N correspond to the radial forces F_r of 188 and 976 N/m, respectively. These magnitude are much higher than the maximum electromagnetic force F_m at $i = I_q$ calculated using (2). For example, in the case of $I_q = 72$ A which is measured for the SC wire, F_m is calculated to be 1.1 N/m. In the case of $I_q = 287$ A for the SC cable, F_m is equal to 16.5 N/m.

In our experimental bobbin, the edge part of the winding is partially supported by the bobbin and may move more easily than the central part of the winding. This may result in that the sufficient high winding tension is required to completely suppress the mechanical instabilities.

In the future, we should carry out the detailed investigation on the magnitude of the winding tension which can completely suppress the mechanical instabilities by estimating the minimum quench energy and so on.

V. Conclusions

Dependence of quench characteristics of an a.c. Nb-Ti SC wire and cable on the winding tension were discussed. A new type of experimental bobbin have been developed to uniformly apply the tension to the sample and to be adjustable for the winding tension from the outside of the cryostat. We measured the a.c. (60 Hz) quench current level I_q under the different conditions of winding tension F_T and prospective current level I_p. The quench current degradation due to the mechanical instabilities were suppressed by high I_p or fast $\mathrm{d}i/\mathrm{d}t$ as well as high F_T in both the SC wire and the SC cable. Furthermore, it is experimentally found that I_q increases with I_p ($\mathrm{d}i/\mathrm{d}t$) in the case with the mechanical disturbance.

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