Position of Quench Initiation in 6 kV-200 A Class Superconducting Fault Current Limiter

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***Abstract*—We have developed a 6 kV - 200 A class superconducting fault current limiter (SC-FCL). The SC-FCL has eight co-axial coils connected in order to minimize total inductance. In the present paper, taking consideration of the self-magnetic field in the SC-FCL, we discussed the position of quench initiation. We calculated spatial profiles of the strength and the direction of the self-magnetic field in the SC-FCL. As a result, the self-magnetic field is applied to almost sections of the superconducting cable (SC cable) in transverse direction (maximum value : 6.42×10^{-4} T/A). The connective section between coils, however, suffers the magnetic field with longitudinal component of 3.34×10^{-4}T/A. In the case of a short sample of the SC cable which was used for the SC-FCL, the quench current levels were measured to decrease at the rate of 40 A per 0.1 T in transverse magnetic field and 100 A per 0.1 T in longitudinal one. Taking these results into consideration, we pointed out that the quench may be initiated in the connective section between coils where the self magnetic field is applied in the longitudinal direction.**

I. INTRODUCTION

A superconducting (SC) power apparatus consists of coils wound with multiply-twisted a.c. SC cables. The quench current level of the SC power apparatus must be influenced by the self-magnetic field induced with the current carried in the windings. The quench current level I_q of the superconductor is well known to depend on the magnetic flux density B. The $I_q - B$ characteristics of a multifilamentary superconductor or strand differ among different directions of the magnetic field applied to the conductor [1].

In power apparatus consisting of co-axial coils such as transformers or fault current limiters, the self-magnetic field is applied in transverse direction to almost sections of SC cable. In such section, the longitudinal component of the applied magnetic field to the strand is not very large. However, in the connective section between coils, the SC cable can be exposed to the self-magnetic field with large longitudinal component. To investigate the influence of the self-magnetic field in SC apparatus on the quench, it is necessary to grasp not only the strength but also the direction of self-magnetic field applied to the SC cable.

TABLE I
SPECIFICATION OF SC STRAND

Parameter	Value
SC strand diameter	ϕ0.193mm
CuNi strand diameter	ϕ0.193mm
NbTi : Cu : CuNi ratio	1 : 0 : 1.83
NbTi filament number	23,749
NbTi filament diameter	ϕ0.744μm
Twist pitch	1.83mm(S twisted)
Electric insulation	None

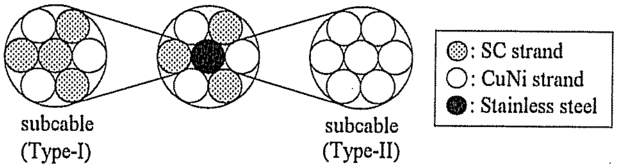

Fig. 1. Cross-sectional view of SC cable. Type-I subcable is formed with four SC strands and three CuNi strands. Type-II subcable is formed with seven CuNi strands.

This paper discusses the position of quench initiation in a 6 kV - 200 A class superconducting fault current limiter (SC-FCL) developed by us. Firstly, we analyzed the spatial distribution of the self-magnetic field in the SC-FCL to estimate the strength and the direction of magnetic field applied to the SC cable. Secondly, we measured the $I_q - B$ characteristics of short sample whose specification was same as the SC cable used for the SC-FCL. The experiments were carried out in three cases with the external magnetic field applied in the same, the transverse and the opposite direction to the current carried in the sample. Taking derived results into consideration, we predicted the position of quench initiation and quench current level of the SC-FCL.

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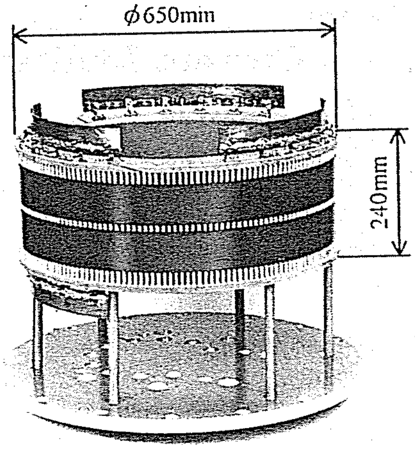


Fig. 2. External view of 6kV-200A class SC-FCL.

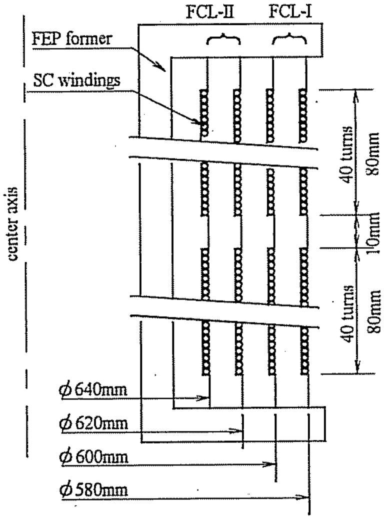


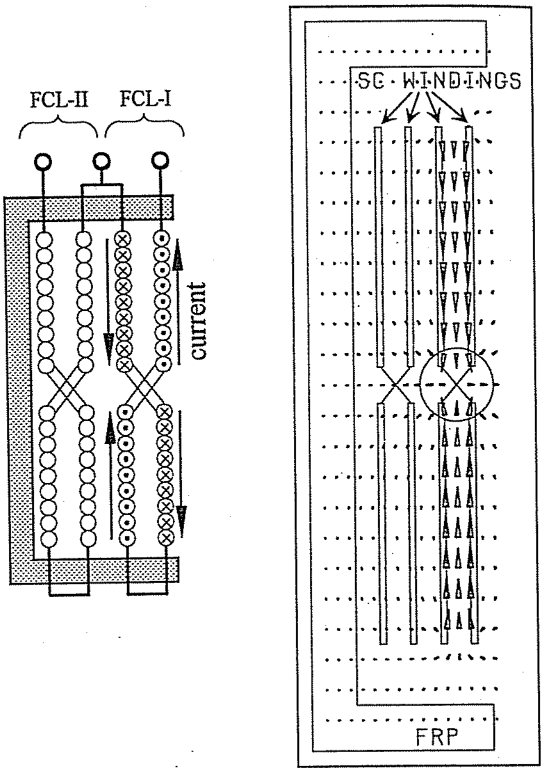
Fig. 3. Structure of windings.

II. Self-Magnetic Field in the SC-FCL

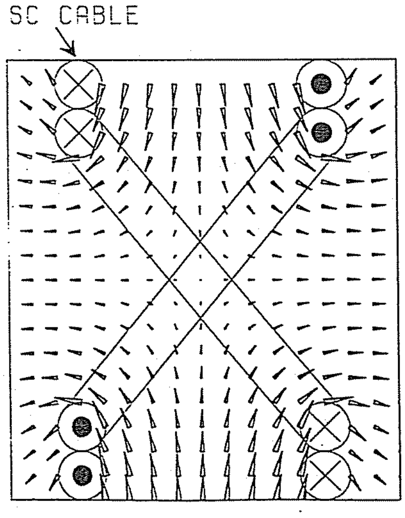
A. *Structure of 6 kV - 200 A Class SC-FCL*

Table I summarizes specification of the SC strand used for the 6 kV - 200 A class SC-FCL. Fig. 1 shows the cross-sectional view of the SC cable with the strands. The SC cable consists of three SC subcables (Type-I) and three CuNi subcables (Type-II) which are twisted around a stainless wire. The Type-I subcable is formed with four SC strands and three CuNi strands. The Type-II subcable is formed with seven CuNi strands.

Fig. 2 and 3 show the external view of the SC-FCL and the structure of windings, respectively. The SC-FCL has eight co-axial coils connected each other in order to minimize total inductance. The SC-FCL transits to normal conducting state at once if an overcurrent passes through it. The produced normal conducting resistance suppresses the overcurrent. The SC-FCL can be divided into FCL-I and FCL-II. FCL-I and FCL-II are structured with four outer coils and four inner coils, respectively. The current limiting level of the FCL-I was 368 A in instantaneous value [2].



(a) Current direction (b) Spatial distribution of magnetic flux density.



(c) Enlarged figure of connective section between coils.

Fig. 4. Calculated spatial distribution of magnetic flux density in FCL-I.

B. *Self-Magnetic Field*

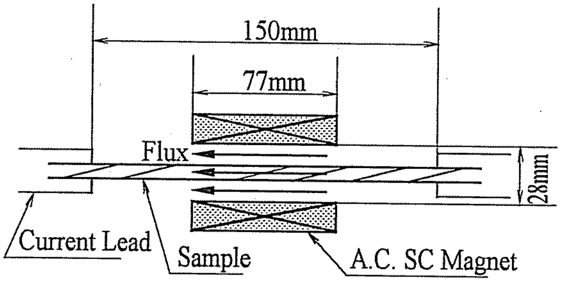
The spatial profile of the self-magnetic field induced by the current in the windings was computed only for the FCL-I using the Biot-Savart's law [3]. Fig. 4 (a) indicates the direction of the supplied current. Fig. 4 (b) shows the calculation result of spatial distribution of magnetic flux density. The size and direction of marks Δ

correspond to the magnitude and direction of magnetic flux density, respectively. The magnetic field is applied to almost sections of the SC cable in transverse direction to the SC cable because the SC-FCL consists of co-axial coils. The maximum value of the magnetic flux density whose direction is transverse is 6.42×10^{-4}T/A.

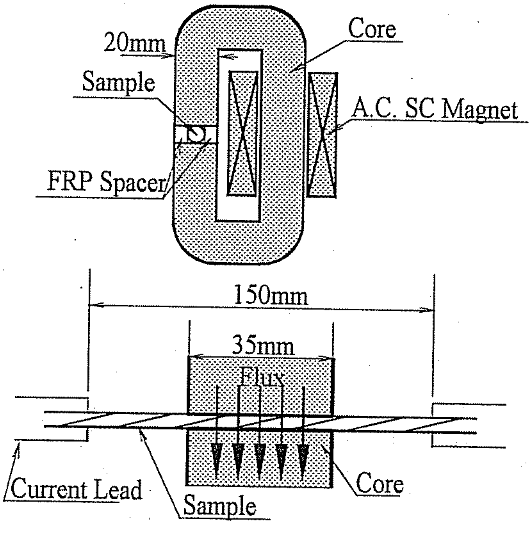
Fig. 4 (c) enlarges the part enclosed by open circle in Fig. 4 (b). In this part, the magnetic field is obliquely applied on the crossing cables connecting each coil of the SC-FCL. The maximum value of the parallel component of the magnetic flux density is 3.34×10^{-4}T/A, which is about half of the maximum value of transverse magnetic flux density.

III. QUENCH CURRENT LEVEL OF SC CABLE EXPOSED TO MAGNETIC FIELD

To estimate the influence of self-magnetic field on quench current level of the SC-FCL, the a.c. quench current level of the SC cable used for the SC-FCL was measured as functions of magnitude and direction of an a.c. magnetic flux density.



(a) Longitudinal direction.



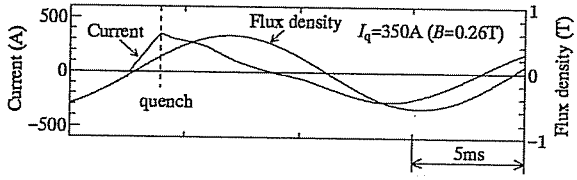
(b) Transverse direction.

Fig. 5. Experimental set-up for application of magnetic field.

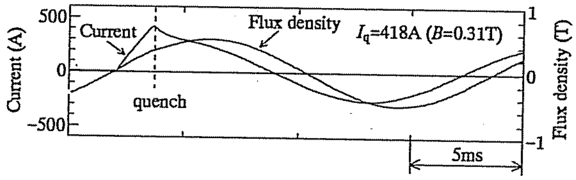
A. *Experimental Set-up and Procedure*

We measured the quench current level of a short sample whose specification was same as the SC cable used for the SC-FCL. The sample conductor is 150 mm in length. The experiments were carried out in three cases with the external magnetic field applied to the sample in the same, transverse and opposite direction to that of the transport current. Fig. 5 shows an experimental set-up. In Fig. 5 (a), the magnetic field is applied parallel to the sample conductor by the a.c. SC magnet. Arranging the sample along the center axis of the a.c. SC magnet, we applied the magnetic field in same or opposite direction to the sample. Fig. 5 (b) corresponds to the case with the transverse direction magnetic field. The center portion of the sample conductor is inserted into the air gap of an iron core. The magnetic field is applied in transverse direction by a magnetizing a.c. SC coil.

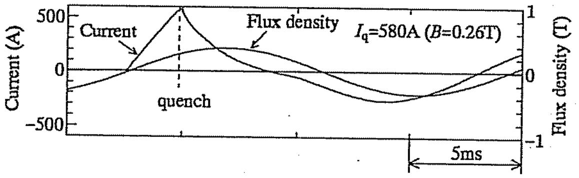
After an external magnetic field is applied to the sample, the overcurrent with prospective current of 820 A_{peak} is supplied suddenly to cause quench. Fig. 6 shows examples of the waveforms of the current in the SC cable and magnetic flux density. The both frequencies of magnetic field and current are 60 Hz and the phase difference between magnetic field and current is adjusted to be 0°. From this figure, the quench current level is found to be 350 A at B=0.26 T in same direction, 418 A at B=0.31 T in transverse direction and 580 A at B=0.26 T in opposite direction. The quench current were measured for different magnetic flux densities.



(a) Same direction.



(b) Transverse direction.



(c) Opposite direction.

Fig. 6. Examples of waveforms of current in sample conductor and applied magnetic flux density.

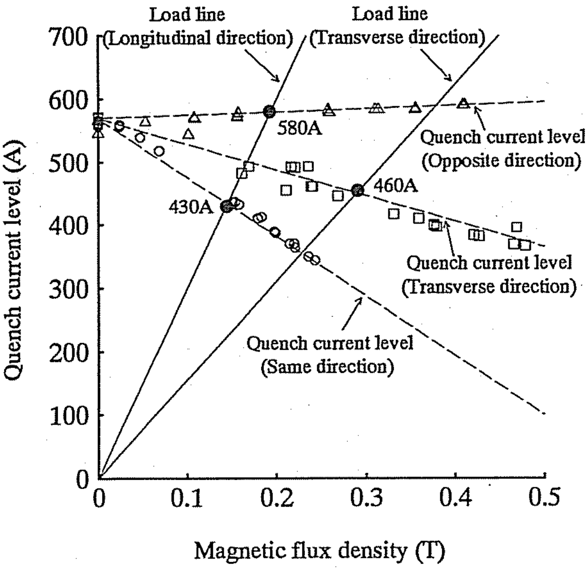


Fig. 7. Dependence of quench current level of sample on applied magnetic field. ○ : same direction magnetic field, □ : transverse direction magnetic field, △ : opposite direction magnetic field.

B. Dependence of Quench Current on Magnetic Field

Fig. 7 shows quench current levels as a function of the strength of the applied magnetic field. Both quench current level and magnetic field are represented in instantaneous values. The circles correspond to quench current levels of the sample exposed to same direction magnetic field. The squares and the triangles indicate the results in cases of transverse and opposite direction magnetic field, respectively.

The quench current level of the sample conductor is about 570 A without the applied magnetic field. In the case of the same direction magnetic field, the quench current level decreases with an increase in the strength of the applied magnetic field at the rate of 100 A per 0.1 T. This decreasing rate is largest in the three cases. In the case of transverse direction magnetic field, the quench current level also decreases with an increase in the magnetic field strength. The decreasing rate is 40 A per 0.1 T and only half of that in the same direction magnetic field. In the case of opposite direction, the quench current level increases slightly with a rise in the strength of the magnetic field.

IV. POSITION OF QUENCH INITIATION IN THE SC-FCL

Fig. 7 also shows two load lines of the winding of the SC-FCL for magnetic field whose direction is longitudinal and transverse. The load line indicates the relation between the current in the winding and the maximum density of the self-magnetic flux induced by the load current. If the quench current level of the SC-FCL is determined by its self-magnetic field, the intersection point of load line and quench current level line represents the quench current level of the SC-FCL.

The quench current level is estimated to be 430 A from the magnetic field applied in same direction. This quench current level is smaller than the value of 460 A decided by the transverse magnetic field although the strength of longitudinal magnetic field is smaller than that of transverse one. This is because the magnetic field in the same direction to the load current reduces the quench current level more greatly than that in transverse one.

Consequently, in the SC-FCL developed by us, the quench is considered to be initiated in the connective section between coils which is exposed to the longitudinal magnetic field. It is also important for the design of power apparatus such as transformers, reactors and current limiters that the joints of coils are arranged to minimize the longitudinal component of self-magnetic field.

V. CONCLUSION

The spatial profile of the magnetic field is estimated for the 6 kV - 200 A class superconducting fault current limiter (SC-FCL) developed by us. The self-magnetic field is applied in transverse direction to the almost regions of the SC cable. The maximum value of transverse magnetic flux density applying to the SC cable is 6.24×10^{-4}T/A. However, in the connective section between coils, the magnetic field with longitudinal component is applied to the SC cable. The maximum value is 3.34×10^{-4}T/A and half of that of transverse magnetic field. On the other hand, we measured the a.c. quench current level of short sample in the external a.c. magnetic field. In the experiment, the external magnetic field were applied in the same, transverse and opposite direction to that of the transport current of sample conductor. The quench current level decreases linearly with an increase in the strength of same direction magnetic field at the rate of 100 A per 0.1 T. The decreasing rate is largest in three cases. The decreasing rate for transverse direction magnetic field is 40 A per 0.1 T and is about half of that for the same direction magnetic field. In the case of opposite direction, the quench current level increase slightly with a rise in the strength of the magnetic field. Taking these results into consideration, it is pointed out that the quench may be initiated in the connective section between coils where the self-magnetic field is applied in the same direction to that of the current.

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