

Quench Current Level - Time Characteristics of AC Insulated Multi-strand Superconducting Cables

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Abstract—The quench current level of a multi-strand superconducting (SC) cable for a.c. use varies with the magnitude of a.c. overcurrent. We have defined this feature as the quench current - time characteristic, i.e. the $I_q - t$ characteristic. In this paper, we experimentally compared the $I_q - t$ characteristics of two kinds of SC cables, with and without a low resistive stabilizing matrix. The results proved that the difference $I_q - t$ characteristics were caused by the difference of the current redistribution process where each SC strand quenches successively. Furthermore, it was pointed out by numerical simulation using an equivalent electrical circuit model that the difference in resistivity of SC strand could be the reason for the various $I_q - t$ characteristics.

I. INTRODUCTION

Superconducting (SC) apparatus loses its superconductivity if the carrying current exceeds a certain critical current level, i.e. the quench current level. This means that the overcurrent in a electric power system may drive SC apparatus to the normal conducting state. The overcurrents caused by the system faults or some system operations have different waveforms in the magnitude and shape etc.. In our previous paper[1], it has been proven that the a.c. quench current level I_q varies with the increase in the magnitude of a suddenly supplied overcurrent. We have defined this feature as the quench current-time ($I_q - t$) characteristic referencing to the voltage-time ($V - t$) characteristic in a gap flashover due to overvoltage surges.

On the other hand, there are many types of superconducting cables with different compositions. We can roughly classify multi-strand SC cables in four categories according to whether the strands are electrically insulated from each other or not and whether a low resistive stabilizing matrix (usually copper) is used or not. In the present paper, we experimentally and numerically compare the difference in the $I_q - t$ characteristics of the SC cables with and without the copper stabilizing matrix.

Manuscript received August 26, 1996.

This work was supported by a Grant-in-Aid for Scientific Research, Experiment Research (C) (No.07050324) from the Ministry of Education, Science and Culture, Japan.

TABLE I

TECHNICAL DATA ON SC CABLE

Parameters	Cable I	Cable II
Strand electrically insulated	Yes	Yes
Copper matrix	None	Yes
SC-STRAND		
Diameter of strand (mm)	0.13	0.22
Number of filaments	15367	39546
Diameter of filament (μm)	0.46	0.55
NbTi : Cu : CuNi	1 : 0 : 2.3	1 : 1.2 : 1.7
Pitch of twist (mm)	0.98	2.3
Electric insulation	PVF	PVF
CABLE		
Number of SC strands	6	7
Number of normal strands	1	0
Pitch of twist (mm)	3.05	7
Diameter of cable	0.4	0.67
Length of cable (m)	7	7
Normal resistance (Ω at 300K)	28	2

II. EXPERIMENTAL ARRANGEMENT

A. SC cables adopted

Table I summarizes the technical data on the SC cables used in the experiments. Cable-I has CuNi matrix only, but Cable-II has copper stabilizing and CuNi matrix. Both Cable-I and -II are composed of seven strands cabled in a "six around one" pattern. The center strand of Cable-I is a CuNi one but that of Cable-II is SC one. The center strand was not connected to power source in the experiments. This is because following reasons : 1) It is necessary to compare the results obtained in both SC cables under same conditions. 2) It is known that if the center strand is a SC one, current in the center one flows in an inverse direction comparing to the external SC strands and this reduces the a.c. quench current level of the SC cable[2].

B. Circuit diagram

The circuit diagram is shown here in Fig. 1. The frequency of the power source was 60Hz. The peak value of the prospective current I_{pro} (an AC current which would be supplied to the cable if it never went normal) was first adjusted to a specified value by a voltage regulator. Then the overcurrent was supplied to the SC sample by turning on a pair of thyristors. The turn-on phase angle was adjusted so as to contain no d.c. transient component in the supplied current. The peak value of the I_{pro} was changed

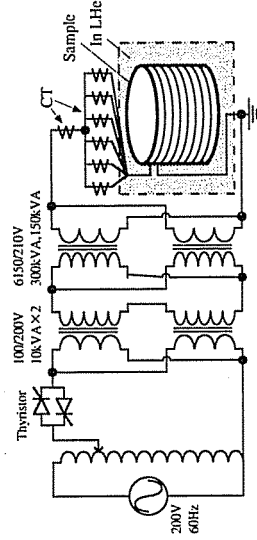


Fig. 1. Experimental circuit diagram for supplying overcurrent.

up to about 8 ~ 10 times of the lowest prospective current.

As shown in the right side of Fig. 1, the SC cable 7m long was wound around an FRP former with a diameter of 100mm in a bifilar way as to minimize the inductance[1]. The wound SC cable was fixed on the surface of the FRP former by epoxy resin, which was spread so thin that every strand of the SC cable could be effectively cooled by liquefied helium. To measure the current in each individual SC strand, one end of the SC cable was untwisted into six separate SC strands (except the center one), which were connected with separate power leads. The impedance of these power leads and their differences were kept as small as possible.

III. QUENCH CURRENT-TIME CHARACTERISTICS

Figures 2 and 3 show current waveforms measured in Cable-I and Cable-II respectively. The a.c. quench current levels (I_q) of the SC cables are shown by filled circles. They were defined as the instantaneous value of current when an abrupt increase in the voltage across the sample was detected. From these figures, it is clear that the I_q 's are not constant but vary in accordance to the magnitude of the overcurrent.

In the case of Cable-I, the I_q was almost constant (around 85 A) at small values of I_{pro} . Then, it gradually rose with an increase in the peak value of the I_{pro} . The I_q increased by only 12% even if the peak value of the I_{pro} increased from 90 A_{0-p} to 885 A_{0-p} .

Cable-II, on the other hand, had a steep rise in the level of the I_q when the peak value of the I_{pro} was small. The I_q increased by about 47% as the peak value of the I_{pro} increased from the lowest I_{pro} of 260 A_{0-p} to the largest I_{pro} of 2000 A_{0-p} . As mentioned above, the $I_q - t$ characteristics are quite different depending on whether strands have low resistive copper matrix or not.

In the case of Cable-I, the I_q 's were nearly equal to the peak values of the limited current waveform. The current abruptly dropped to a low level as soon as the SC cable changed to the normal state. This was caused by the absence of the copper stabilizing matrix in the strands. A large normal resistance appears after Cable-I changed from the superconducting state to the normal one. On the other hand, in the case of Cable-II, the I_q 's shown by filled circles were smaller than the peak values of the measured current waveform. The normal resistance of Cable-II is so small because of the copper matrix, that the current

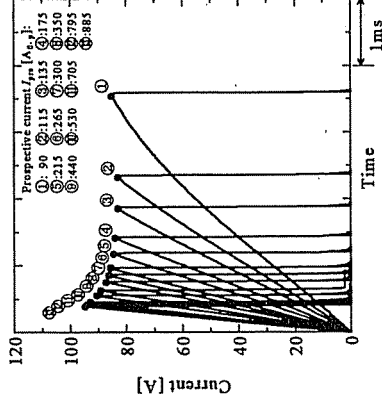


Fig. 2. Measured waveforms of current limited by Cable-I.

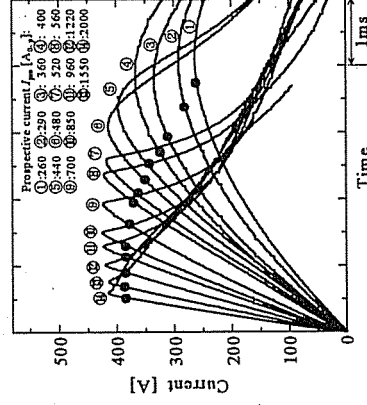


Fig. 3. Measured waveforms of current limited by Cable-II.

continue to increase through the copper matrix even if the SC cable is in the normal state.

IV. QUENCH DEVELOPING PROCESS IN SC CABLES

Significant differences of the $I_q - t$ characteristics between two kinds of SC cables were found in our experiments. To explain these differences, the quench developing processes in these SC cables were experimentally investigated. Figures 4 and 5 show examples of the quench developing processes in Cable-I and Cable-II respectively. In each figure, there are waveforms of the current in six SC strands as well as that of the total current in the SC cable. The SC strands are numbered in a clockwise direction from strand-1 as shown in Figs. 4 and 5. Difference in quench developing in the six strands can be seen in the figures.

As shown in Fig. 4, the current in strand-1 began to decrease at time t_1 . In other word, only strand-1 initially changed to the normal state at time t_1 , while the other strands were still in the superconducting state. The reduction in the current in strand-1 was redistributed to the other strands. Then, strands-2, -6, -3 and -4 changed to the normal conducting state successively. Finally, strand-5 lost superconductivity at time t_q . At this time, all SC strands have changed to the normal state, and Cable-I can be regarded as having fallen into the normal state as a whole. The instantaneous value of the total current at t_1 was defined here as the initial quench current level (I_{qini}), and that at t_q as the final quench current level (I_q) of