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 different $I_q - t$ 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.

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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

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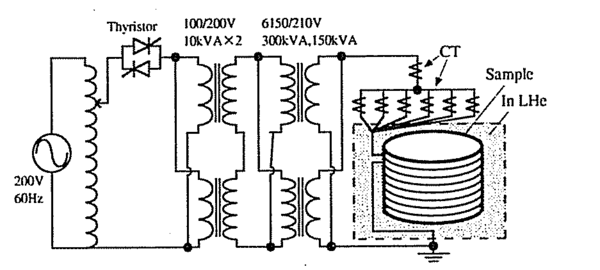

Fig. 1. Experimental circuit diagram for supplying overcurrent.

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 260A_{0-p} to the largest I_{pro} of 2000A_{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

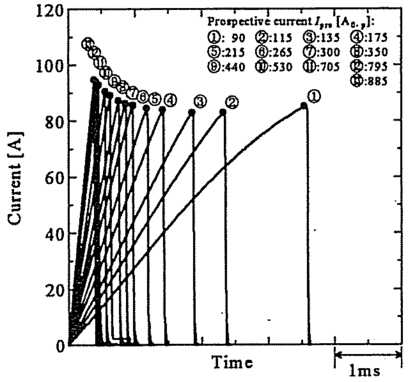

Fig. 2. Measured waveforms of current limited by Cable-I.

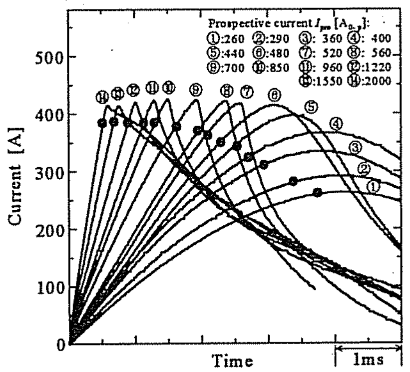

Fig. 3. Measured waveforms of current limited by Cable-II.

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_i. In other word, only strand-1 initially changed to the normal state at time t_i, 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_i 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 to the power supply are taken into account as the inductance L and resistance R in series with the power supply voltage V_G. The R_{cm} is the contact resistance between current leads and each strand, and the $M_{mm} = L_m$ is self-inductance of strand m, M_{mn} ($m \neq n$) mutual inductance between strand m and n. The r_m is resistance of normal region in strand m produced by the transition to the normal conducting state. The r_m of Cable-I is larger by a factor of 10^3 than that of Cable-II.

Usually, the time variation of the r_m, i.e. the propagation of the normal zone along the strands could be numerically evaluated by solving simultaneous equations of heat balance[3][4]. In our simulation, however, we dealt with the increment of resistance Δr_m as a function of the instantaneous value of the current in the strand. The polynomial for the Δr_m was chosen so that the caluculated waveforms of the current redistribution in the six strands agreed with the measured ones at the lowest prospective current of Cable-I.

It was derived from the simulation for Cable-I that the values of the delay in time Δt remained almost constant around 100 μsec for all I_{pro}, which is represented by the solid line in Fig. 6. On the other hand, the similar calculations for Cable-II were carried out by reducing the r_m by a factor of 10^{-3}. It was derived that the Δt decreased nonlinearly with the increase in the I_{pro}, which is indicated by the dotted curve.

As shown in this figure, it was pointed out that the difference of the $\Delta t - I_{pro}$ characteristics between Cable-I and Cable-II was given by the difference of the normal resistivity of the strands. The higher resistivity brought about the higher speed of the current redistribution among strands after the quench so that the small Δt was derived in Cable-I.

VI. Discussion

Here, we consider the qualitative dependence of the I_q on the Δt. In Fig. 8, three currents are shown by the solid curves which have different peak values with same frequency. It is well known that the quench current level of the SC strand decreases with increase in the peak value of the current[5]. The initial quench current level (I_{qini}) corresponding to the quench current of the SC strand are plotted by the square in the figure. As shown in the curve for I_{pro1}, during the Δt_1, the current I_{pro1} increases from the I_{qini} marked by the square to the I_{q1} indicated by the circle. Similarly, currents I_{pro2} and I_{pro3} increase from the square to the circle during Δt_2 and Δt_3 respectively. If $\Delta t_1 = \Delta t_2 = \Delta t_3$, the final quench current level marked by circles may be nearly equal for the I_{pro1} and I_{pro2}, but is much greater for the I_{pro3}. The a.c. quench current levels I_q may increase as shown by the thin dotted curve. This curve indicates the $I_q - t$ characteristic of Cable-I.

On the other hand, for the case of $\Delta t_a > \Delta t_b > \Delta t_c = \Delta t_3$, the magnitude of the I_q is marked by the triangles in the figure. The triangles indicate the $I_q - t$ of Cable-II.

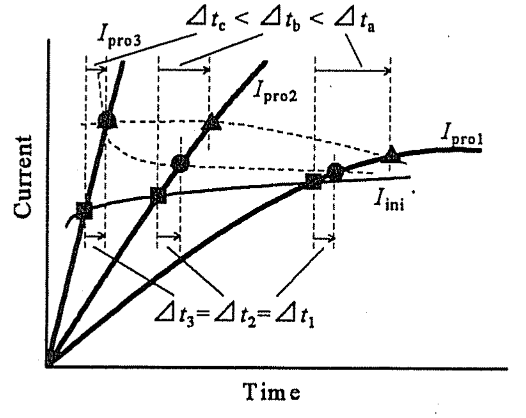

Fig. 8. Difference of influence of Δt on I_{q2} of SC cable.

VII. Conclusion

Following aspects were found out in this paper.

- The a.c. quench current levels I_q of two kinds of multi-strand SC cables were measured for sinusoidal overcurrent with different peak values, respectively. The I_q's of two cables varied with the increase in the magnitude of overcurrent. Different $I_q - t$ characteristics were confirmed.
- In the SC cable, all strands did not change to the normal state simultaneously, and the current redistribution took place among the strands. Thus a successive quench developing process appeared with a delay in time Δt. The time Δt characterized the I_q of SC cables.
- The duration of the Δt depends on the speed of the current redistribution among the strands. The speed of the current redistribution is affected by the resistivity of the stabilizing matrix. This was proven using the equivalent electric circuit model.

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