Normal transition in YBCO thin film and its effect on current limiting characteristics

Onishi T., Sasaki K., Kayoda T.

Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

An active method for quenching the whole area of superconducting thin film homogeneously by a pulsed field was investigated. From measurement of the dissipative power triggering off a spontaneous SN (super-to-normal) transition, it is shown that the substrate will affect considerably the SN transition. In the active quenching method, it is revealed that the film carrying 50 Hz transport current over the critical current will be quickly quenched by a pulsed field. A method for producing pulsed field automatically when a transport current exceeds around 1.3 I_c is also proposed and proved.

INTRODUCTION

The various types of fault current limiter (SFCL) have been investigated for application to a reliable and flexible power line system [1]-[4]. The resistive type fault current limiter with YBCO thin film is thought to be one of the promising candidates for the high performance SFCL among them. When an ac transport current increases, however, a sudden normal transition will occur spontaneously at around 2.5 J_c of YBCO film [1]. At such a high current density, a part of the film of lower critical current density may turn into normal state faster than in other part, resulting in damage of the film by a hot spot. In order to avoid such damage, a whole area of YBCO film has to quickly turn into normal state at very early stage of a fault, that is, at a current as close as the critical current density.

In the present study, the dissipative power triggering off spontaneous SN transition of the film was firstly studied as function of frequency of ac current in order to clarify the mechanism of SN transition. Secondary, the experiments on the active quenching of the whole area of superconducting thin film by pulsed fields were conducted. Finally, a method producing a pulsed field automatically at the current over I_c is proposed and proved.

EXPERIMENTAL

The characteristics of the conductors used in the experiments are as follows; the superconductor is YBCO thin film in which the thickness is 300 nm and the width is 2×10^{-3} m, the Au coating thickness is 100 nm and the substrate is sapphire whose thickness is 300μm. The resistivity of Au is 9.21×10^{-9} Ωm at a temperature just above T_c of 87 K. The strip conductor length is 70 mm and the electrodes were soldered over 10 mm at both ends of the conductor by Indium. In the experiments on active quenching, a pulsed field was applied perpendicularly to the film surface. The conductor was set between a split coil in which the size of each coil is 50 mm in diameter, 55 mm high and 52 turns. Each coil was connected in series with separation of 19 mm and a coil current was supplied from 1,940 μF condenser which was charged up to a maximum voltage of 250 V. The field strength is 6.89×10^{-4} T/A. A free-wheeling diode was connected in parallel with the condenser and the split coil. Therefore, the rate of increase of field is as high as 700 T/s and the decay is slow and the pulse width at a half-value is around 2.6 ms.

RESULTS AND DISCUSSIONS

Spontaneous SN transition

The spontaneous SN transition is defined as a transition in which a quench occurs first when a current in the film increases from 0. In this study, the spontaneous one occurred at around 2.2 I_c ~ 2.5 I_c when 50 Hz ac voltage is applied to the film. Typical waveforms of current and voltage are shown in Fig.1 together with the frequency dependency of the flow voltage just before the SN transition. The voltage was measured between the voltage taps of 10 mm separation. J_c of the film is 2.67×10^{10} A/m^2. The SN transition occurred at ~ 0.019 s and the film returned to the flux flow state just after the transition due to the rapid decrease of current, as shown in Fig. 1(a). It is also shown in Fig.1(b) that the flow voltage increases with increasing frequency and hence depends strongly on *dI/dt*.

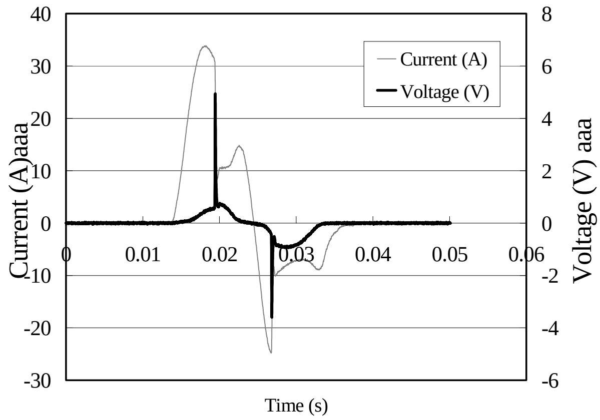
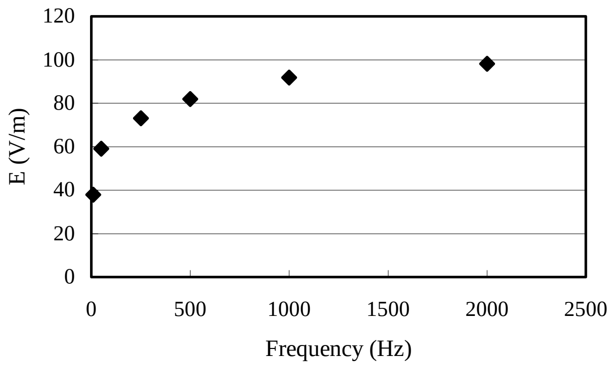


Fig.1. (a) Waveform of flow voltage and current.



Fig, 1 (b) Electric field vs. frequency.

The dissipative instantaneous powers just before the SN transition occurs and the total amount of heat generation until the SN transition occurs were measured as a function of frequency of ac current. In those experiments, the SN transitions during first half cycle of current were taken into account. The result is shown in Fig. 2. The instantaneous power *g* increases with increasing frequency, that is, *dI/dt*, but the total amount of heat *q* decreases

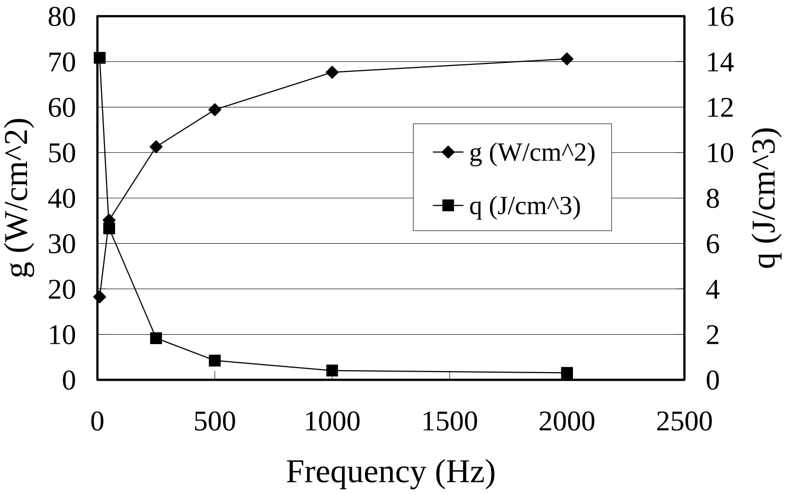


Fig. 2. Dissipative instantaneous power and total amount of heat generation.

rapidly with increasing frequency because the period of time when the heat is generated becomes shorter for higher frequency. The magnitude of heat q_{sc} required to heat the unit volume of YBCO conductor including its substrate over T_c is around 2.4 J/cm^3. From Fig. 2, the heat generation q is less than q_{sc} in frequency range over 250 Hz. This means that only a portion of the substrate near YBCO film will be heated up over T_c in a higher frequency due to the effect of thermal diffusion. Accordingly, it shows that when a disturbance of high frequency is applied to YBCO conductor in order to quench it, the energy may be much less than the one heating up the whole conductor including the substrate over T_c. It is concluded that the mechanism of SN transition will be mainly due to the heating of the conductor including its substrate over T_c.

Active SN transition

AC current of 15 A (peak) which is approximately equal to I_c was supplied to the film in a constant current mode and then a pulsed field was applied perpendicularly to the face when the current attained to a specified value in the range of 0.5 I_c to 1.5 I_c. Quenches were triggered by the pulsed field whose rate of increase is as high as 700 T/s and pulse width at the half value of the amplitude is around 2.6 ms. Typical results on the active SN transitions are shown in Fig. 3 for the cases of B = 220, 254, 338 and 424 mT which are applied at $I = 0.75\ I_c$. The quenches occurred at around the peak of the current and those SN transition points are shown by the arrow in the figures. The voltage was measured between the voltage taps of 15 mm separation. J_c is 2.54x10^{10} A/m.

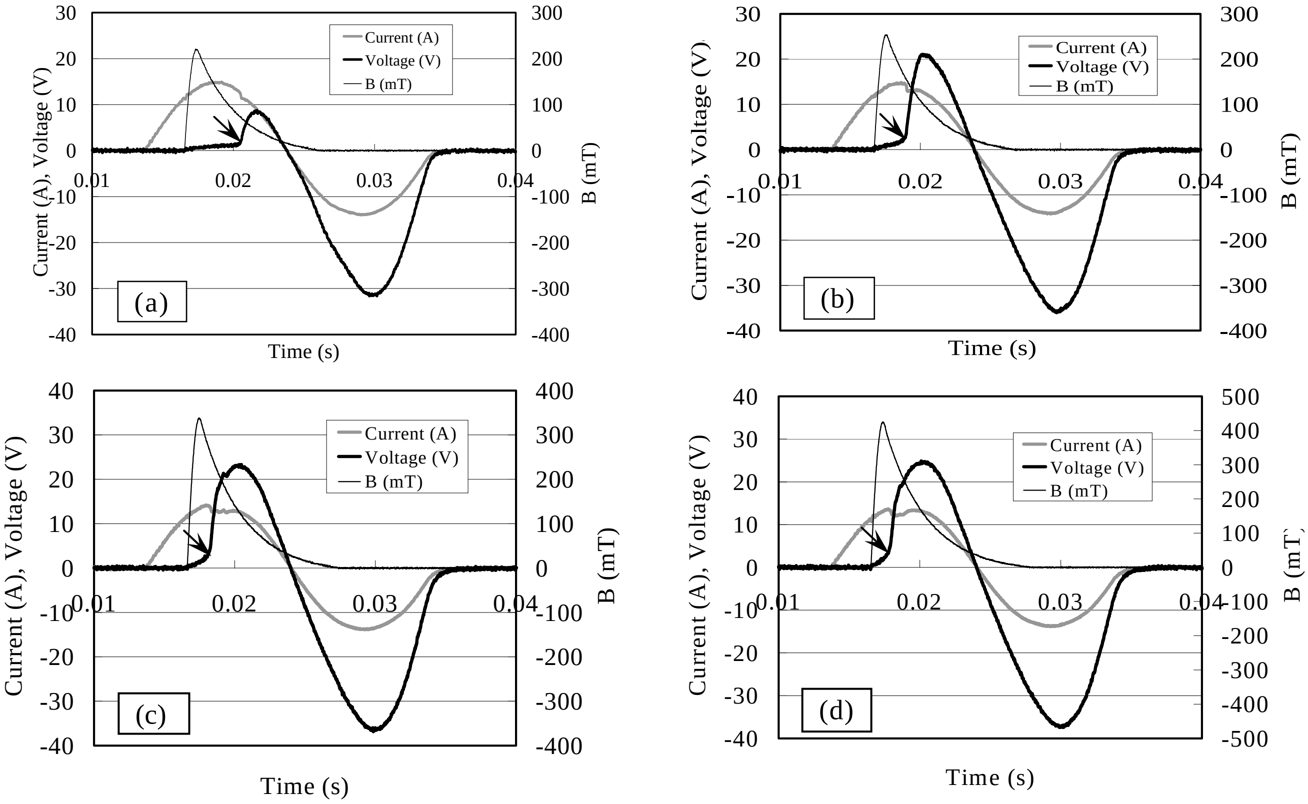


Fig. 3. Active SN transition triggered by pulsed field. (a) B=220 mT, (b) B=254 mT, (c) B=338 mT, (d) B=424 mT.

The result indicates that the whole area of the YBCO film used for, for example, a fault current limiter can be quenched quickly and homogeneously by the pulsed field at a current slightly larger than the rating current of FCL, which is usually designed to be 0.9 I_c~ 0.95 I_c. When the field of 220 mT is applied, the electric field of 50 V/m is generated at a transport current density J which is equal to J_c, as shown in E - J curves in Fig. 4. Therefore, the calculated heat generation by the pulsed field is estimated to be over 3 J/cm^3 per unit conductor volume. Since this value is almost the same as q_{sc}, the conductor can be heated over T_c by the field above 220 mT. The total amount of heat and time before SN transition starts were obtained as a function of field strength by using the data in Fig.3 and is plotted in Fig.5 in case of I_{peak} = 15 A. It was found that the heat and time become longer with decreasing field and there occurred no SN transition below B = 220 mT. The reason is mainly due to the cooling effect. It occurred when I_{peak} was increased to 20 A (~ 1.3 I_c) even in case of B = 120 mT because the heat generation increases with increasing current. Therefore, the field strength of less than 220 mT will be sufficient for quenching the film for the

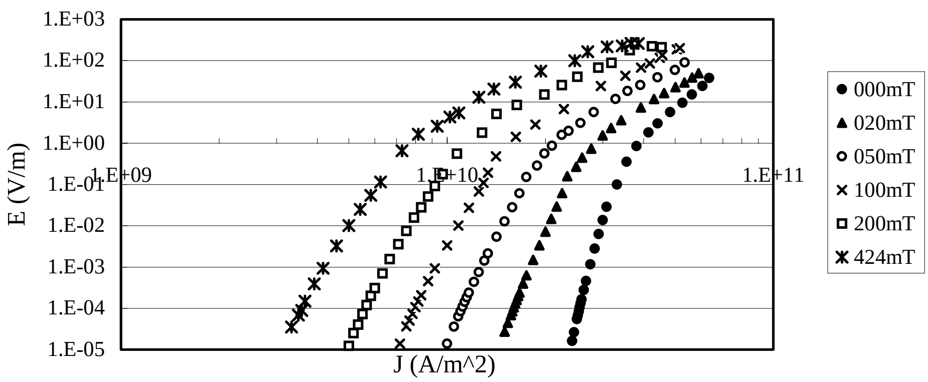


Fig. 4. E - J characteristics of YBCO thin film.

case of $I_{peak} > 1.3\ I_c$. The amount of heat for quenching is 3 ~ 4 J/cm^3, which is almost equal q_{sc}, for the fields except 220 mT. For the case of 220 mT, the heat generation is small and hence more energy will be required for quenching because a fairly large part of energy generated is cooled by liquid nitrogen. These considerations point out that the film can be easily quenched by the heat disturbance of the order of q_{sc} when the peak current of 1.3 I_c or more flows in the film.

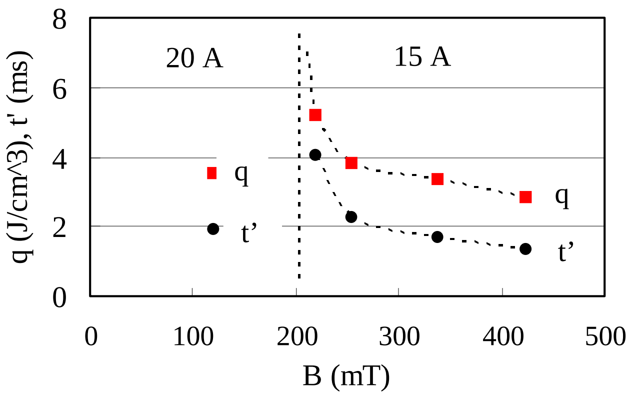


Fig. 5. Field dependency of q and t'.

Automatic generation of pulsed field

A method in which the energy stored in a condenser is discharged automatically to a pulsed coil and produces a pulsed field was investigated. A SCR is automatically fired when the current flowing in the conductor attains to a prescribed value in the range of (1.3~1.5) I_c or more. The circuit used is shown in Fig. 6. A 1,940 μF condenser was first charged to a specified value of voltage. Then, ac current was supplied to the conductor. As an example, when it attained to 1.5 I_c, the flux flow voltage of ~ 0.9 V/m will appear in the conductor, as shown in Fig. 4. In the present experiment where the current of 1.5 I_c is supplied to the film, the voltage of 0.015 V appeared across the voltage taps of 15 mm separation. It was amplified to 1 V and then the signal was supplied to the gate of the SCR. The condenser was successfully discharged and hence a pulsed coil was produced automatically. The input to the gate shown in Fig. 6 is effective only for the positive half cycle of ac current. For the negative half cycle, another amplifier will be required but is not shown there.

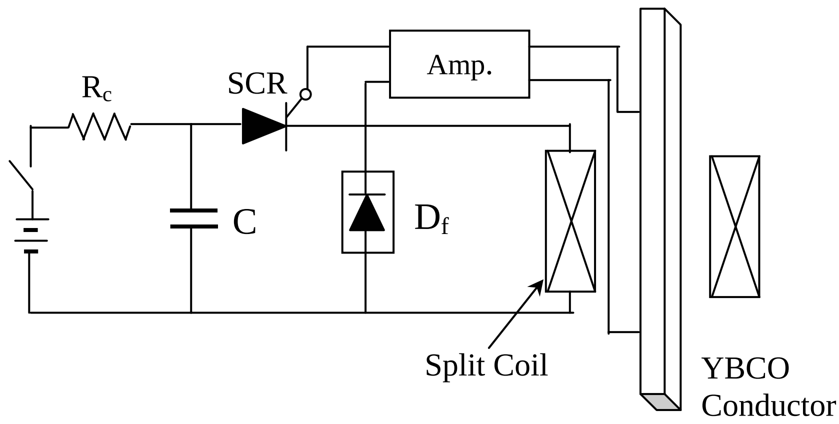


Fig. 6. A circuit for automatic generation of pulsed field.

CONCLUSIONS

The spontaneous and active quench phenomena were investigated. In the spontaneous one, it is shown that 300 nm-YBCO film coated with 100 nm Au suddenly turns into normal state at (2.2 ~ 2.5) I_c. The active quench was also studied and it is revealed that the film carrying 50 Hz transport current larger than around I_c can be quickly quenched by pulsed field. In these studies, it is pointed out that the mechanism of SN transition will be mainly due to the heating of the YBCO film above T_c and its substrate will affect considerably the heating characteristics. A method producing a pulsed field automatically when a transport current exceeds around 1.3 I_c is proposed and proved. This method will be effective for quenching quickly and homogeneously the whole area of thin film which will be used for, for example, the fault current limiter and preventing the hot spot problem.

REFERENCES

[1] Decroux, M., Antognazza, N., Musolino, N., de Chambrier, E., Reymond, S., Triscone, J.-M., Fischer, Φ., Paul, W. and Chen, M., Properties of YBCO films at high current densities: implications for a fault current limiter, IEEE Trans. on Applied Superconductivity (2001) 11(1) 2046-2049

[2] Onishi, T., Sasaki, K. and Akimoto, R., A proposal of fast self-acting and recovering magnetic shield type superconducting fault current limiter and the analyses of their characteristics, Cryogenics (2001) 41 239-243

[3] Boenig H. J., Paice D. A., Fault current Limiter Using a Superconducting Coil, IEEE Trans. on Magnetics (1983) MAG-19 1051-1053

[4] Sasaki, K., Yamagata, A., Nii, A. and Onishi, T., Thermal Design and Performance Tests of a Current Limiter with a Conduction Cooled Nb_3Sn Screen, IEEE Trans. on Applied Superconductivity (2001) 11(1) 2114-2117