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Quench properties of superconducting fault current limiters connected in parallel

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병렬 연결된 초전도 한류소자의 퀜치 특성

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Abstract

We investigated the quench properties of superconducting fault current limiters (SFCLs) connected in parallel. It was carried out as an effort to scale up the current capacity of SFCL systems. SFCLs were based on $YBa_2Cu_3O_7$ films coated in-situ with a gold layer and fabricated by patterning the films into 2 mm wide and 42 cm long meander lines by photolithography. Two SFCLs were connected in parallel and tested with simulated AC fault currents. Initially the current was divided unequally into branches of parallel connection due to unequal resistance of the branches. However, once quench started in the SFCLs, the current oscillated between the branches and then was distributed nearly equally between the branches. In other words, the elements quenched simultaneously. The oscillation amplitude decreased as the source voltage was increased: the oscillation was the most prominent near the quench current. The observed oscillation and the consequent simultaneous quench was understood in terms of quench start and development in the SFCLs.

Keywords : superconducting fault current limiters, $YBa_2Cu_3O_7$, quench, parallel connection

I. Introduction

Superconductors are attractive for fault current limiter applications, because they can transform into the normal state in a few milliseconds, have high resistivity in the normal state, and return to the superconducting state once fault conditions are removed. For that reason there has been active research going on superconducting fault current limiters (SFCLs) [1], [2].

Knowledge on quench properties of superconductors is important for the research and development of SFCLs because quench property essentially determines their performance. Information regarding the quench properties of SFCLs connected in parallel are particularly useful in practical applications in terms of increasing the current capacity of SFCL systems. Since the current capacity of individual current limiters of thin film type is limited, it is necessary to connect them in parallel to increase the current capacity of SFCL systems. Although there is considerable amount of works done on quench properties of low temperature superconductors, there is not much work done on those of high temperature superconductors [3]-[6].

In this work, we investigated the quench properties of two SFCLs connected in parallel. The SFCLs are based on Au/$YBa_2Cu_3O_7$ (YBCO) thin film meander lines. Data were interpreted in terms of quench start and development in SFCLs.

II. Experimental details

SFCLs were fabricated based on 0.3 μm thick YBCO films grown on two-inch diameter sapphire substrates. The YBCO films were purchased from Theva in Germany. In order to disperse the heat generated at hot spots, the YBCO film was coated in situ with a 0.2 μm thick gold layer. The gold layer also plays a role of bypass around hot spots, and protects the film surface from ambient, particularly, moisture. The YBCO film coated with gold was patterned into a 2 mm wide and 42 cm long meander line by photolithography (Fig.1).

Quench characteristics of SFCLs were measured using the circuit shown in Fig. 2. SFCLs used in the experiments were nearly identical both in structure and in superconducting properties. V_o is the source voltage, R_o the standard resistance to protect the circuit, R_F the resistance to simulate the fault resistance, and R_L the load. An AC power supply was used as the voltage source. The fault current was generated by closing switch SW2, and cut off with switch SW1 several cycles after the fault so that the sample would not be subjected to fault currents for unnecessarily long times. Voltages across SFCLs and the current were measured simultaneously with a multi-channel data acquisition system. During the measurement the sample was immersed in liquid nitrogen for effective cooling.

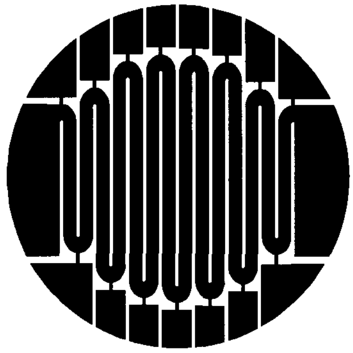

Fig. 1. The pattern of individual thin film fault current limiters used in this experiment.

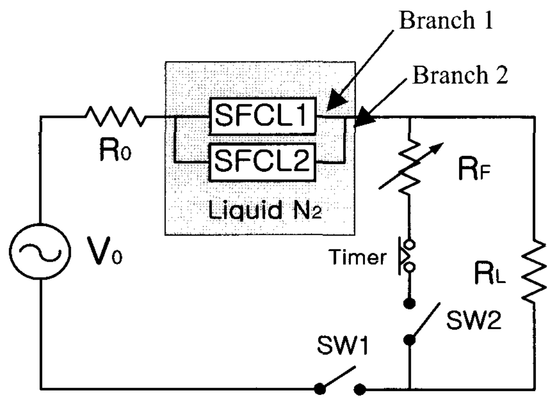

Fig. 2. A schematic of the quench property measurement circuit.

III. Results and discussion

Figure 3 shows the current and the resistance of SFCLs connected in parallel at various source voltages. Fault was started at 2 msec. At 30 V_{rms} (Fig. 3(a)), the current was the same as that without an SFCL in the circuit because the peak current was below quench current, at which quench starts. The result that I_1, the current in branch 1 of Fig. 2 was larger than I_2 indicates that the resistance of branch 1 was smaller than that of branch 2. The resistance of each branch includes those of wires connecting SFCLs as well as those of SFCLs themselves, R_1 and R_2. At 50 V_{rms}(Fig. 3(b)), I_1 reached quench current first, which was 21 A, and the flux flow resistance appeared in SFCL1. As a result I_1 increased less steeply and I_2 more steeply, which caused I_2 to reach the quench current and flux flow resistance to appear in branch 2 also. When R_1-R_2 became large enough for the resistance of branch 1 to surpass that of branch 2, the current distribution was reversed. As the current decreased after the peak, the resistance decreased and when R_1-R_2 became small enough for the resistance of branch 1 to become smaller than that of branch 2, the current distribution was reversed once again. At 59.3 V_{rms}, the behavior was more or less the same as at 50 V_{rms} (Fig. 3(c)). R_1-R_2 stayed nearly constant and I_1 stayed smaller than I_2 during the whole period when the current was higher

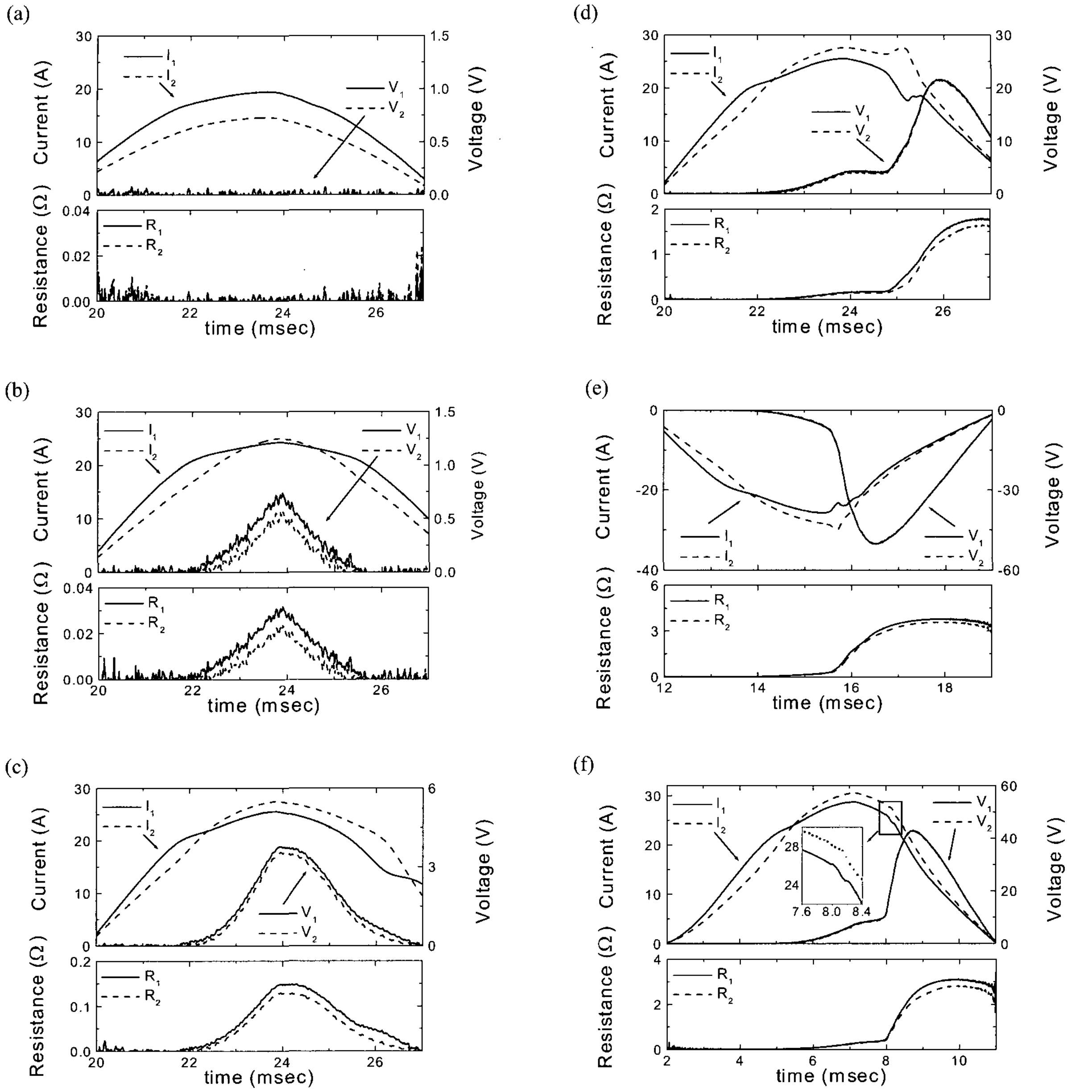

Fig. 3. The current, the voltage, and the resistance of SFCLs connected in parallel at various voltages. (a) 30 V_{rms}, (b) 50 V_{rms}, (c) 59.3 V_{rms}, (d) 59.7 V_{rms}, and (e) 63 V_{rms}, (f) 65 V_{rms}.

than the quench current. No current distribution inversion other than the initial and the final ones was observed.

At 59.7 V_{rms}, the behavior was noticeably different (Fig. 3(d)). As quench started in the third half cycle around at 25 msec, the current and the resistance oscillated. The behavior at 63 V_{rms} was similar except that the current oscillation amplitude decreased noticeably (Fig. 3(e)). At 65 V_{rms}, the amplitude decreased further and the current oscillation was

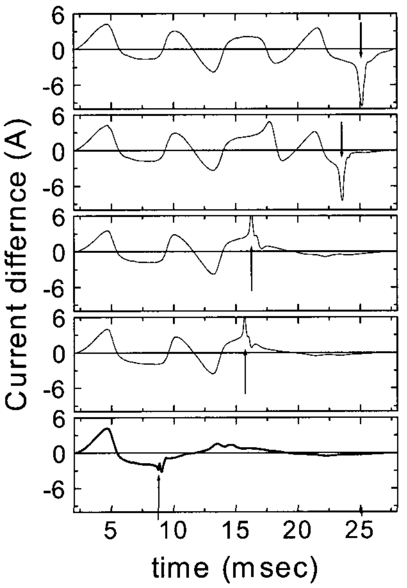

Fig. 4. Current differences, I_1-I_2, at various source voltages, which were 59.7, 61, 62, 63, and 64 V_{rms} from top to bottom. Arrows indicate the positions of current oscillation.

barely noticeable (Fig. 3(f)). The inset provides a magnified view of current oscillation. This trend can be seen more clearly from Fig. 4, which shows the current difference, I_1-I_2, at various source voltages. The current oscillation amplitude decreased with increasing source voltage.

In order to understand the observed phenomenon, power dissipation data at 59.7 V_{rms} are presented in Fig. 5 along with the current and the resistance data. Quench started simultaneously at position A, but R_1, which had been slightly larger than R_2 in the flux flow state, increased faster than R_2 in region A-B. This caused I_1 to decrease steeply, and power dissipation, P_1, to increase slowly in region A-B. This, in turn, slowed down quench propagation in SFCL1 and caused slower increase in R_1 in region B-C (refer to [7] about the propagation of quench in SFCLs based on Au/YBCO thin films). As a result, I_1 increased. After R_1 increased slowly to the point that it became nearly the same as R_2 (position C), R_1 started increasing faster. The increase in I_1 in region B-C meant faster increase of dissipation power in SFCL1, which resulted in faster quench propagation and faster resistance increase in the region beyond C. R_1-R_2 stayed constant after a while. In the region

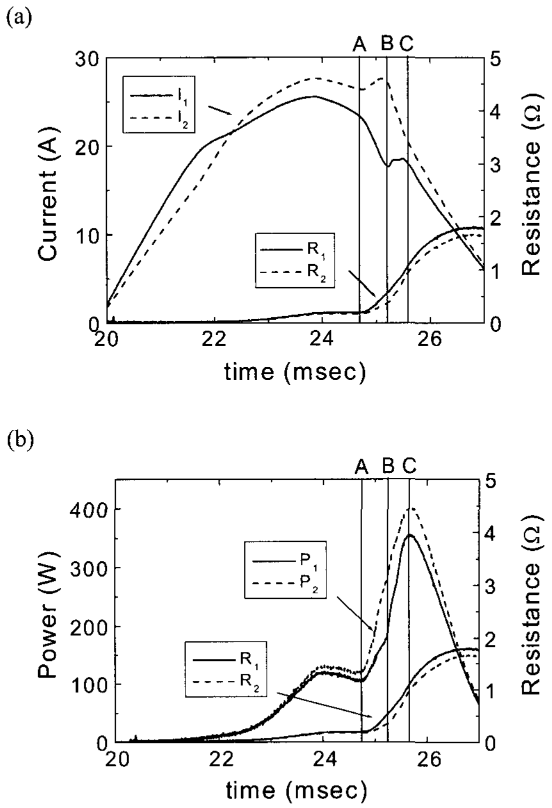

Fig. 5. The quench properties at 59.7 V_{rms}. (a) Current and resistance, (b) power and resistance.

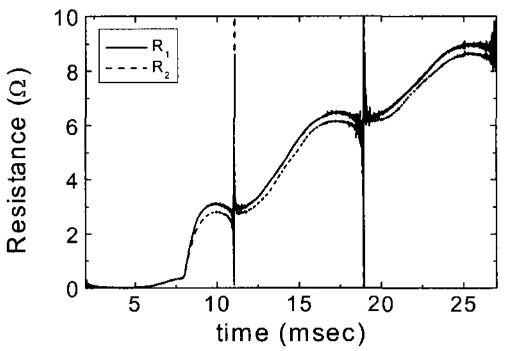

Fig. 6. The resistance of SFCLs connected in parallel at 65 V_{rms}.

beyond C, I_1 also decreased due to AC nature of the source voltage, and the dissipated power was low both in SFCL1 and SFCL2. The amplitude decrease at higher voltages is related to quench propagation speed. At lower source voltages it is low and it takes longer for quench resistance to develop.

Figure 4 shows that, in all cases, the current difference decreased significantly after the current oscillation. Figure 6 shows R_1 and R_2 during three half cycles after the fault started at 2 msec. The resistance difference stayed more or less constant. This phenomenon is technically important because it means that the power dissipation was nearly equally distributed between SFCLs connected in parallel. It prevented the thermal runaway in SFCLs and thereby protected them. The behavior at higher voltages was similar.

III. Conclusions

We investigated the quench properties of superconducting fault current limiters (SFCLs) connected in parallel. The SFCLs were based on Au/YBCO thin films. Initially the current was divided unequally into branches of parallel connection. However, once quench started in the SFCLs, the current oscillated between the branches and then was distributed nearly equally between the branches. That is, SFCLs quenched simultaneously. This is technically important because it prevents thermal runaway in SFCLs. The observed oscillation and the consequent simultaneous quench was understood in terms of quench start and development in the SFCLs.

Acknowledgments

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