Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.6, No.2, (2004), pp.11~14

Quench characteristics of YBCO thin films using magnetic field source for superconducting fault current limiters

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***Abstract*-- YBCO thin films have good characteristics for current limiting materials due to compact size and high current carrying capability. But the irregularities and the extreme thin thickness of YBCO films cause some difficulties in simultaneous quench and thermal shock protection.In order to solve these problems, vertical magnetic field generated from solenoid coil was applied to the YBCO element. And also to minimize the inductance caused by the serial connection of magnetic field source with superconducting elements, magnetic field source was separated from the power lines adapting protective current transformer.In this study, electric field-current (E-I) and quench characteristics of YBCO films were analyzed both by electrical measuring method and observations of bubble propagation.From the experiment results, it was revealed that the magnetic fields generated by surrounding coil could induce the uniform quench distribution for all stripes of current limiting units and finally simultaneous quenches were realized in all serial connection of YBCO elements. In addition, the separation of magnetic field source form electrical network could be good solution for simultaneous quench of YBCO films without any unnecessary effect caused by serial connection.**

1. INTRODUCTION

Recently, due to the continuous increase in electric power demand, the fault current of electrical network has also been greatly increased. In order to protect the electrical equipment and the electric power facilities more efficiently from tremendous fault current, the introduction of fault current limiters are inevitable and their role is to reduce and limit the peak of fault current and arc duration time. Various types of fault current limiting apparatus have been proposed, but due to the insufficient capability and high price, these limiters were not supplied generally. In 1986, high temperature superconducting materials(HTS) were announced, and electric equipment using high temperature superconductors has been investigated all over the world. Fault current limiters adopting superconductors were also investigated[1]-[3].

Current flowing through superconductors has no loss caused by resistance during normal operation of fault current limiters. But, when abnormal currents or fault currents flow, superconductors change from the superconducting state to the normal state (S-N Transition). Due to this phenomenon, which is called quench of superconductors, some resistance is generated and fault current can be greatly reduced.

Then, superconductors are recovered to the superconducting state from the resistive state, then current begin to flow in a normal state[4]-[5]. The typical superconducting materials for resistive fault current limiters are YBCO films or Bi-2212 bulk. The resistive fault current limiter is much smaller and lighter than the inductive one. But the resistive type is vulnerable to excessive heat during the quench state, because it is directly connected in series to the power lines.

In case of serial connection of YBCO films or Bi-2212 bulk material in order to enhance operating voltage, it is not easy to achieve simultaneous quench when superconducting materials have irregularities caused by manufacturing imperfection. For that reasons there have been active research to achieve uniform quench distribution after quench in HTS element for current limiting.

In this research, magnetic field application to initiate simultaneous quenches for the series-connected FCL components was investigated by bubble inspection during quench. When the superconducting materials are quenched into the normal state, bubbles could be observed at the surface of YBCO films. Using our high-speed camera, the region where the first bubble occurred and bubbles propagation could be visualized and the quench characteristics of films could be investigated for all elements by using an electrical measuring method as well.

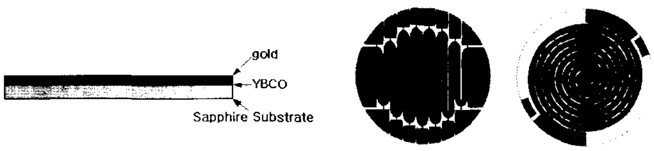
Magnetic field generating source was also studied; As for previous studies, magnetic coil is connected in series with FCL components, which have some problems caused by serial connection to the electrical network[6]. In this paper, the possible application of the protective current transformer (p-CT), as available current source to the magnetic coil was confirmed. This system was inductively coupled to the circuit; therefore, it has no impedance to the circuit. Fault current of the electric network is the source for generation of magnetic fields using the protective current transformer, and generated magnetic field was large enough to reduce critical current density of the components.

2. EXPERIMENTAL ANALYSIS

2.1. Experimental set-up

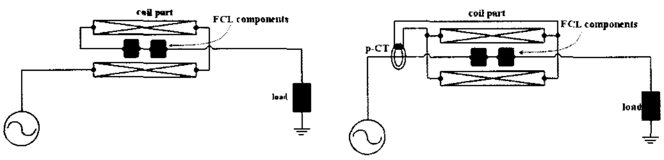
Fig. 1 shows the schematic view of YBCO thin film and patterns masked on it. Superconducting elements were based on 0.3μm thick YBCO films grown on two-inch diameter sapphire substrates. In order to disperse heat from the hot spot and to bypass the current, YBCO film was coated with a 0.2μm thick gold layer. Then the YBCO film with gold layer was patterned into 2mm wide and 42cm long meander lines and 50cm long bi-spiral lines by photolithography[6,7].

Schmes of magnetic field applying system and resistive fault current limiters are shown in Fig. 2 In Fig. 2 (a), magnet coil was directly connected to the electrical network in series, and offers magnetic field during quench. In this configuration, quenches are successfully initiated in all components connected in series. But this configuration has some serious problems including significant inductance occurrence, lowering normal current flowing capacity, and depressing critical current density of FCL components. So in this paper, newly developed structure which use inductively coupled system with the FCL components were introduced(Fig. 2 (b)). In this system, protective current transformer was adopted to provide enough current to the surrounding coil.



(a) Schematic of YBCO (b) meander and bi-spiral pattern

Fig. 1. YBCO film structure and masked patterns.



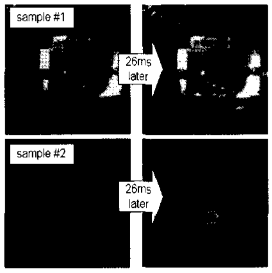
(a) Series connection with FCL (b) Separate connection with FCL

Fig. 2. Configurations of the system to apply magnetic field to the FCL.

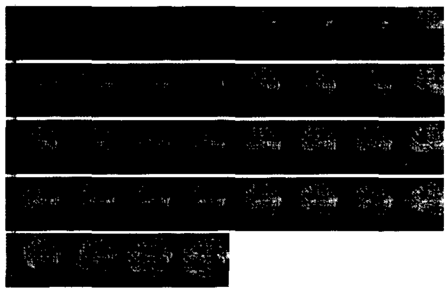
2.2. Bubble propagation characteristics

When the quench of superconducting materials was observed, the resistance of quenched YBCO film was increased very rapidly, so fault current could be limited due to the newly occurred resistance value. During quench, bubble formation is inevitable because energy heating dissipation is caused by Joule.(Fig. 3 (a)). Using high speed camera, it was possible to visualize the first quenching phenomenon occurrence and quench propagation.

It was shown that the first quenching was always taking place at the local area where the critical current density was the lowest in entire films and this trend was independent of the magnitude of fault currents and patterns.



(a) Bubble formation after quench initiation



(b) Quench propagation

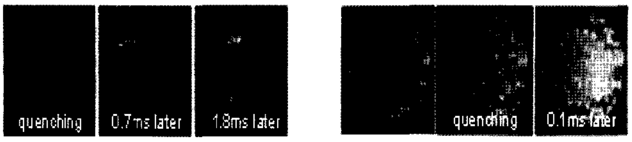
Fig. 3. Visualization of quench propagation.

Fig. 3 also shows the quench propagation to the neighbored area. Quench was propagated to the neighborhood area in the same direction of thermal propagation. And it was revealed that the generated heat was propagated both through gold layer and sapphire substrates evenly because sapphire substrates had good thermal conductivity.

When the YBCO films have some irregularities, simultaneous quenching is very difficult to achieve, so it is not easy to increase voltage ratings by series connection of YBCO films. Due to irregularities, heating is intensified on the local spot, YBCO films could not withstand on the increasing input energy. In case of serial connection of YBCO films, these input energies are intensified on some YBCO films, and others might not operate at all. And finally local heating and partly quenching cause YBCO films to be burned out.

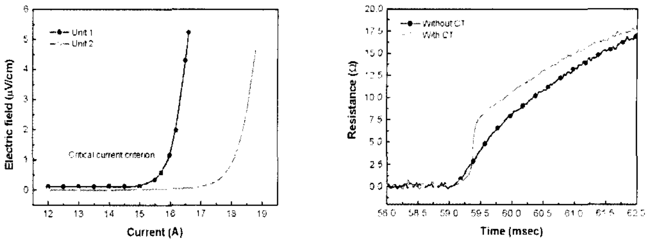
In order to solve these non-simultaneous quenching problems, vertical magnetic field was generated using encircling coil outside the superconductors.

From the experiment work, it was revealed that applied magnetic fields could make uniform quenching distribution for all regions. Fig. 4 shows the effect of magnetic field on quenching. When the magnetic field was applied to superconductors, the time delay for entire quenching was almost zero.



(a) Without magnetic field (b) with magnetic field

Fig. 4. Different quenching phenomena according to magnetic field.



(a) V-I characteristics (b) Comparison of resistance rise

Fig. 6. V-I characteristic of the two YBCO films in series.

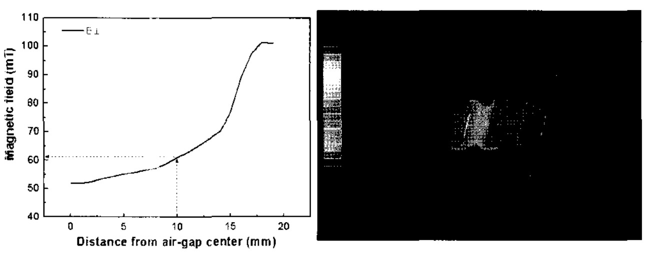
2.3. Magnetic Field application with protective CT

Magnetic field application is one of the prospective ways of inducing simultaneous quenches for the series-connected resistive FCL components. Typically, magnetic field was generated by the fault current through a coil, which is connected to the components of the fault current limiter in series. In order to remove the possible defects caused by serial connection, solenoid coil should be electrically isolated during normal operation. One of the possible methods to achieve this goal is the application of protective current transformer (p-CT), which could offer current source to the magnetic coil. This system was inductively coupled to the circuit and has no effects to the superconductors during normal operation. In case of fault currents, high currents by the protective current transformer were directly fed to the coil, generating magnetic field large enough to reduce critical current density of the components. This system successfully has induced simultaneous quenches of the series-connected resistive FCL components.

When 40 mm long core magnet was installed, the magnetic field distribution inside the core magnet and the field density along the center line is shown in Fig. 5. In this experiment, two current limiting elements were installed symmetrically on the spot which was 10 mm off from the center line,(Fig. 5 (b)) and the measured field density was 60 mT, and the inductance of core magnet 5.9 mH. This value is enough to cause S-N transition when the critical density difference between two current limiting elements is below 10%.

The phase difference observed between input current and CT output current, it might be negligible. So it was confirmed that this type of CT can be used as current source for magnetic field generation.

Fig. 6 (a) shows the different E-I characteristics between two YBCO films. The critical current densities of unit 1 and unit 2 was 16A and 18.1 A respectively. So the critical current difference between two YBCO elements was about 11%. This discrepancy is much higher than the normal conditions, but these units were useful for the simultaneous quench test when the magnetic field was applied.

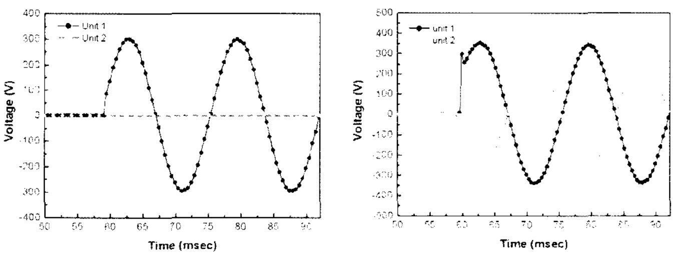


(a) B field in the air-gap (b) field distribution in the air-gap

Fig. 5. Field analysis of the core magnet.

Fig. 6 (b) shows the different characteristics of the resistance rise in case of applying the p-CT and without p-CT. When the magnetic field was applied to the YBCO films by the protective current transformer, the resistance grows very rapidly and steeply comparing to the normal case. This result can be explained assuring that the S-N transition begins not from the weakest point of the YBCO films but from the entire region of YBCO films which was under influence by magnetic field. On the contrary, when no magnetic field was applied, S-N transition occurred from the weakest point of superconducting films and the quench was propagated to the adjacent region. In other words, quench was initiated from the lowest critical current density region, and the thermal energy was transferred to the gold layer, YBCO layer and sapphire substrate. So it took a rather much longer time for total quench of unit superconducting module.

Fig. 7 shows the quench characteristics when the two



(a) without the p-CT (b) with the p-CT.

Fig. 7. Quench properties of the series-connected components.

current limiting elements were connected in series. From the test results, it was notable that magnetic field could realize simultaneous quench between the two series connected units(Fig. 7 (b)). But in Fig. 7 (a), when no magnetic field was applied to the components, only unit 1 component, which has rather bad critical current density compared to unit 2, was transferred to normal state from superconducting state. In this case, thermal energy was focused on the localized area and finally cause the breakdown of the superconducting unit.

3. CONCLUSIONS

In this research, it was confirmed that the magnetic field application to the superconducting elements is an effective method to realize simultaneous quench for the series-connected resistive fault current limiters. And we also suggested newly developed method which can generate enough magnetic fields for quenching of YBCO superconducting films when the fault current flows to the systems, by adopting protective current transformer as a current source. This magnetic field applying system has no influence to the fault current limiters in case of normal operation. Thus, it was possible to eliminate the serious problems including reduction of critical current density and inductance cause by series connection of the magnetic coil to the superconducting units.

Consequently, these investigation results can be applied to the practical design and development of resistive fault current limiter in the near future.

ACKNOWLEDGMENT

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

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