Numerical Study on Fundamental Properties of a Resistive Type Fault Current Limiter with QMG Bulk Superconductor Reinforced by Metal Bypass

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Abstract—This paper describes the numerical results of electrical, thermal and mechanical properties in a model current limiting device with QMG bulk superconductor reinforced by various kinds of metal bypass. The electric circuit analysis for simulation of current sharing is coupled at each time step with the finite difference method to calculate the temperature distribution inside the device. The obtained results are compared with experimental data carried out previously, and they have a good agreement with each other. The profile of internal stress in the limiting devices is also estimated by means of a commercial code of finite element analysis, and it is concluded that the magnitude of mechanical stress applied to the superconductor is less than an allowable level for each model device.

Index Terms—Fault current limiter, numerical calculation, QMG bulk superconductor, resistive type.

I. INTRODUCTION

Development of a fault current limiter, which can quickly suppress an overcurrent below an allowable level, has been desired for flexible supply of the electric power to users all over the place. Up to now, various kinds of current limiters with high-Tc superconductors have been examined such as inductive types [1], [2], resistive ones [3], [4] and so on. The QMG (Quench and Melt Growth) processed bulk superconductor is one of the most promising materials for the current limiter because it has the large resistivity in the normal state as well as the current capacity of kA class alone. For the realization of current limiter with the bulk superconductor, however, it is important to establish a technique to estimate numerically the distributions of internal temperature and stress in the superconductors during limiting operation. This enables us to obtain the information useful for further improvement of mechanical structure in limiting devices, which it is hard to evaluate in experimental investigation.

In this study, the numerical analysis for main physical properties is carried out in a current limiting device with the QMG bulk superconductor reinforced by soldering a normal metal, which has been proposed by the present authors [5], [6]. The comparison with the previous results by the experiment [5] verifies the proposed simulation for current limitation. The availability of the reinforcement with metal is also discussed by evaluating the distribution of mechanical stress in the superconductor for thermal expansion due to the temperature rise during limiting action.

II. NUMERICAL ANALYSIS

The cross-sectional view of a numerical model in the present study is given in Fig. 1(a), where the regions under consideration are surrounded with thin lines for electrical, thermal and mechanical evaluation. The current limiting device used in the experiment [5] had the structure reinforced by soldering two metal bypasses to both wide faces of a QMG bulk superconductor in the form of a capital letter ‘I’ as shown in Fig. 1(b), whose surface was coated with a thin layer of silver alloy in advance. The effective cross-sectional area and length of the superconductor were 0.8 × 2.2 mm² and 20 mm, respectively. The GFRP (Glass Fiber Reinforced Plastic) plates of 2 mm in thickness were also attached with epoxy resin for further mechanical reinforcement. The detailed sample preparation was given in [3].

In the experiment [5], an external resistance of 6.6 mΩ was connected in parallel to both terminals of the limiting device, and the excess currents of a half cycle of pseudo-sine wave were applied with a pulse width of about 4.1 ms. In order
to reproduce the experimental results numerically, the current limiting operation is simulated with a lumped electric circuit as shown in Fig. 2, where the effects of inductance can be ignored because of no phase difference between the experimental results of voltage and current [5]. It is also considered that the preliminary discussion has given a negligible current in the layer of silver alloy [6]. For the temperature distribution inside the limiting device, the one-dimensional heat balance equation in the thickness direction is numerically solved by means of a finite difference method. The GFRP plates outside the metal bypass are taken into account as indicated by the dotted line in Fig. 1(a), but it is assumed that the term of heat transfer from their surface to the coolant can be eliminated. Furthermore, the good thermal contact is supposed between the other materials.

By using the obtained distribution of temperature in the limiting device, the mechanical stress is numerically calculated with a commercial code of finite element analysis, ANSYS. The static evaluation of internal stress at fixed time is carried out for a half part of the cross section as indicated by the broken line in Fig. 1(a) because of the symmetry.

III. NUMERICAL RESULTS

Three kinds of materials such as stainless steel (SUS), nichrome (NiCr) and Titanium (Ti) alloy are chosen as the reinforcement metal with the thickness of 0.5 or 1.0 mm. Half a cycle of sinusoidal current with the peak of 4.2 kA is applied to the limiting device at initial temperature of 77 K. Fig. 3 show the comparison between the experimental and numerical results of terminal voltage and current distribution in the device reinforced by NiCr with thickness of 0.5 mm. It can be seen that the experimental results are well reproduced by the numerical simulation.

Fig. 4 shows the numerical results of terminal voltages in the limiting devices reinforced by different kinds of metals. It is found that the current sharing in thin layer of the solder is quite significant, and therefore it is necessary to enlarge the resistance of solder part for the achievement of further improvement toward high voltage endurance.

Fig. 6 shows the numerical results of temperature distribution inside each device with different metal bypass during the current limiting operation. One can see that the temperature rise is very severe in the solder layer due to the huge amount of Joule heating. It is also found that the thermal conduction into GFRP is negligible in the time scale under consideration.

The numerical results of mechanical stress along the length after the initial cooling with liquid nitrogen are given in Fig. 7, where the reference temperature without strain is set at 300 K. It can be seen that the initial stress in the superconductor is obtained directly from the difference between the thermal...
expansion coefficients in the materials. Fig. 8 shows the distribution of longitudinal stress just after the overcurrent test for various kinds of limiting devices. The numerical results for the devices reinforced by metal bypass are given in Fig. 8(a)–(d), which display the permissible compressive stress of several tens MPa applied to the bulk superconductor. This comes from the attachment of metal bypass for the suppression of stress concentration in the superconductor due to almost simultaneous increase in both the temperatures as shown in Fig. 6. In the case without metal bypass as shown in Fig. 8(e), on the other hand, the superconductor is exposed to the compressive stress of a few hundreds MPa, which is comparable to the maximum level of the allowable compressive stress.

IV. CONCLUSION

The distributions of current, temperature, and stress were numerically evaluated in the superconducting devices for current limitation strengthened by soldering various kinds of metals. The combined calculation with the electric circuit model and the one-dimensional heat balance analysis gave a good agreement with the experimental results. By the help of the numerical code of finite element method, the availability of the bulk superconductor reinforced by a suitable metal was confirmed for realization of the distribution of mechanical stress without damage. These results will supply a precious guide to develop the fault current limiter.

REFERENCES


Fig. 7. Distribution of internal stress along length after initial cooling (at 77 K) for limiting devices reinforced by (a) SUS, 1.0 mm, (b) NiCr, 1.0 mm, (c) Ti alloy, 1.0 mm, (d) NiCr, 0.5 mm and (e) no metal.

Fig. 8. Distribution of internal stress along length just after overcurrent test (at $t = 4.1$ ms) for limiting devices reinforced by (a) SUS, 1.0 mm, (b) NiCr, 1.0 mm, (c) Ti alloy, 1.0 mm, (d) NiCr, 0.5 mm and (e) no metal.