Experimental study on resistive type superconducting fault current limiter

K. W. See and N. A. Hamid
Department of Engineering Sciences & Mathematics, College of Engineering, Universiti Tenaga Nasional, 43009 Kajang, Selangor, Malaysia

(Received 28 December 2007)

Superconducting fault current limiter (SFCL) offers an ideal solution for protection in the event of a fault since the transition from superconducting state into the normal conducting state passively limits the fault current. A prototype of resistive fault current limiter using composite reaction texturing (CRT) processed Bi-2212 superconducting elements was developed and tested in order to study their fault current limitation characteristics based on different number of elements connected in series. The performance of the current limiting device depends on various parameters such as critical current density, E-J characteristics, thermal conductivity, transition temperature and electrical by-pass. The effects of each parameter on the current limiting performance are considered throughout the assembly of the prototype. The behavior of these parameters on Bi-2212 elements was studied and presented in this work. Theoretical model is also included to demonstrate the correlation of the physical property that dominating the current limiting behavior of high-temperature superconductors (HTS) with temperature. Finally, fault current limiting results based on number of elements connected in series are addressed.

I. INTRODUCTION

The development of new materials known collectively as BSCCO (ceramic compounds containing bismuth, strontium, calcium, copper and oxygen) has initiated a large number of research programmes around the world, aimed at creating superconducting devices for electrical power applications [1]. Research is focused on a number of applications including transformers, generators, motors, cables, magnetic energy storage systems and fault-current limiters. Among these, the high temperature superconducting fault current limiter (FCL) is unique in being essentially a new device rather than an existing application into which high-temperature superconductors have been incorporated. It is also one of the applications closest to commercial exploitation. Given that fault levels exercise a significant influence over the design of electrical power networks and can adversely affect system components, the high-temperature superconducting FCL is likely to be of major practical importance [2].

The fault current limiter (FCL) started off as an imaginary device in the minds of power system protection engineers. When a surge current produces havoc (fault, as it is usually called) in the power grid, some engineers perceived that it would be great to save the day with an FCL. This conclusion usually came amid burned out equipment, unpredicted power outages, and long hours of work to effect the repairs. By definition, the term FCL, which was created perhaps as early as fifty years ago, means a device that can limit or eliminate fault currents in an electric power system [3]. Typical sources of these fault currents are shorts to ground produced by lightning, metallic balloons, malfunctioning equipment, or unwary animals. An ideal FCL should features instantaneous detection of the fault, rapid reduction of the fault current to a desirable percentage of its original value, capability to intercept and handle a series of faults, automatic recovery of the device so that no human physical reset is necessary and finally a compact, lightweight package that is both reliable and inexpensive [4].

Superconductors have always been considered a natural for FCL application because of their ability to change rapidly from a superconducting to a normal-conducting state upon a quench. Put in another way, they normally have zero resistance and can swiftly shift to a highly resistive state in a fault situation. Equipped with the proper power or control electronics, a superconducting FCL can rapidly detect a surge and take action and can also readily recover to normal operation, by means to the superconducting state, after a fault is cleared. This conceptual advantage has led to the development FCLs.

II. THEORETICAL MODEL

The $E(j)$ characteristics can be practically described by subdividing it into three regions: the “superconducting”, the “flux flow” and the normal conducting regions. In each of the three regions $E(j)$ is approximated by a power law. For the first region, the “superconducting” regime, the following equation applied [5];

$$E^{(1)}(j,T) = E_c\left(\frac{j}{j_c(T)}\right)^{\alpha(T)} \quad (1)$$

with j_c the critical current density defined at $E_c = 1$ μV/cm. $j_c(T)$ and $\alpha(T)$ is fitted to experimental $E(j)$ curve. The second region, "flux flow" regime, is given as follows;

$$E^{(2)}(j,T) = E_0\left(\frac{E_c}{E_0}\right)^{\beta/\alpha(77K)} \frac{j_c(77K)}{j_c(T)}\left(\frac{j}{j_c(77K)}\right)^{\beta} \quad (2)$$

and the third region, "normal conducting regime";

$$E^{(3)}(j,T) = \rho(T_c) \bullet \frac{T}{T_c} j \quad (3)$$

where ρ is the normal resistivity and T_c is the critical temperature of the HTS. Note that although the dependence of $E(j)$ on magnetic fields, *B*, is not apparent from the above equations, the self-field effect is automatically included in the experimental data.

It should be noted that $E(j)$ is strongly temperature dependent and a small increase in temperature would give rise to a huge increase in *E*. This strong temperature dependence, coupled with the low thermal conductivity of HTS, renders the material to be very sensitive to so-called "hot-spots", which during a fault could cause damage to the superconductor elements.

III. CHARACTERIZATION OF MATERIALS

The superconducting materials that employed is based on composite reaction texturing (CRT) process which is the promising method for forming large highly textured bulk ceramic components with fully connected high quality grain boundaries. The general properties of CRT Bi-2212 elements are illustrated in Table I.

TABLE I. General properties of CRT Bi-2212 superconducting elements.

General Properties	Value
Thermal conductivity @ 77 K	2 $Wm^{-1}K^{-1}$
Critical temperature (T_c)	90 K
Density	250000 kgm^{-3}

The oxygen content of this composite ceramic depends on the temperature of anneal in 2% oxygen, as a consequence both the critical temperature T_c and the critical current density j_c can be adjusted in a controlled way. Samples that are over doped are more metallic and have a critical current that is degraded less by applied magnetic fields.

As discussed, the $E(j,T)$ characteristic for Bi-2212 bulk can practically be subdivided into three sub-regions, with different power laws as illustrated in Fig. 1(a). The parameters $j_c(T) = j(E = 1$ μv/cm), E_0, ρ, α, β at 77 K depend on material processing conditions and fall into the following range: $1000 \le j_c \le 10000$ A/cm^2, $0.1 \le E_0 \le 10\ 10$ mV/cm, $100 \le \rho \le 2000$ μΩcm, $5 \le \alpha \le 15$, $2 \le \beta \le 4$ [6].

Fig. 1(b) shows the experimental $E(j, 77$ K) curves of Bi-2212 elements. The change in the power law from α to β corresponds to the transition of the HTS from superconducting state into the flux flow state. At higher *E* field, the transition from the "flux flow" region to the normal conducting state where $E \sim j$ should occur, but it is beyond the reach of the experiment, due to excessive heating of the samples. The critical current density, j_c for this material was approximately 2000 A/cm^2 with the surface area that the current feed through is 4 mm^2 and this allows a maximum current flow of 80 A before turns the material into the quenching state.

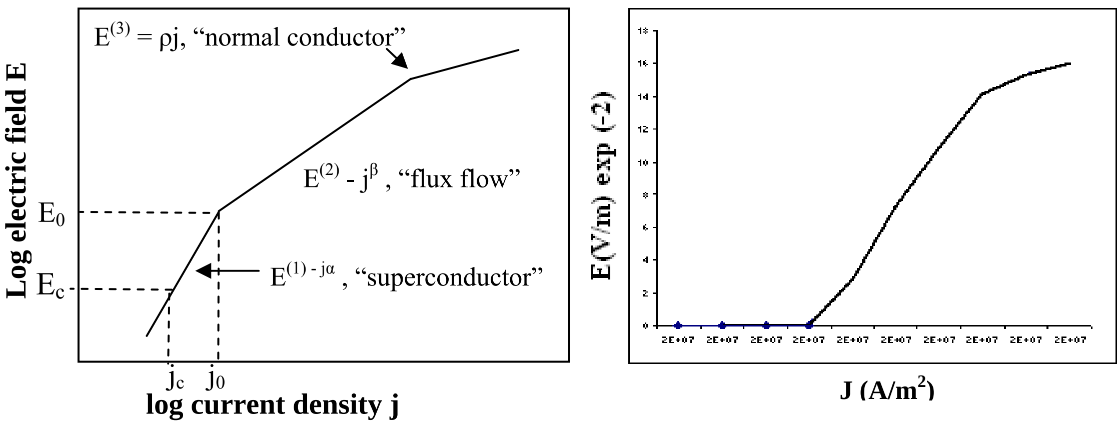
IV. EXPERIMENTAL RESULTS

The main component of the experimental set-up comprised of an external circuitry to incorporate with superconducting fault current limiter. CRT Bi-2212 superconductor elements are connected in series with copper connections and mounted on a disk shape acrylic for internal circuitry. One of the main purposes of the designed circuit is to provide the current flow for certain specified period where the miniature circuit breaker will trip the circuit after the period. This is accomplished by setting the timer that will send the signal to circuit breaker for tripping after the specified time. A second timer and an auxiliary relay are incorporated to monitor the current and time at a specified current value. An over-current relay is needed to detect the current whenever there is a fault (specified value) and send the signal to the auxiliary relay to initiate the timer. After the fault is being limited to a certain value (specified value), the auxiliary relay will detect signal from the overcurrent relay and stop the timer. This operation will give the time reading when the short-circuit current is initiated and limited to a certain value which would be specified.

Fig. 2 shows the limiting behavior of the fault current limiter unit for 10, 20 and 30 Bi-2212 elements, which are connected in series. The horizontal grid corresponds to 50 ms per unit while vertical grid denotes 50 A per unit throughout the scope results. From the figure, the superconducting elements take roughly 2 cycles to stabilize after the limiting circumstance or quenching stage [7,8] and the nominal current increases with the number of elements connected in series. As the superconducting materials increases, the volume also increases thus allowing for higher nominal current and limitation during the superconducting and flux flow state, as the ability to withstand higher thermal load increases. The short circuit current or designated as simulated fault current that feed through the unit has the approximated value of 100 A for 10 connected elements, 150 A for 20 connected elements and 200 A for 30 connected elements. With the current above the critical value, each of the series connected system would exhibit their limiting response until the system stabilized and returned to superconducting state. The breaker (MCCB) was fixed to initiate at the instant of 0.5 s from short circuit for 10 elements connected in series, and 0.3 s for both 20 and 30 elements, respectively.

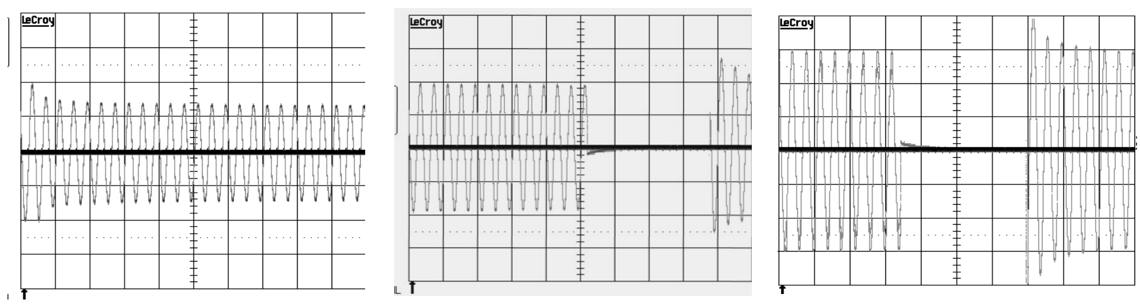
V. CONCLUSION

The resistive type superconducting fault current limiter described in this work demonstrates the viability of utilizing high-temperature superconductor as a new and unconventional design in power systems. The primary issue surrounding this type of device lies in ensuring that the fault current energy is safely dissipated without permanently damaging the elements itself, manifesting itself as Joule heating in the high-temperature superconductor elements. The prototype fault current limiter demonstrated a stable operation at its normal operating current of which below the critical current of approximately 90 A. Influenced by the duration of faults, the response of the superconducting element would possibly 10 times faster. As such, the promising application of superconductor in current limiting device has brought to several economical benefits. Major economical benefits of superconducting current limiter would be more cost-effective designs of new power system and more cost-effective up-grading of existing grids.



(a) (b)

FIG. 1. (a) Current-voltage characteristic of high-temperature superconductor (HTS) materials, (b) $E(j)$ for Bi2212 superconductor elements.



(a) 10 elements (b) 20 elements (c) 30 elements

FIG. 2. Limiting behavior of fault current limiter for (a) 10 Bi-2212 elements connected in series, (b) 20 Bi-2212 elements connected in series, and (c) 30 Bi-2212 elements connected in series.

ACKNOWLEDGEMENT

The supports from Universiti Tenaga Nasional, Ministry of Science, Technology and Innovation, Malaysia, and TNB Research Sdn. Bhd. are greatly acknowledged.

REFERENCES

[1] M. Noe and B. R. Oswald, IEEE Trans. Appl. Supercond., **9(2)**, 1347 (1999).
[2] W. V. Hassenzahl, IEEE Power Eng. Rev., **20**, 4 (2000).
[3] E. M. Leung, G. Albert and P. Haldar, IEEE Trans. Appl. Supercond., **7(2)**, 985 (1997).
[4] K. Tekletsadik and M. P. Saravolac, IEEE Trans. Appl. Supercond., **9(2)**, 672 (1999).
[5] M. Chen, W. Paul, M. Lakner, L. Donzel, M. Hoidis, P. Unternaehrer, R. Weder and M. Mendik, Physica C, **372-376**, 1657 (2002).
[6] T. Ikegami, Y. Yamagata and K. Ebihara, IEEE Trans. Appl. Supercond., **3(1)**, 566 (1993).
[7] H. Hattta, T. Nitta, T. Oide, M. Chiba, Y. Shiral and A. Mochida, Supercond. Sci. Technol., **17**, S276 (2001).
[8] J. R. Cave, D. W. A. Willen, R. Nadi, W. Zhu, A. Paquette, R. Boivin, and Y. Brissette, IEEE Trans. Appl. Supercond., **7(2)**, 832 (1997).