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EXPERIMENTAL INSTRUMENTS AND TECHNIQUES

A New Concept for a Current Switch Based on a High-Temperature Superconductor

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Abstract—A new concept for a device for protecting an alternating-current network is offered. It is based on a combination of a superconducting limiter of a short-circuit current and a circuit breaker. A high-temperature superconductor in the form of a pile of plane rings is used as the active element of the limiter. The test results of a model of such a limiter are obtained in the steady-state short-circuit regime. The characteristics of composite silverless materials used for design of the breaker are given. © *2001 MAIK "Nauka/Interperiodica".*

INTRODUCTION

The possibility of using superconductors as active elements for short-circuit (sc) current limiters has long attracted researchers' attention [1, 2]. However, high costs of both the devices and the coolant (liquid helium) for low-temperature superconductors have hampered their wide use. The discovery of high-temperature superconductivity has regenerated interest in investigations in this field, because the high temperatures of the transition to the superconducting state (90–120 K) allow one to use liquid nitrogen as a coolant [3–8].

The simplest current limiter is based on the transition of a superconductor from the superconducting state, in which the resistance equals zero, to the normal state with a finite conductivity value, when the current exceeds the critical value. In the emergency case accompanied by an increase in the circuit current, the presence of an additional ballast resistance (equal to zero in the normal regime) softens the sc regime. The advantage of using a superconducting active element is that the element (unlike a mechanical disconnector) has a very short response time [2] and higher reliability. It should be noted that the behavior of a superconducting active element in the overload regime was mainly investigated in the publications on current limiters [4–8]. In this work, we offer a new concept for the protection apparatus, in which most attention is paid to the combination of a circuit breaker (the contacts are made of composite materials without silver [9–13]) with a current limiter based on a high-temperature superconductor (HTSC).

COMBINATION OF A BREAKER AND A SUPERCONDUCTING CURRENT LIMITER

Let us consider the load of a superconducting current limiter connected in series with a breaker (switch). In the absence of a current limiter, the switch's ability to protect the load is determined by the critical value of the power W_{SW}^{CO}, which, when reached, trips the switch. In the presence of a current limiter, the total power in the sc regime W_{ex} is redistributed between the limiter and switch

$$W_{\mathrm{ex}} = W_{\mathrm{CSL}}^{C} + W_{\mathrm{SW}}^{CO}.$$

The critical power W_{CSL}^{C}, at which the current limiter is overwhelmed, is determined by the resistivity of a superconductor in the normal state, its mechanical strength, and specific features of the limiter design. In the combined system of a switch and current limiter, the power released in the switch is lower than that without a superconducting limiter. Hence, the critical power value for the switch W_{SW}^{C} may be decreased:

$$W_{\mathrm{SW}}^{C} = W_{\mathrm{SW}}^{CO} - W_{\mathrm{SCL}}^{C}. \qquad (1)$$

Expression (1) is valid for $W_{\mathrm{SW}}^{CO} > W_{\mathrm{SCL}}^{C}$. If $W_{\mathrm{SW}}^{CO} < W_{\mathrm{SCL}}^{C}$, all the power in the sc regime is released in the superconducting current limiter. The practical importance of expression (1) is that it is possible to reduce the requirements on the circuit breaker in the combined system of the current limiter and switch. Therefore, for such switches cheaper contact materials can be used, for example, silverless composites consisting of copper

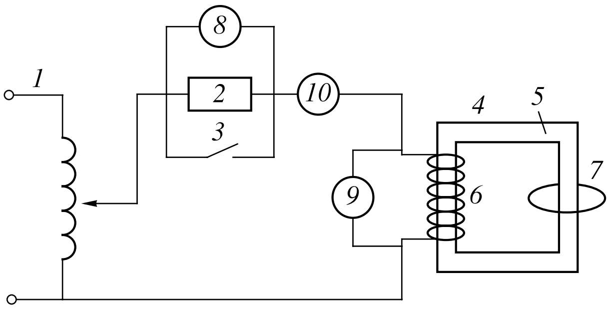

Fig. 1. Circuit diagram for HTSC ring tests in the sc regime: (*1*) external network transformer (50 Hz); (*2*) load; (*3*) sc regime simulation switch; (*4*) current limiter, which consists of core *5* made from transformer steel (μ = 100), primary winding *6* (23 turns), and superconducting ring *7*; (*8*, *9*) voltmeters measuring the voltage drop across the load and limiter, respectively; and (*10*) ammeter measuring the circuit current.

with small additions of superdispersed diamonds [9–13]. Another advantage of such a combined system is the higher operation reliability, because the HTSC element protects both the switch and the load.

A CURRENT LIMITER BASED ON HTSC

Presently, several concepts of current limiters exist [3]. The so-called resistive and inductive limiters are the most widespread [4]. In resistive current limiters, a superconductor is directly included in the circuit with the protected load [4, 7, 8]. Limiters of such a type require the development of a technological process for manufacturing contacts between the HTSC and the current lead. In inductive current limiters, an active superconducting element, usually made in the form of a ring or a cylinder, is inductively coupled to the load [4–7]. To produce such limiters the following factors should be taken into account: the large dimensions of devices, in which the superconductor screens the magnetic field; and the possibility of destruction of superconducting elements under ponderomotive forces at a high current density. In devices of both types, the heat released in the short-circuit regime should be effectively removed from a superconductor.

Table 1. Results of bench tests of materials at direct and alternative currents

Material	Switching wear, g/cycle × 10^6		R_J, mΩ	
	anode (+)	cathode (–)	current	
Cu–Cd–Cdia	–1.2	–4.4	11.9	24.0
Cu–Cd–Nb–Cdia	–0.5	–1.6	8.8	15.7
Cu–Cd–C	–2.5	–3.6	23.3	2.3
Ag–15CdO	–0.6	–0.7	1.2	1.2

High-temperature superconductors in the form of a hollow cylinder screening the primary winding field are often used in inductive current limiters [4]. An iron core is set inside the superconductor. In devices of this type the space factor is about 0.6. For effective heat removal, the thickness of the cylinder walls should not exceed ~2 mm [4, 5]. The cylinder is exposed to considerable loads under the ponderomotive forces, according to the data in [4], with axial compression up to ~1500 N, and pressure on the outer surface at 0.2 bar, which is close to the ultimate stress of ceramic HTSC. For this reason, most designs need a band to unload the active element.

In this work, we modified the design of an inductive current limiter. High-temperature superconductors were made in the form of a pile of thin rings with relatively large radial size. The rings were separated by a gap equal to the ring thickness of ~2 mm. This allowed one to increase the HTSC volume and, hence, the operating power of the limiter. Calculations showed that a fivefold increase in the radial size (up to 10 mm) allows one to abandon a band, because the axial load on a superconducting ring is distributed over a larger area than in the case described above [4], and the tension on a unit length of the superconducting pile of rings is also less. The space factor in this design is close to unity, since the magnetic circuit and set of rings are separated only by a wall of a styrofoam cryostat. An additional advantage of this design is that the value of the operating current of the limiter can be varied in a wide range by a change in a number of rings.

The $Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_2Cu_3O_x$ HTSC [14] was synthesized from Bi_2O_3, PbO, $SrCO_3$, $CaCO_3$, CuO according to ceramic technology at temperatures of up to 840°C for up to 250 h with multiple intermediate millings. The small-angle Debye powder patterns showed that the Bi-2223 phase is dominant. The resistivity measurements by the four-probe method have shown that the transition to the superconducting state begins at

$$T_C = 113\text{ K},\quad T_C(\rho < 10^{-6}\ \Omega\text{ cm}) = 105\text{ K},$$
$$\rho(T_c) \approx 2\text{ m}\Omega\text{ cm}.$$

The superconducting rings for the measurements were prepared from this powder in a special mold. The pressed rings were finally annealed in a uniform temperature field. The rings obtained had an outer diameter of 10 cm, an inner diameter of 8 cm, and a thickness of 2–6 mm. The critical current density J_c of the dummy rings determined by the four-probe method was 150 A/cm^2 at 77 K (according to the criterion of 1 μV/cm).[1]

The rings were tested at a frequency of 50 Hz using the circuit shown in Fig. 1. The measurements showed the following results. At a circuit current of 1 A, the voltage drop across the load was U_r = 19 V, the voltage

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[1] Investigations on optimization of the final annealing of the rings aimed at increasing the critical current density are currently being conducted.

drop across the limiter was $U_{SC} = 0$ (<10 μV). In the sc mode, the current was 9 A, the voltage drop across the limiter was $U_{SC} = 17$ V (the ring current density was 760 A/cm^2), and the voltage drop across the load, $U_r \approx 0$ (the voltage drop at the leads was ≈2 V).

The *I–V* characteristic of one of the rings is shown in Fig. 2. It was measured by the inductive method using the circuit in Fig. 1. It is seen that the active element has a rather high overload ability; i.e., it can operate in a steady-state regime without being overwhelmed at currents much higher than the critical ones. The power released in the ring is ~150 W (20 W/cm^3) and is effectively removed by liquid nitrogen. The experiments with a set of rings have shown that the threshold current of the limiter is additive with respect to the critical currents of separate rings.

Note that the experimental results were obtained in the steady-state regime. Naturally, in a quasi-pulse mode, in which the protecting device will operate (we mean the actuation time of the breaker), it is possible to achieve higher characteristics of the limiter [6, 7], at least by a power of ~2 kW per one superconducting ring.

Thus, in our view, the offered design of a superconducting current limiter with an active HTSC element in the form of a set of plane rings is promising, as well as the design, in which the active element is made as a thin-walled cylinder [4, 5].

INTERRUPTING COPPER-BASED CONTACTS

The current limiter is used as a protection mechanism; its main contacts operate in the long-term switch-on mode and, hence, the main requirement is a low value and long stability of the transitional resistance (R_J) in the symmetric contact pair.

The main obstacle in using copper as a basic material for interrupting contacts used in air is its rather high oxygen affinity. Attempts to reduce oxidation of the copper matrix and, thus, the value of R_J are carried out by both doping the material with different additions and introducing a reducing agent (more often graphite).

Contacts of a copper–graphite system have a common drawback: low hardness and strength. Therefore, they cannot usually be used in devices with multicycle shock loading.

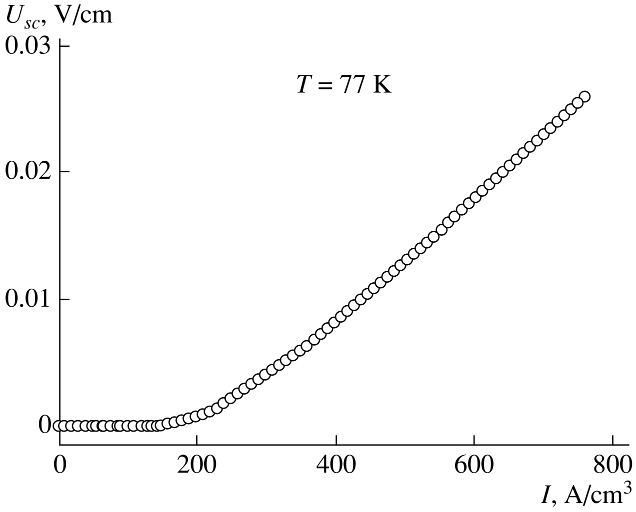

Fig. 2. Typical steady-state current–voltage characteristic of the HTSC ring measured at 77 K for the stimulated sc regime.

It has been suggested to introduce carbon in the form of a relatively cheap diamond powder (obtained by explosive synthesis) with the main fraction <1 μm in size [9, 10]. In this case, the chemical nature of the addition is the same, while the mechanical characteristics of the composite are radically improved. When solid refractory particles of diamond are introduced into the matrix, the durability to welding increases, and the material is additionally strengthened. Diamond increases the erosion durability of the contacts by cooling the arch base (due to the high thermal conductivity of diamond), leading to the quenching of the arc. Refractory metals additionally introduced into the composite reduce the value of R_J, and increase its stability, and bolster its mechanical and electrical durability of contacts (Tables 1 and 2).

Up to currents of 1000 A, Δ*T* values are within a normalized range. Similar data are obtained for ac contactors (*I* = 20, 40, 100 A): the absolute *T* values of contact pairs ranged from 315 to 342 K.

The processing behavior of powder composites [11, 12], their oxidation in air at temperatures close to

Table 2. Typical results of the temperature excess of the parts of dc apparatuses

Rated parameters of apparatus	Δ*T*, K			
	upper terminals	lower terminals	mobile contacts	stationary contacts
250 A, 110 V	32.6–36.5	25.6–26.0	41.2–43.7	40.6–45.1
870 A, 770 V	46.2–49.7	35.3–40	63.7–66.1	72.1–74.7
600 A, 1500 V	55.7–57.7	41.8–42.6	66.9–69.6	62.6–63.4
600 A, 1500 V	–	–	69.7–71.5	73.8–74.9

the working temperature of contacts (330–390 K) [13], and tests in industrial apparatuses have shown that the contact elements of copper-based powder composites considered have the necessary service properties and are capable of providing the reliable operation of communication apparatuses.

The critical power of the electrical contact W_{SW}^{CO} can hardly be tested experimentally or estimated theoretically. As a rule, it is possible to indicate only an approximate value of W_{SW}^{CO}. For the contact pair described in this paper, a power of ~30–50 kW can be considered critical. The current limiter with a set of ten HTSC rings allows one to decrease the critical power of a switch by a value of W_{SCL}^{C} ~ 20 kW which is comparable with the value of W_{SW}^{CO}. According to our estimates, the combined device (current limiter + switch) will be able to operate at currents of 100–1000 A to protect unique equipment at industrial enterprises, transport, and during dangerous processing.

Further investigations on the development of a prototype of the sc network protector based on a superconducting current limiter and a breaker with silverless contacts include the following: (i) improvement of the critical parameters of the HTSC rings; (ii) design of an operation element based on silverless contacts; and (iii) study of the behavior of the limiter in the pulse regime.

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