Technical Physics Letters, 2023, Vol. 49, No. 6

05.5

Stabilization of superconducting protective resistors by means of mesh electrical insulation

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Received April 5, 2023
Revised April 21, 2023
Accepted April 22, 2023

The possibility of using high-temperature superconductors of the second generation in protective resistors (HTS resistors) for electrical equipment is considered. It is proposed to use mesh fiberglass electrical insulation in the HTS resistors to ensure the efficiency of the heat sink and maintain a stable overloaded operation. Physical modeling of such resistors was performed, which showed the preservation of their overload capability and the suppression of thermal instabilities due to the presence of mesh insulation.

Keywords: high-temperature superconductor, protective resistor, mesh insulation, refrigerant, resistive state, thermal breakdown.

DOI: 10.61011/TPL.2023.06.56380.19579

Protective resistors fabricated from high-temperature superconductors (HTSs) are designed to prevent the failure of power-generating equipment in emergency operation modes [1]. As is noted in [1], the term „protective resistor“ is used due to the fact that such a resistor may protect grid equipment from a current overload. It is used as an element of electrical device (see connection circuits in [1]), but does not function as a stand-alone superconducting current limiter. Since a resistor is fabricated from a superconducting material, it is called a superconducting one, although its operation is governed by the transition from a superconducting state to a resistive state. The operation of protective HTS resistors relies on the existence of stable overload conditions in HTS wires with a stabilizing metallic layer/matrix that are cooled by a liquid coolant (nitrogen) [2]. A nonzero active impedance of a wire coupled with a resistive state of an HTS layer is a characteristic feature of these conditions. The wire temperature exceeds the coolant temperature in this case, but does not reach the critical point of HTS transition to the normal state. Stable overload conditions may be maintained in an HTS resistor for an indefinite time without any parameter degradation [3], thus making it unnecessary to use a quick-response emergency protection system for switching off the current.

The results of experiments with physical models of grid equipment with HTS resistors fabricated from first-generation (1G) HTS wires have been reported in [1]. Owing to their fairly high critical temperature (110 K), these wires feature a stability margin under current overload. However, for technological reasons, a silver matrix occupies no less than 60% of the cross section of a 1G wire, making its resistive state fairly low-ohmic and thus increasing the amount of wire required for protection. Although second-generation (2G) HTSs have a lower critical temperature (92 K), a copper stabilizing layer in them may be fabricated with a target thickness that varies from several micrometers to several tens of micrometers and is determined in preparatory calculations of parameters of an HTS resistor [4]. This is the reason why the present study was aimed at demonstrating the possibility of application of insulated 2G HTS wires in protective resistors. To achieve this goal, one needs to find electrical insulation that does not impair the overload capability of an HTS wire by interfering with the transfer of heat to the coolant. This cannot be avoided if the used insulation is a solid dielectric coating [5,6]. With a solid insulation, the time of thermal endurance to irreversible breakdown of an HTS wire under emergency operating conditions does not exceed 1 s [7]; therefore, the current needs to be switched off. In the present study, mesh electrical insulation is proposed to be used in protective resistors to block electrical contacts between the layers of an HTS wire. The coolant will then be in direct contact with the wire surface in mesh cells, providing the needed cooling efficiency, while mesh fibers will separate adjacent wires from each other. Since HTS resistors in known circuit designs are inserted into low-voltage circuits of electrical equipment [1], the presence of a two-phase coolant (during boiling) in HTS resistor layers does not lead to electrical breakdown. Owing to bifilarity of the resistor design, it is not prone to the emergence of substantial mechanical stresses of a magnetic origin.

Resistor models were fabricated from a composite 2G HTS tape produced by SuperOx [8]. One and the same segment of an HTS tape was used for all samples and tests. Its parameters were as follows: an Ag/Cu stabilizer thickness of $44\,\mu$m (Ag — $4\,\mu$m, Cu — $2\times 20\,\mu$m), a length of 71 mm, a width of 12 mm, and a critical current of $I_c = 370$ A. Several layers of mesh fiberglass insulation

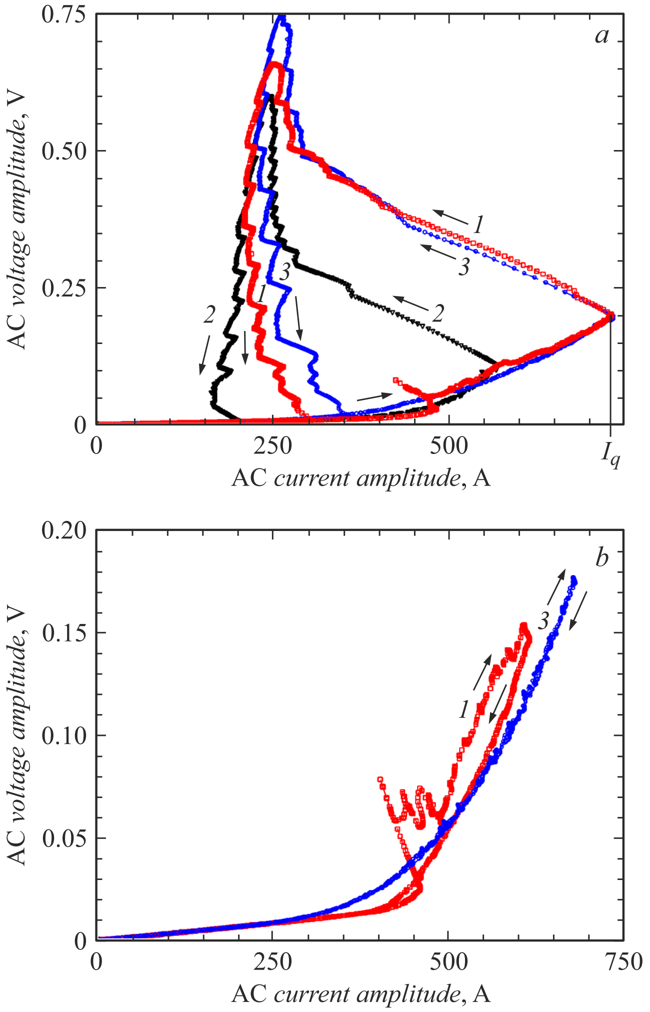

Figure 1. Amplitude CVCs for 2G HTS resistors. *1* — without insulation, *2* — with one insulation layer, and *3* — with five insulation layers.

with cells 3×4 mm in size were deposited onto both sides of the HTS tape. Each insulation layer had four cells in width. Lateral fibers of the mesh were removed to facilitate the penetration of liquid nitrogen deeper into the insulation. The first mesh layer was positioned at the tape center. The other layers were shifted along the tape width by 0.25 of a cell relative to the previous layer. The insulated tape was positioned between laminated fabric pads with their thickness equal to that of the tape. These pads were pressed together and held in this position; the mean thickness of one insulation layer was then 0.1 mm.

All measurements were performed with an AC current of a commercial frequency (50 Hz), which corresponds to the operating conditions of HTS resistors in power-generating equipment. The voltage signal, which included the HTS wire voltage proper and the current-terminal voltage, was measured. This is due to the fact that current terminals are an integral part of an HTS resistor performing protective functions in electrical equipment. The measurement results reported below reflect the presence of contact and inductive impedances that are joined by the active impedance of an HTS wire in resistive and normal states. Having performed simultaneous measurements of instantaneous current and voltage values, we obtained amplitude current-voltage curves (CVCs), which are generally consistent with the ones characterized in [4]. CVCs feature an initial linear segment, which evolves into a segment of steep monotonic growth. Both segments are steady-state (except for the case of instability emerging in an uninsulated HTS wire; see below). CVCs become nonmonotonic at a certain current value I_q and acquire an unsteady „backward" branch. The next CVC segment is governed by the wire heating regime, and hysteresis is observed upon voltage withdrawal. The loss of CVC stationarity at current I_q is attributable to the disruption of thermal balance due to a sharp increase in heat output. Current I_q is commonly called the thermal breakdown current. A complex of phenomena related to thermal breakdown has been examined in [4,5,9].

Guided by the aims of the study, we performed measurements for HTS resistors without insulation and with 1–6 layers of mesh insulation (with a thickness up to 0.6 mm). The obtained results revealed that the thermal breakdown current of a resistor with one layer of insulation decreased considerably relative to the initial value in an uninsulated HTS resistor. When the number of insulation layers rose to two or three, the breakdown current increased relative to its value for a single insulation layer. With four layers of mesh insulation, the breakdown current reached a value close to I_q of an uninsulated wire. As the number of layers increased further, the I_q value varied only weakly.

Thermal breakdown current I_q was determined by examining the CVCs in Fig. 1, *a*. To avoid overloading Fig. 1, *a*, only a few select measured CVCs (the curves for an uninsulated HTS wire (*1*), single-layer insulation (*2*), and five-layer insulation (*3*)) are shown. The transition from a forward CVC branch to a backward one is an indicator of thermal breakdown. This occurs at close current values in curves *1* and *3*. Thus, it was found that multilayer mesh electrical insulation, which is needed to prevent contact between HTS wire layers, does not reduce the thermal breakdown current and may be used in the design of protective HTS resistors.

Alongside with thermal breakdown, uninsulated 2G HTS wires feature a different type of instability at much lower currents, which is associated with a change in the mode of heat transfer (from convection to nucleate boiling) to the liquid nitrogen coolant [5,10]. This instability manifests itself in the full-scale CVC (curve *1* in Fig. 1, *a*) in the 450–500 A current range. The corresponding instability region is shown separately in Fig. 1, *b* (curve *1*). The obtained measurement data demonstrate that this instability vanishes in the presence of single-layer (curve *2* in Fig. 1, *a*) and multilayer (curve *3* in Figs. 1, *a* and *b*) mesh insulation. Hysteresis phenomena are also not observed in this region of the CVC of an insulated HTS wire (curve *3* in Fig. 1, *b*). Thus, mesh electrical insulation enables stable operation

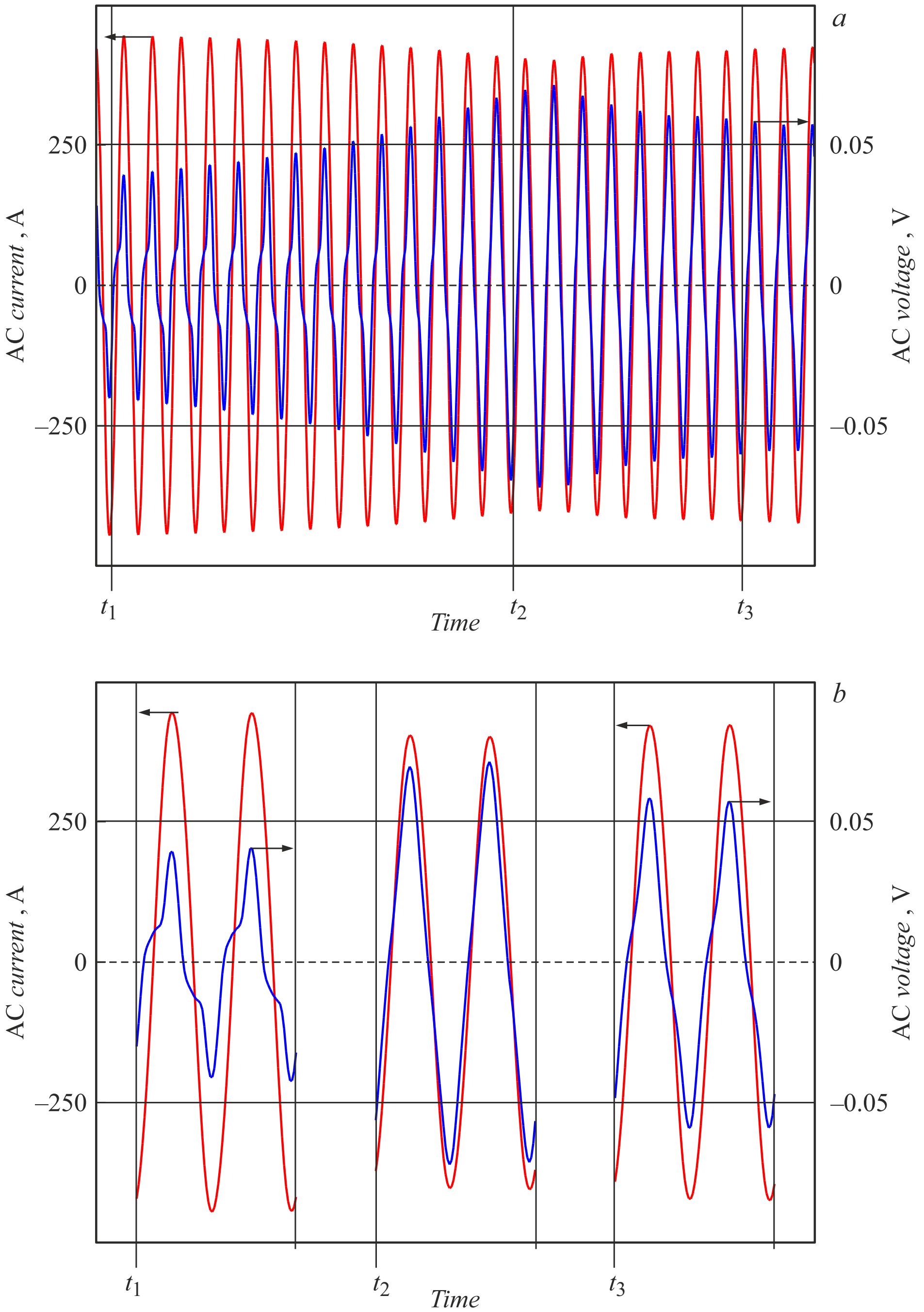

Figure 2. Oscilloscope records of voltage and current in the circuit with an uninsulated HTS resistor. *a* — Current and voltage envelopes for a large number of periods, *b* — isolated periods of current and voltage at different points in time. The frequency is 50 Hz.

of protective HTS resistors within the entire range of parameters corresponding to a resistive state.

Processes unfolding in a circuit with an HTS resistor in the course of development of an instability may be traced using oscilloscope current and voltage records (Figs. 2, *a*, *b*). Figure 2, *a* presents the oscilloscope records for an uninsulated HTS wire and several tens of periods. Isolated periods at time points t_1, t_2, and t_3 are shown in Fig. 2, *b*. It can be seen that the voltage at time point t_1 is non-sinusoidal due to the nonlinearity of the CVC of a wire in a resistive state. At time point t_2, the voltage is sinusoidal in shape, indicating that the CVC is linear due to the transition to a normal HTS state. The resistance of an HTS resistor reaches its maximum at this point (this follows directly from Fig. 2, *a*). At time t_3, the voltage again assumes a non-sinusoidal shape, and the resistor resistance decreases. Thus, instability in an uninsulated wire induces periodic transitions from a resistive state of a superconductor to a normal state, and vice versa [10].

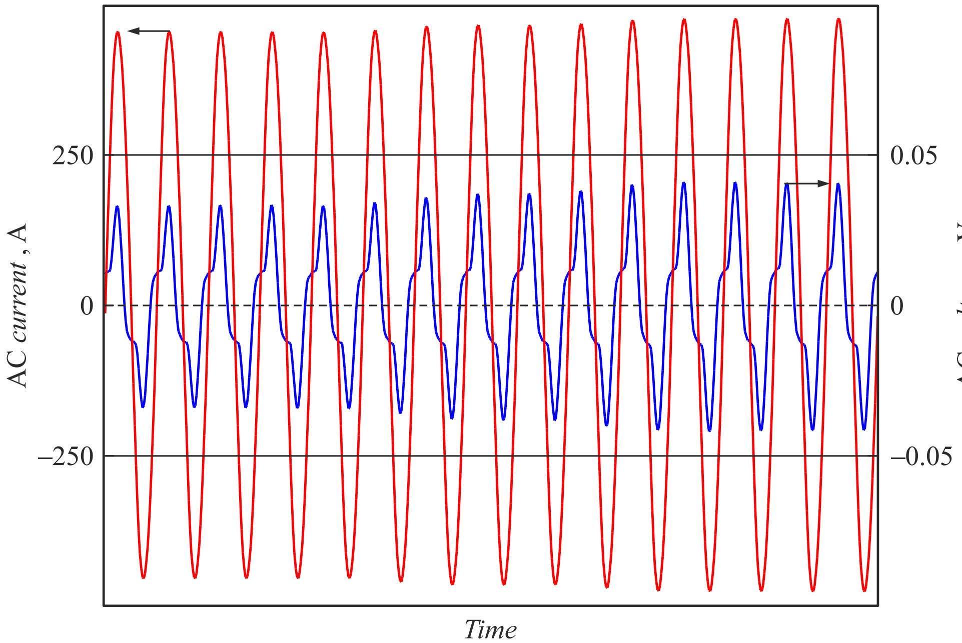

Figure 3. Oscilloscope records of voltage and current in the circuit with an HTS resistor with mesh electrical insulation. The frequency is 50 Hz.

The pattern changes radically in the presence of mesh insulation (Fig. 3). The voltage signal remains non-sinusoidal in shape throughout the entire duration of the oscilloscope record, and the signal amplitude increases monotonically with current. No oscillatory processes are observed in the current and voltage envelopes. Oscilloscope traces recorded upon current injection and withdrawal match each other, and no CVC hysteresis is seen (curve *3* in Fig. 1, *b*), which implies that an HTS resistor with mesh electrical insulation remains in a stable resistive state within the considered range of current and voltage values. This is attributable to the fact that an insulating mesh inhibits coolant convection; when the critical current is exceeded, the wire gets heated to a greater degree (curve *3* lies above curve *1* in Fig. 1, *b* at currents of 300–500 A), inducing nucleate boiling and intensifying the heat transfer. Stability and overload capability are advantage factors facilitating the application of 2G HTS resistors with mesh electrical insulation as components of several types of electrical equipment.

Funding

This study was carried out under state assignment AAAA-A19-119083090048-5.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin