Study of superconducting fault current limiter model with AC circuit-breaker

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Absract. The electric circuit and physical model of superconducting fault current limiter with a circuit-breaker (SFCLCB) are designed and studied. The nonlinear resistor (superconducting coil) is connected in series with the switching device. The purpose of this device is to limit a fault current up to a permissible level and to switch it off at the first current passing through zero value. The circuit is found to limit the current amplitude in SFCLCB by factor about 5-7 without destruction of the HTS tape.
The 2G HTS tape with a critical current 270 A is used as a superconducting nonlinear resistor whereas the high-speed vacuum circuit-breaker is used as a switching device. To study current limiting properties of the HTS tape, the test has been carried out in ac circuit with a current amplitude up to 4700 A. The circuit is found to limit the current amplitude in SFCLCB by factor about 5-7 without destruction of the HTS tape. A current limiting operation of this circuit is simulated taking into account the temperature dependent non-linear resistance of the HTS tape. An influence of the coil design on recovery time of the superconducting tape immersed in liquid nitrogen is studied using an oscillatory test circuit with the oscillation period near 20 ms at the maximum voltage up to 3 kV. The coils with flat bifilar winding have been tested for various winding density of the HTS tape. The tape temperature rise in the current limiting mode is estimated. Results of these estimations are well correlated with our experimental data.

1. Introduction

One of ways to decide a problem of fault current limitation is the design of current limiting devices with high-temperature superconductor (HTS) as a working element. From economic reasons the volume of a superconducting tape in the current limiting device should be minimized [1].

The most perspective way to reduce the HTS volume at given temperature rise ΔT of a superconducting tape is to minimize a duration of a current limiting mode. It is offered to use for this purpose the superconducting current limiting circuit-breaker (SFCLCB) [2, 3]. Such a SFCLSB is designed as an electric circuit in which the superconducting nonlinear resistor is connected in series with a high-speed vacuum circuit-breaker. The aim of such a circuit design is to limit the amplitude of fault current up to a comprehensible level and to break it at the first current passing through zero value.

The current-limiting characteristics of the SFCLCB can be enhanced also if a superconduction tape of second generation (2G HTS tape) is used as a nonlinear resistive working element. Such materials have a reduced metal content (small thickness of a substrate and stabilizer), high value of the critical current and high stability to emergency currents in normal state.

To design the SFCLCB with 2G HTS tapes as working element, it is necessary to know the relation between the temperature rise of a tape and the attenuation degree of current limitation during one half-cycle of a fault current pulse, as well as the recovery time of this tape to superconducting state at cooling period after the end of pulse. Current limiting characteristics of the HTS tape are defined by such specific parameters as an electric field intensity and linear energy dissipation along the tape length [4, 5]. In the laboratory conditions it is more convenient to carry out the study of tape heating and cooling using several short pieces of the HTS tape at a low voltage.

The HTS recovery time is related to the design of the superconducting coil made from a tape up to several meters in length. The voltage drop along the HTS tape appreciably increases after the tape transfers to a normal state. Therefore, to study the dynamic characteristics of such HTS coils for a voltage level up to several kV, it is necessary to provide an effective power supply.

Results of experimental study of HTS elements in a current limiting mode during the first half wave of an alternating current are presented. The 2G HTS tapes with a critical current 270 A are used. Current limiting property of short HTS samples are investigated in the circuit with ac frequency 50 Hz and current amplitude up to 4700 A. Below, the experimental data are compared with our calculation results for a temporal variation of the tape temperature at the heating period during a half wave of the ac current pulse.

2. Test of short HTS samples

2.1. Operation conditions and measurement technique

The dynamic characteristics of HTS elements have been studied. The tape manufactured by SuperPower Inc. (USA), of type SF12050 of various length (l = 10 cm, 25 cm and 50 cm) with critical current $I_C \approx 270$ A was used.

Our experiments were carried out using the setup containing the transformer with an output voltage U_0 = 20 V (effective value), a load resistor R_0 = 0.2 Ohm, an auxiliary vacuum contactor K_1 and a control system CS (see figure 1).

The thyristor valve VT and additional resistor R_1 in the designed circuit were connected in series. This chain was connected in parallel with resistor R_0. Thyristor valve VT was used for the imitation of the fault current with different amplitude that is adjusted by a variation of resistance R_1. During the experiments, the HTS elements were immersed in a pool with liquid nitrogen.

The control system switched on a key K_1 at the moment of the voltage maximum. Switching on *VT* (for generation of a fault current) occurred approximately through one period load after and switching-off key K_2 occurred in the end of the first half wave of a fault current.

To measure the recovery time to superconductivity state, the switch K_2 was shunted by the resistance R_2 equal 50 Ohm. A whole measurement time of the HTS tape recovery after a fault current end was near 300 ms.

Own network reactance in fault current mode is always small (less than 15 mOhm) in comparison with the HTS element resistance after its transition to the normal state, so all network voltage is loading to the HTS element (when $R_1 \approx 0$). Such conditions are close to real current limiting conditions in the ac networks. A change of current limitation in this case was easily adjusted by a change of the HTS tape length. The relation between the current limitation and the voltage drop at the HTS element was studied for three values of resistance R_1 equal to 0.025 Ohm, 0.05 Ohm, and 0.1 Ohm respectively.

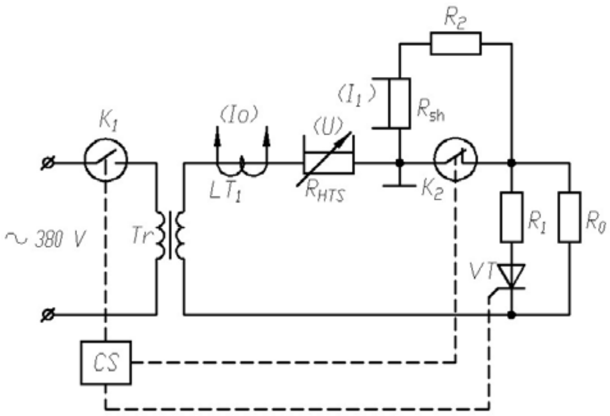

Figure 1. Schematic diagram of low voltage test setup.

Oscilloscope traces of current and voltage were recorded for each a sample. The current I_0 was measured by a galvanic untied detector with the sensitivity 2560 A/B. The coaxial shunt with sensitivity 0.08 A/B was used to measure current I_1 in the resistance R_2.

The voltage registration was carried out using two channels with different sensitivity in the fault current mode and in the recovery mode. The electric signals were registered by means of the Tektronix oscilloscope with the subsequent preservation and data processing of measurements data using a personal computer. The inductive component of a voltage drop on the HTS element Ldi/dt was subtracted from the obtained experimental data at data processing.

2.2. Results of study

After closing of contactor K_1 the load current is flowing into a circuit. The current amplitude 155 A is approximately twice less than the critical current of the HTS tape. To show the fault current limitation effect the oscilloscope traces were recorded in the transformer circuit both with and without the HTS element. If HTS element is present, the current in a circuit was limited owing to the nonlinear increase of the tape resistance after its transition to a normal state. The amplitude of a current I_{max} is determined by a temperature rise level of the HTS element during a half wave of a current. The current limiting mode for the HTS element of 25 cm in length at $R_1 = 0$ is shown in figure 2. The limited current I_0 and voltage U on HTS element as well as the fault current I_f at absence of the HTS element are shown in figure 2. One can see that the current limiting depth I_f/I_0 in this case was near 7. The current limiting depth was changed from 6 up to 10At under the variation of the tape length from 10 cm up to 50 cm.

The temperature of HTS tape T in the heating and cooling modes was estimated on the basis of measured temperature T dependence of the tape electric resistance R_l (Ohm/cm). This dependence was approximated by a quadratic polynomial in a range of temperatures 92÷350 K for the HTS tape of type SF12050,

$$R_l = -0.04 + 0.0015 \cdot T + 9.8 \cdot 10^{-7} \cdot T^2. \quad (1)$$

The maximum temperature T_{max} was reached at the moment of $t \approx 9$ ms for all elements. The obtained results have allowed one to determine the temperature rise of the tape in normal state versus such specific parameters as an electric field intensity $E = U/l$ and linear density of dissipated energy w in the tape during a current limiting mode (i.e., in our case, during a half-cycle of a current). These experimental relations are presented in figures 3 and 4, respectively.

It can be seen that for studied parameter these relations are close to linear ones.

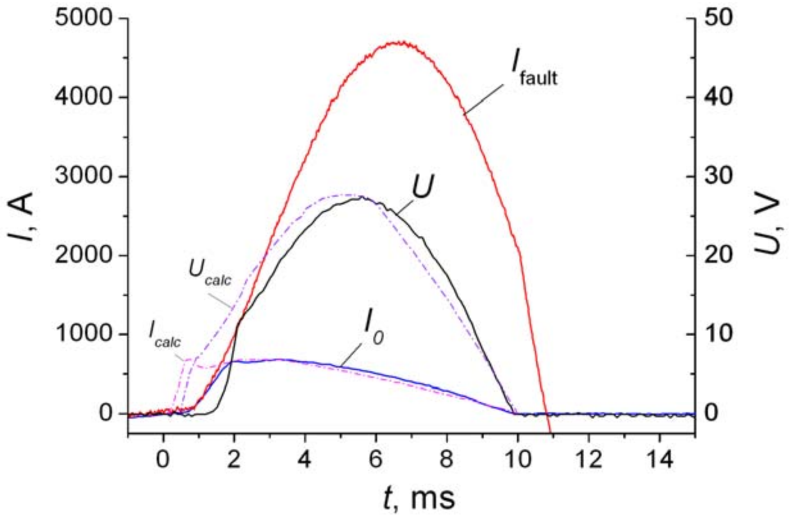

Figure 2. Oscilloscope traces of fault current I_{fault}, limiting current I_0, and voltage for HTS element by 25 cm in length.

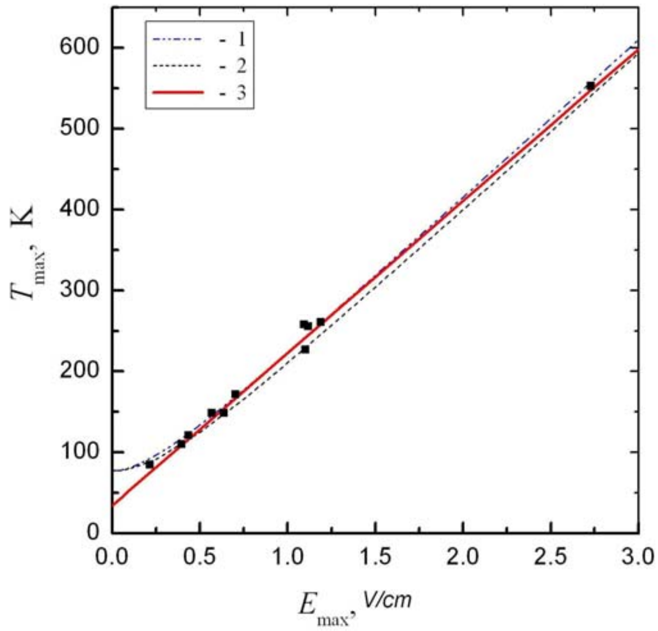

Figure 3. Maximum temperature of HTS tape *vs* maximum electric field intensity along the tape SF12050: (■)– experimental data, 1 – calculation by analytical formula (4), 3 – linear approximation of experimental data by relation $T_{\max} = 34.6+188*E_{\max}$

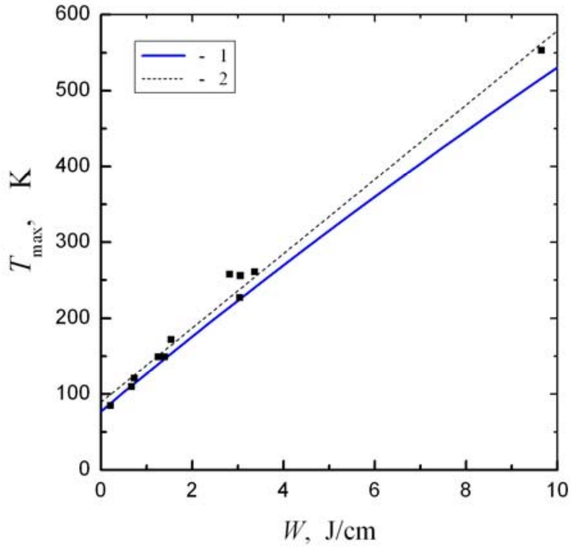

Figure 4. Maximum temperature of tape SF12050 *vs* linear density of dissipated energy: (■) – experimental data, 1 – calculation by analytical formula (6), 2 – linear approximation of experimental data with function T_{max} = 89+49*w.

2.3. Discussion

For a substantiation of relations obtained in the experiment let us consider an adiabatic heating of the HTS tape during one half cycle of ac current with a frequency 50 Hz.

Assume that the dissipated energy in a tape l in length during a half cycle of a sine-wave voltage $U = U_{max}\sin(\omega t)$time dt leads the tape temperature dT increase,

$$(U^2_{max}/l)\sin^2(\omega t)/R_l(T)dt = S\cdot l\cdot \gamma\cdot C(T)dT, \quad (2)$$

where $S = 6\cdot 10^{-7}$ is the cross-section area of a tape (m^2), $\gamma = 8600$ is density of tape material (kg/m^3), $C(T) = 369.7+0.19\cdot T$ (J/kg·K) is a specific thermal capacity of a tape substrate as function of absolute temperature T. By separation of variables t and T, we receive the following differential equation,

$$F(T)\mathrm{d}T = E^2_{max}\sin^2(\omega t)\mathrm{d}t \quad (3)$$

where $F(T) = S\gamma C(T)R_l(T) = -0.049+0.0026\cdot T$ and $E_{max} = U_{max}/l$.

Integrating the left part of equation (3) from $T = T_0 = 77.3$ K to $T = T_{max}$, and the right part from $t = 0$ to $t = \pi/\omega$, we shall obtain,

$$T_{max} = 196{,}1\sqrt{0{,}09 + E^2_{max}} + 18{,}75 \quad (4)$$

Results of calculation using Eq. (4) are depictured in figure 3 by curve *1*. The calculated curve for $E_{max} > 0.5$ V/cm is shown to coincide practically with the experimental data.

To find the relation between the maximum temperature of the adiabatic insulated tape and the energy dissipated in the tape by Joule losses during a half cycle ($\omega t = \pi$) the energy equation of the tape per unit length can be written as follows,

$$S\cdot\gamma\cdot C(T)\mathrm{d}T = E_{max}I_{max}\sin^2(\omega t)\mathrm{d}t \quad (5)$$

Integrating the left part of this equation in limits from T_0 =77.3 K to $T_{\max}$ and the right part of the equation in limits from $t=0$ to $t=\pi/\omega$ we will obtain the following relation,

$$T_{\max} = 450{,}48\sqrt{19{,}97 + W_L} - 1915 \qquad (6)$$

where $W_L = \pi \cdot E_{\max} I_{\max} / 2\omega$ (J/cm). The curve *1* obtained by means of formula (6) is compared in figure 4 with the linear approximation of the experimental data (straight line *2*). It can be seen the agreement between a calculated curve and experimental data.

The obtained relations allow us to estimate the minimum length of the HTS tape (or the maximum electric field intensity) at the given maximum temperature in the end of a current limiting mode.

In a process of fault current limiting it is necessary to consider also the transients caused by the dynamic current-voltage characteristic of HTS element, especially during the first half wave of a current. The mathematical model is developed to simulate the transition in an electric network with SCLCB, which takes into account the variation of tape resistance R_l with the temperature rise. The model allows us to calculate a variation of current, voltage across the HTS element and its temperature during a current limiting mode at given parameters of an electric network and the measured relation R_l (T). Results of such calculation for a tape of 25 cm in length are shown in figure 2. The distinction between calculated and experimental data at an initial stage of current and voltage increase is caused by the fact that this model is inadequate at temperatures of HTS tape below critical T_{cr} = 90 K.

3. Test OF THE HTS modules

To study an influence of the design features on the characteristics of SFCLCB, two HTS modules were manufactured for working voltage up to 3 kV as flat coils of 140 mm outer diameter with height of 25 mm. Bifilar winding were made from the 2G HTS tape SF12100. The length of a tape in the first module was equal to 4.75 m. The windings in the first coil were insulated with a kapron film. Inductance of this winding was 0.3 µH.

The tape and windings have been insulated with a polyethylene skeleton in the second module. Its design allowed liquid nitrogen to penetrate between layers of a tape. The gap between the neighboring coils of winding was near 2 mm, the whole length of a tape was about 2.5 m.

The test of modules was carried out using the high-voltage stand which schematic diagram is presented in figure 5. The stand consists of the charging device G, capacitor banks with total capacitance C_0 up to 10 µF, reactor Lo with adjustable inductance up to 6 mH, DC source, closing switch K_1 and control systems (CS). Parameters of the stand (C_0 = 1.8 µF, L_0 = 6 mH) were selected so that for the fault current mode the discharge current oscillated with a frequency close to 50 Hz (a half-cycle of fluctuations was 10.3 ms).

Switch K_1 serves for connection of the studied module with the preliminary charged capacitor bank. The triggered vacuum switch (TVS) was used as making switch K1. The DC source J served for a measurement of the HTS module resistance at current 1 A in a cooling mode after switching-off the discharge current by a high-speed switch K_2.

The CS generates and gives out signals with an adjustable delay to close K_1 and open K_2. The time delay of a signal for switching-off K_2 is selected from a condition that contacts in K_2 opened in the end of the first half wave of the discharge current I_0. Switching-off of a current occurs at the transition of a current through a zero. The nonlinear resistance R_1 serves for restriction of possible switching overvoltages. The amplitude of the first half wave of a current in HTS module structure was adjusted by change of charging voltage U_0. Electric signals from current and voltage detectors were registered by the Tektronix oscilloscope with the subsequent preservation and processing on a personal computer.

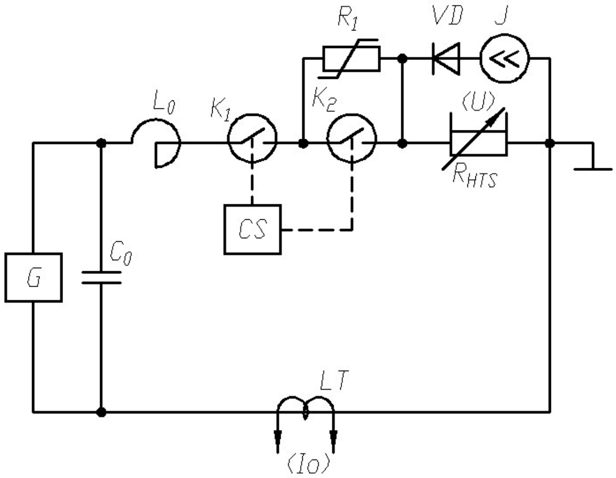

Figure 5. The schematic diagram of the high-voltage stand.

The heating of HTS elements (currents up to 1500 A in one single tape at voltage up to 3 kV) and recovery time of superconductivity after heating was studied. The heating process of HTS modules as well as short length tapes is shown to be considered as adiabatic. The experimental dependences T_{max} on density of energy W for tapes of different HTS tapes (SF1250 and SF12100) are practically coincided. This confirms the universality of the given specific parameter for an estimation of heating the HTS tapes. The recovery time of superconductivity for the module consisting of one flat coil was tens seconds. This time exceeds time demanded for operative autoreclosing mode (AUR, t_r ~1 s). On the contrary, recovery time of the second coil has appeared essentially less (figure 6) and it does not exceed time t_r. at $T_{max} \leq 200$ K

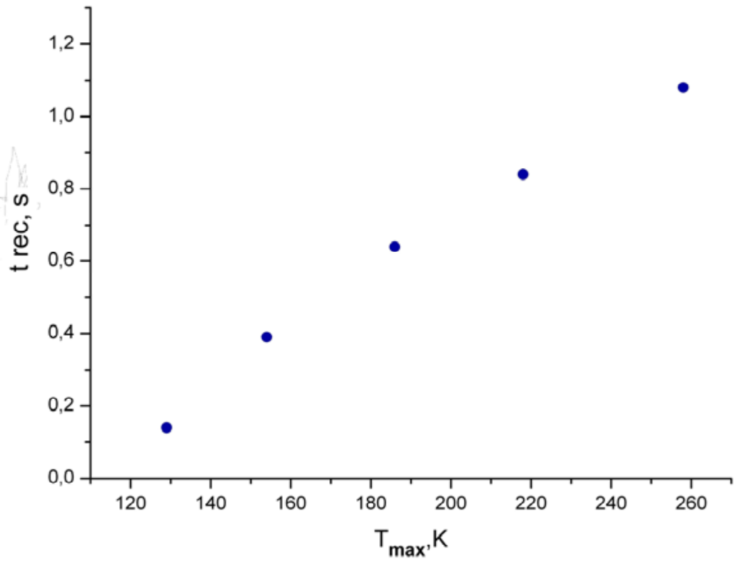

Figure 6. Relation between the recovery time and the maximum temperature for the second coil.

4. Conclusion

The relations between maximum limiting current, maximum temperature and electric field intensity and linear power dissipation along a HTS tape have been found for a model of fault current limiter. The obtained relations allow one to estimate the necessary length of a tape in HTS coil and a number of parallel and in series connected HTS elements for a given class of voltage and current limitation.

5. References

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