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Transient in a vertical superconducting wire at liquid nitrogen level decrease

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The transition to normal state in a vertical second generation high-temperature superconducting wire with alternating current was investigated experimentally at liquid nitrogen level decrease below the top end of the wire. The transition was shown to occur in a jump-like manner at a certain length of the external part of the wire and it is reversible. The stages of the transient were determined. The methods of heat balance recovery after such transition were suggested and realized. Feasibility of using the obtained results to develop an emergency level sensor for liquid nitrogen was pointed out.

Keywords: superconducting wire, liquid nitrogen, level sensor, transient, heat balance.

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Stability of heat balance in superconducting wire with current is determined by a relative position of curves of heat release and heat removal into the refrigerant [1]. If slope of the heat release curve exceeds the slope of the heat removal curve then with current increasing in the superconducting wire a thermal instability develops, which finally results in change of mechanism of heat removal [2–4]. In paper [3], for example, upon current increasing in high temperature superconducting (HTSC) wire a transient process is observed when changing the heat removal mechanism from convection to nucleate boiling, which resulted in stable overloaded mode [5,6].

But the thermal instability in the superconducting wire can be initiated in other way, namely at permanent current value change in the conditions of heat removal into the environment. In case of HTSC-wire this can be provided by level decreasing of liquid refrigerant (nitrogen) such that top part of the vertical wire is in nitrogen vapor above the liquid surface. As result the heat removal from the wire part above the liquid (external part) will be worsened, it will loss stability and go to normal state. In such case for the heat balance recovery after transition it will be necessary, firstly, to decrease current in HTSC-wire, and, secondly, create effective heat removal through wire ends due to thermal conductivity in longitudinal direction. For this the top current lead should be provided with liquid cooling.

The operation principle, based on parameters difference of external and immersed parts of the initial level transducer (sensor), is widely used in devices to measure level of cryogenic liquids (level meters). Different types of level meters, their advantages and drawbacks are described in detail in [7]. The level meters due to their purpose have smooth monotonic relationship between the parameter and refrigerant level. In electrical level sensor, which include the termoresistive and capacitive, such parameters are resistance of vertically located metal wire (including superconducting), and capacitance of cylindrical capacitor partially filled with cryogenic liquid, respectively. Many publications are associated with the electric sensors. In papers [8,9] simultaneously sensors of two above types are used, and in [10] an optical fibre sensor was developed.

The sensors able to response to passage of definite level by the cryogenic liquid surface are of specific interest. The matter is that in case of failure of the system maintaining set level of refrigerant (such systems are widely used in cryogenic engineering [7]) the sensor shall execute function of alarm indicator, which is difficult to implement using the level sensors with smooth characteristic. The signal change of such sensor when the liquid level passes any value is insignificant. The alarm indicator shall ensure significant change of output signal at definite level of the liquid refrigerant.

In terms of the response to liquid level change the diode sensors of discrete level meters are exclusion among the level sensor [8–11]. The operation principle of the silicon diode sensor is based on sudden decrease in its resistance upon temperature increasing [11]. But for the diode temperature significant increasing at exit from the liquid a heating current permanently passes through it, current by three order of magnitude exceeds the rated value of current. Such large current flow under long-time normal operation mode of the cryogenic support system provides additional thermal load.

Due to above mentioned there is need to suggest the operation principle of the alarm indicator of refrigerant level, which under mode of level maintenance does not introduce

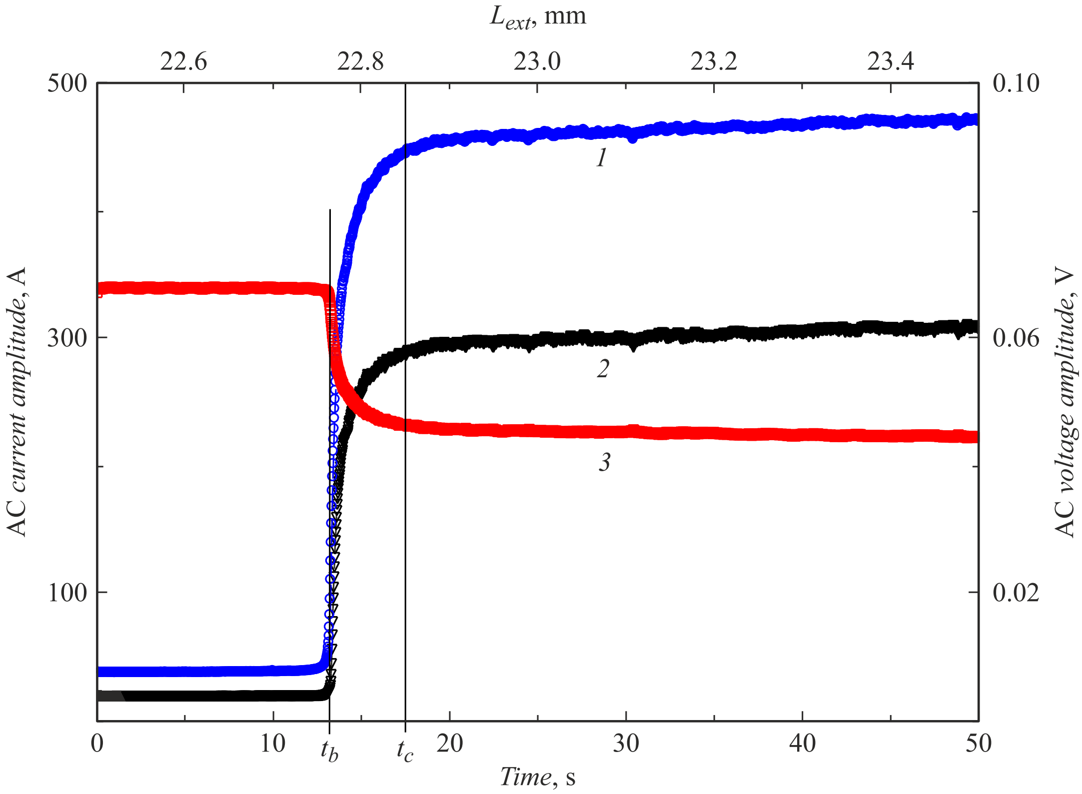

Figure 1. Oscillograms of current and voltage amplitudes at liquid nitrogen level decreasing. *1* — voltage amplitude V_L, *2* — voltage amplitude V_P, *3* — current, initial amplitude is 339 A. The frequency is 50 Hz.

additional incoming heat load to the cryogenic liquid. This paper objective is to show that if above methods are applied to restore the heat balance the reversible transition of HTSC-wire to the normal state is possible when level of the liquid nitrogen decreases below the definite level, and to study features of the appropriate transient process.

Studies were carried out on sample (length 71 mm, width 12 mm, critical current $I_c = 377$ A), prepared from stabilized HTSC-tape manufactured by „SuperOx" [12]. Experimental cryostat ensures visual monitoring and registration as per external scale the level of liquid nitrogen and its position relative to the top edge of the sample. Measurements were made at alternating current of commercial frequency (50 Hz). Sample of HTSC-wire was short-circuited to LV secondary winding of the transformer, the primary winding was powered by control alternating voltage. Such way of connection makes it possible to take advantage of the fact that even wires with very low resistance, including superconductors in normal state, can have significant apparent resistance in the equivalent circuit upon proper selection of the transformer parameters [6]. This was used in [6] to activate the protective HTSC-resistors, which by their apparent resistance limited the current increasing upon load short-circuit. In present paper this circuit executed some other function: upon superconductivity loss it ensured current decreasing in the wire, which facilitated the heat balance restoration. For the same purpose the current lead to the top end of the sample passes through a bath with liquid nitrogen.

At beginning of the measurement cycle the nitrogen level was located above the top contact of sample and current lead. In sample the alternating current was supplied with amplitude not exceeding critical current, then instantaneous values of current and voltage were continuously measured both from full length of sample V_L, and from potential contacts (which are at distance of 5 mm from sample end faces) V_P. Over time the level liquid decreased due to evaporation, and at some level value the sudden changes in amplitudes of current and voltage occurred: current decreased, and both voltages increased. To reproduce this changes from the data array the time interval 50 s is selected, during this interval the studied transient process occurred. Fig. 1 shows behavior of time dependence of amplitudes of voltage (curves *1*, *2*) and current (curve *3*) at initial current amplitude 339 A. Time reference point is beginning of selected interval. Fig. 1 shows that the transient process starts in a jump-like manner, then gradually decelerates, and its full duration is about 10 s.

Top axis in Fig. 1 shows length of external part of the wire L_{ext}. Numeric marks on this axis were obtained by calculations based on level measurements of the liquid nitrogen just before the wire exit from the liquid, and just

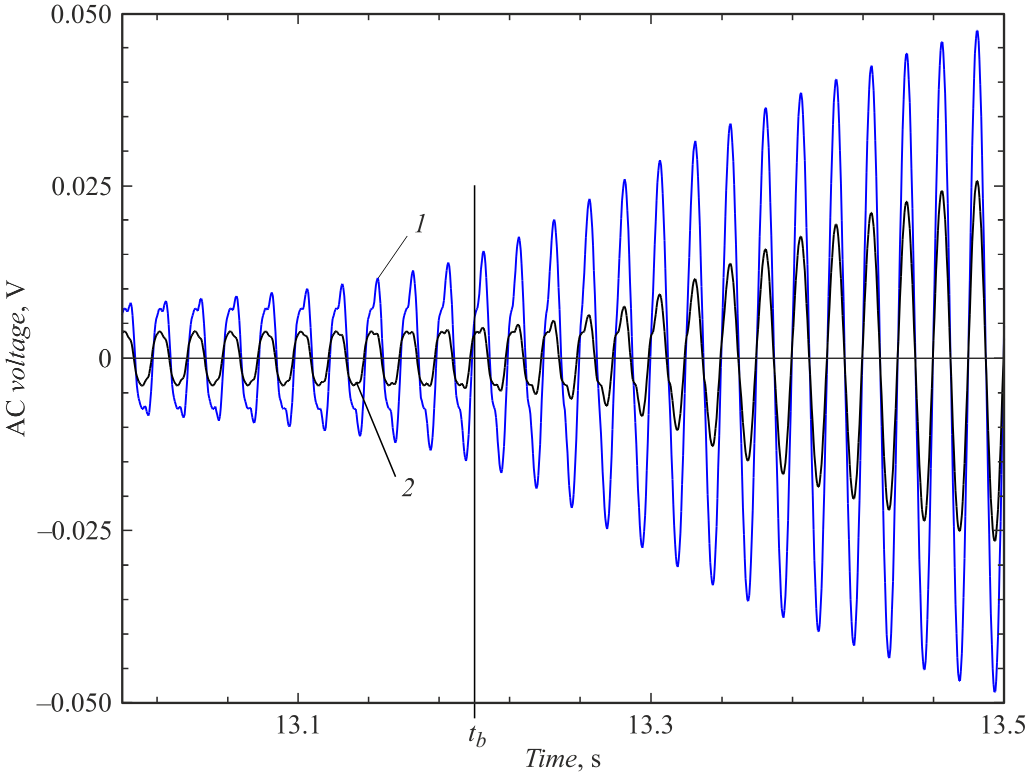

Figure 2. Oscillograms of voltages V_L (*1*) and V_P (*2*) at beginning of transient process. The frequency is 50 Hz.

after end of „activation". Such data ensure evaluation of both length of sample part about the nitrogen level at the time of „activation", and rate of its increasing during transient period.

Fig. 2 shows in detail the initial stage of the transient process by voltage, when the most significant signal changes occur. Forms of the voltage signals became nonsinusoidal. At that changes on form and amplitude of voltage V_P occur with some time delay relative to similar changes V_L.

Finally, Fig. 3 shows oscillograms of signals during small number of alternating current cycles. The oscillograms in Fig. 3, *a* were recorded upon sample full immersion into liquid nitrogen, and Fig. 3, *b* and *c* — at time moments t_b and t_c, shown in Fig. 1 and 2. These oscillograms show that upon full immersion of wire into the nitrogen current and voltage are sinusoidal, and phase shift between them is close to quarter of cycle (Fig. 3, *a*); upon transient process development the voltage is nonsinusoidal (Fig. 3, *b*); upon the transient process completion all signals are sinusoidal, and current and voltage are in phase (fig. 3, *c*).

Overall, from Fig. 1–3 it follows that before the transient process HTSC-wire is in superconducting state, it impedance represents inductive reactance, and heat releases are insignificant; the transient process develops via the resistive state, when nonlinearity of the current-voltage curve results in nonsinusoidal signals [4], basic increase in voltage occurs during 0.5 s (Fig. 2 and 3, *b*); the process ends by the transition to normal state with linear current-voltage curve and predominance of resistance (Fig. 3, *c*). The process delay in sample part between the potential contacts as compared to its development at full length is due to normal zone formation at the top end of sample and low speed of its propagation along the wire [13].

At next level increasing of the liquid nitrogen the superconductivity restored, i.e. the transition is reversible, and long-time flowing of current did not result in worsening of the wire parameters [14]. During multiple repetitions of measurements at different initial amplitudes of current the scatter in values of the nitrogen level, at which „activation" occurred, did not exceed 4 mm. As in many types of HTSC-electrical equipment, for example, in transformer [15], the work level exceedance of the liquid nitrogen above the top edge of HTSC-winding is at least 100 mm [16], the specified repeatability of the results is acceptable in terms of timeliness of alarm signal generation.

These results ensure the conclusion that the suggested circuit of transient process registration in vertical HTSC-wire complies with the set requirements. It provides significant change in sensor signal when the cryogenic liquid level passes the definite level. Use of alternating current and cooled current leads ensures state stability of HTSC-wire. So, such circuit can be used to create alarm indicator of liquid nitrogen level.

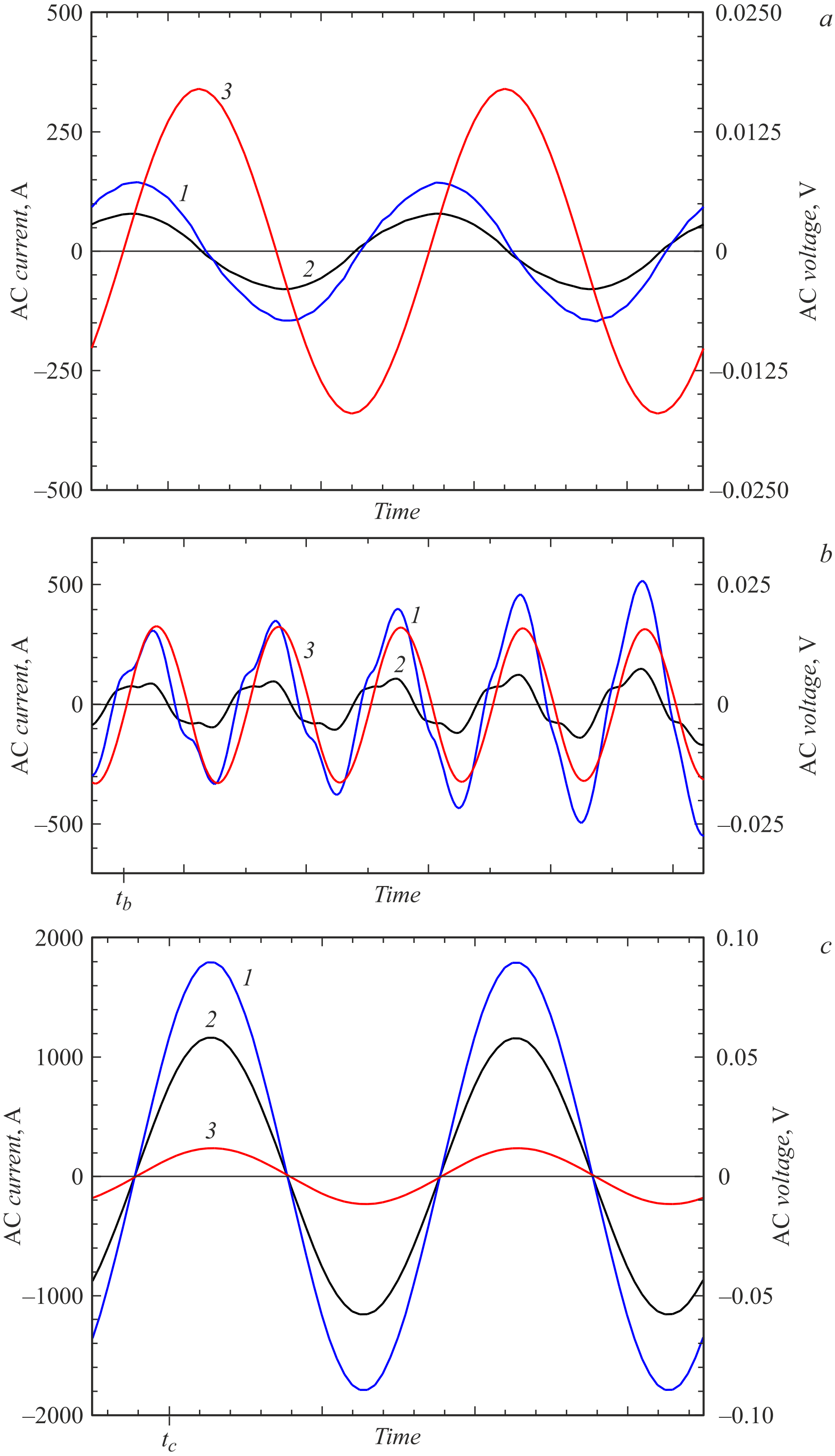

Figure 3. Oscillograms of current and voltage at different time moments. *a* — at beginning of measurement cycle, *b* — at time t_b, *c* — at time t_c. *1* — voltage V_L, *2* — voltage V_P, *3* — current. The frequency is 50 Hz.

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Conflict of interest

The authors declare that they have no conflict of interest.

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