05

Physics simulation of a superconductor gaseous phase sensor for long nitrogen cryostat

© V.A. Malginov[1], L.S. Fleishman[2]

[1] Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
[2] Sergo Ordzhonikidze Russian State University for Geological Prospecting, Moscow, Russia
E-mail: malginovva@lebedev.ru

Received October 8, 2024
Revised December 9, 2024
Accepted December 20, 2024

The concept is proposed of a gaseous phase sensor for long nitrogen cryostat using high-temperature superconducting wires. The principle of operation of the sensor is based on jump-wise transition to normal state of a superconducting bifilar current carrying wire when a part of the bifilar is under nitrogen vapor. Experiments have been carried out on the sensor physics simulator that confirm its working ability and its feasibility to be scaled up to the long cryostat size.

Keywords: high-temperature superconducting wire, gaseous phase sensor, long cryostat, bifilar.

DOI: 10.61011/TPL.2025.04.61008.20141

Studies into technical applications of superconductivity are often aimed at both reducing losses in electrical power equipment [1] and ensuring the reliability and failure-free operation of such facilities [2]. Monitoring of the cryogenic supply system for superconducting electrical equipment is of great importance [2–9]. Superconductors may be used in this context as thermal parameter sensors in control and automation devices. For example, the concept of an emergency liquid nitrogen level alarm based on a vertical high-temperature superconducting (HTSC) current-carrying wire was proposed and verified experimentally in [3]. Vertical liquid helium level sensors with low-temperature superconductors (see, e.g., [4]) are also commonplace. However, such sensors are designed for bulk cryogenic vessels (cryostats with a height on the order of 1 m) with a uniform liquid level for the entire vessel and are ill-suited for a so-called long cryostat used to cool a superconducting cable in a near-horizontal position. A long nitrogen cryostat with a superconducting cable is several hundred meters in length; its entire volume needs to be filled with liquid coolant [5,6], and a gas bubble/vapor lock may form at any point along its length. This is the reason why monitoring of the thermal state in the vicinity of a superconducting cable is a very challenging task.

Continuous monitoring necessitates the installation of temperature and flow meters in the terminals of HTSC cable lines [5], which also provide power current leads (up to 5 kA), current leads for sensors, and joints. Because cable cryostats are hermetically sealed and owing to their large length, measurements of thermal parameters in a nitrogen cavity require innovative engineering solutions. The use of distributed fiber-optic temperature sensors appears to be promising in this case [7–9]. However, such sensors require calibration, which makes it rather hard to perform accurate measurements of the absolute value of temperature [7,8].

It should be noted that even high-accuracy measurements of the coolant temperature (or its variation) do not solve the problem of detection of an emergent gas phase in a cable cryostat, since the difference in gas and liquid temperatures near the phase boundary is small and the temperature varies along the cryostat [6,8].

Thus, the search for reliable methods of detection of the gas phase in a long nitrogen cryostat is a relevant scientific and practical problem that arose no more than three decades ago in connection with the production of HTSC cables and has not yet been solved. The results presented below should facilitate rapid advances in solving this problem. The proposed approach involves the use of a second-generation (2G) non-stabilized HTSC wire extending along the entire length of a cryostat as a sensor. At the present moment, at least five companies in the world mass-produce such wires. They are manufactured in the form of multilayer tapes with a superconducting YBCO (or GdBCO) layer 1–3 μm in thickness. Manufacturers provide basic electromagnetic and thermal characteristics of these materials. Specifically, it is known that the critical current remains virtually unchanged in fields up to 30 mT; i.e., when a sensor is located outside an HTSC cable, where the leakage field is on the order of 1 mT, the variation of current in the cable should not affect the reproducibility of sensor characteristics. The collapse of thermal equilibrium in a superconducting current-carrying wire, which is accompanied by an abrupt transition to a normal state due to impairment of heat removal when a local gas phase emerges in the vicinity of a wire [3], underlies the operation of such a sensor.

The aim of the present study is to verify experimentally the performance efficiency of the proposed concept of a superconducting gas phase sensor and to demonstrate the feasibility of its application in long cryostats. Physical modeling, which does not require the construction of a

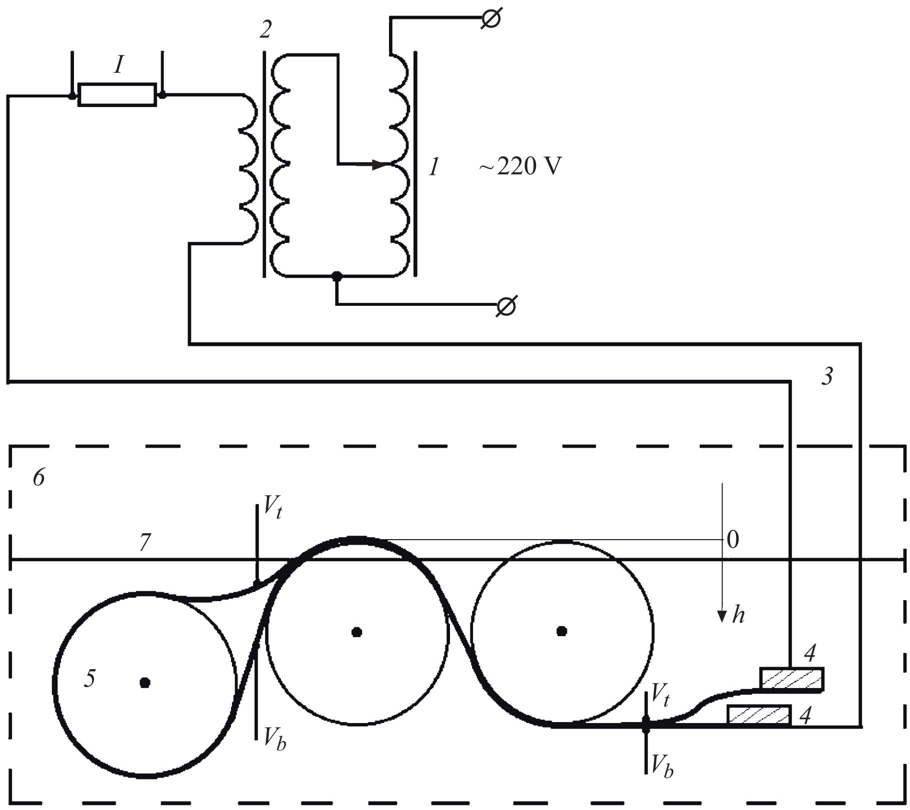

Figure 1. Schematic diagram of the gas phase sensor model. *1* — autotransformer, *2* — step-down transformer, *3* — current leads, *4* — contact clamps to HTSC tapes of the bifilar, *5* — return loop of the bifilar, *6* — nitrogen cryostat, and *7* — liquid nitrogen level. I — current in the circuit, V_t — potential probes on the upper tape, and V_b — potential probes on the lower tape of the bifilar.

sensor with a length comparable to that of the cryostat [7], was performed for this purpose. Instead, sections of a current-carrying HTSC wire no longer than 1 m were used in measurements. The gas phase was produced in their middle part, and wire sections on either side of it were immersed in liquid nitrogen. An HTSC wire in its normal state is a low-resistance conductor. An increase in resistance with local loss of superconductivity may be detected reliably in AC measurements in a transformer circuit, which allows for a many-fold enhancement of the resistance of a circuit with a wire due to the so-called apparent resistance [3]. The inductive reactance, which needs to be minimized to produce a functional sensor, is another factor that specifies the possibility/impossibility of measuring the resistance of a small section of a wire with a large total length. Therefore, a bifilar with oppositely-directed currents (Cooper bifilar) was fabricated for experiments from non-stabilized 2G HTSC tapes provided by SuperOx [10]. The tapes were 12 mm in width, and their critical current in liquid nitrogen was close to 400 A. To minimize thermal resistance between the tapes, they were separated from each other by mesh insulation [11]. Two bifilar designs (non-insulated and insulated) were investigated. In the insulated version, the bifilar was positioned between layers of adhesive insulating paper. This ensured mechanical stability of the HTSC tapes in the process of current input and provided an opportunity to reduce the inductive reactance per unit length to 14 $\mu\Omega$/m at the commercial frequency (50 Hz).

To simulate the conditions of application of a gas phase sensor in a long cryostat, the HTSC bifilar was completely immersed horizontally in liquid nitrogen (Fig. 1). Its middle part was curved vertically in the form of an arc with a radius of 32 mm. Thus, when the liquid nitrogen level was lowered, the upper point of the HTSC bifilar arc was the first to enter the gas phase, and the length of the bifilar section in the gas environment increased gradually as the liquid level dropped (shifted along the h axis) further. The key element of a transformer current source was a step-down transformer. Its low-voltage winding was short-circuited through the HTSC bifilar. The current (I) and voltages at the upper and lower tapes (V_t, V_b) were recorded in different sections of the bifilar.

The measurement cycle began with the HTSC bifilar immersed in nitrogen. An alternating current with initial amplitude I_{0i} (below the critical current) was introduced into the circuit with the HTSC bifilar. The nitrogen level then decreased continuously due to evaporation, causing the upper part of the bifilar arc to be immersed in nitrogen vapor. When the nitrogen level reached certain position h below the upper point of the bifilar, the HTSC sensor

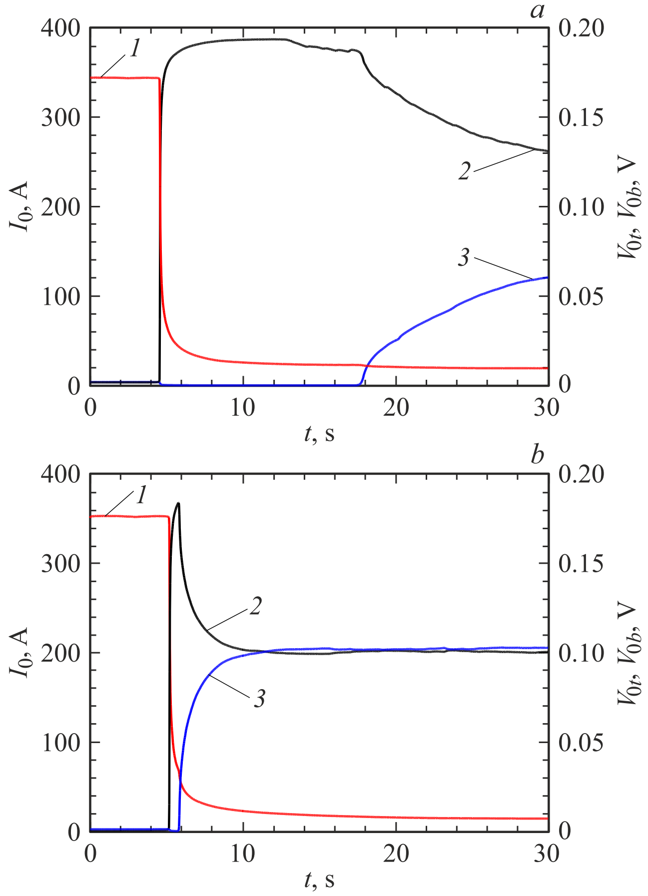

Figure 2. Time dependences of the current amplitude (I_0) in the HTSC bifilar and the voltage amplitudes at the upper (V_{0t}) and lower (V_{0b}) HTSC tapes in the case of non-insulated (*a*) and insulated (*b*) bifilars. *1* — I_0, *2* — V_{0t}, and *3* — V_{0b}.

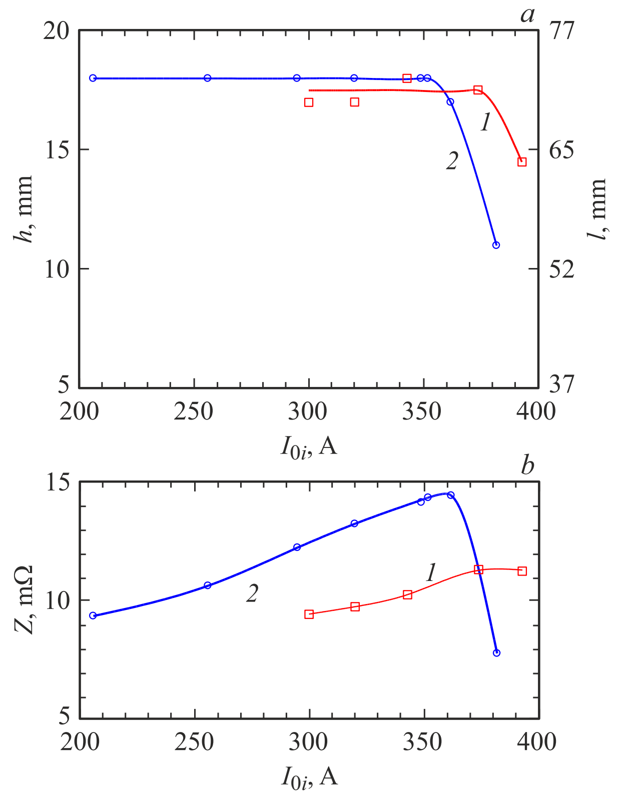

Figure 3. Distance h from the top point of the bifilar to the nitrogen level, length l of the bifilar section immersed in nitrogen vapor at the moment of sensor triggering (*a*), and impedance Z after the completion of the transient process (*b*) as functions of initial current amplitude I_{0i} in the case of non-insulated (*1*) and insulated (*2*) bifilars.

was triggered: this was manifested in a sudden reduction in current in the power supply circuit and a corresponding increase in voltage at the curved sections of the upper and lower tapes in the gas environment. The measurements were continued for 150 s after sensor triggering, and the sensor supply current was then switched off. Having added liquid nitrogen and changed the introduced current amplitude to I_{0i}, we repeated the above cycle.

Figure 2 shows typical time dependences of current amplitude I_0 in the bifilar and voltage amplitudes at the arc sections of the upper and lower HTSC tapes in the case of non-insulated (*a*) and insulated (*b*) bifilars. These dependences correspond to initial current amplitudes I_{0i} around 350 A and cover the first 30 s after triggering. In both cases, an abrupt several-fold reduction in current (sensor triggering) is observed at a certain instant, which is followed by a smooth decay of current. The current amplitude ultimately decreases by more than an order of magnitude. As a result, no irreversible overheating/destruction of the bifilar occurred until the end of the cycle. This may be attributed in part to its longitudinal thermal conductivity [12] and the improvement of conditions for heat transfer between the tapes by virtue of mesh electrical insulation [11]. This was verified by a control measurement (which was completely reproducible) of the critical current and the current–voltage curve after multiple sensor triggering events. The amplitudes of voltage at the tapes vary in qualitatively different ways in the cases shown in Figs. 2, *a* and *b*: in the non-insulated bifilar, amplitude V_{0t} at the upper tape increases simultaneously with a reduction in current, while V_{0b} at the lower tape lags approximately by 10 s; in the insulated bifilar, the indicated delay does not exceed 1 s. As the voltage at the lower tape increases, the voltage at the upper tape decreases; in the case of the insulated bifilar, they equalize within 6 s after sensor triggering. The mentioned features of dynamics of the transition of tapes to a normal state are due to the fact that the thermal interaction between the tapes after heating of the upper tape, which is located higher above the liquid level, is significantly more intense in the case of the insulated bifilar.

Figure 3 shows dependences $h(I_{0i})$ (h is measured with an error of ± 0.5 mm) at the moment of triggering (*a*) and the steady-state values of impedance Z of the HTSC sensor, wherein the resistive component is dominant, after the completion of the transient process (*b*) for non-insulated

(*1*) and insulated (*2*) bifilars. The calculated values of length l of the bifilar section in gas are indicated on the right axis in Fig. 3, *a*. It follows from Fig. 3, *a* that when the initial current approaches the critical value, the sensor is triggered at a smaller nitrogen level drop h. Accordingly, a reduction in length l of the wire section immersed in nitrogen vapor limits the growth of $Z(I_{0i})$ in the non-insulated bifilar and reduces Z in the insulated bifilar (Fig. 3, *b*).

The data in Figs. 2, 3 suggest that the results of model experiments confirm the validity of the proposed operating principle of the HTSC gas phase sensor for liquid nitrogen. It is triggered when the vertical dimension of the gas phase is close to 10 mm; a triggering event causes a sharp (several-fold) current drop, which may be used to generate an emergency alarm; gluing the tapes, one minimizes the inductive reactance of the bifilar and ensures its mechanical stability upon the introduction of current; insulation of HTSC tapes of the sensor from direct contact with the liquid and the use of mesh inter-tape insulation accelerates significantly the equalization of electrical and thermal parameters in the upper and lower tapes of the bifilar, thereby expanding the safety margin of sensor operation. It should be noted that the sensor efficiency was demonstrated at the largest HTSC tape width values in the manufacturer's dimension range. Thus, in addition to verifying the operating principle, we tested successfully the implementation of needed current input and power sources at the maximum operating currents. Since the heating of the tape and heat removal from it depend on the specific characteristics of the HTSC material and liquid nitrogen and are largely independent of the tape width, the use of a narrower HTSC tape with the same structure will be sufficient if the operating current and the requirements for the current source and current leads are to be reduced.

The feasibility of practical application of an HTSC gas phase sensor in a long cryostat should be determined by scaling it to the factory length of the power cable (i.e., the standard length of the cable product in a single section). The factory length of an HTSC cable (determined by the outer diameter of the cryostat, which is normally close to 100 mm [4]) does not exceed 450 m [13]. It can be seen from Fig. 3, *a* that size l of the normal region after sensor triggering depends on the size of the gas bubble and does not depend on the total bifilar length. With a sensor length of 450 m and an inductive reactance per unit length of the bifilar of $14\,\mu\Omega$/m, the inductive reactance of the sensor is below $7\,\mathrm{m}\Omega$. This implies that the impedance of the bifilar section (approximately $10\,\mathrm{m}\Omega$) shown in Fig. 3, *b* should provide a reliably recorded emergency alarm as a result of sensor triggering.

The presented data suggest that the proposed concept of a superconducting gas phase sensor for a long nitrogen cryostat is usable, and the results of physical modeling substantiate the feasibility of its practical application.

Funding

This study was carried out under state assignment using the facilities of the Center of Collective Use of Lebedev Physical Institute of the Russian Academy of Sciences.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.V. Zubko, S.Yu. Zanegin, S.S. Fetisov, V.S. Vysotsky, A.A. Nosov, E.S. Otabe, T. Akasaka, Sverkhprovodimost: Fundam. Prikl. Issled., No. 1, 53 (2024) (in Russian). DOI: 10.62539/2949-5644-2024-0-1-53-62

[2] T. Masuda, M. Watanabe, T. Mimura, M. Tanazawa, H. Yamaguchi, J. Phys.: Conf. Ser., **1559**, 012083 (2020). DOI: 10.1088/1742-6596/1559/1/012083

[3] V.A. Malginov, L.S. Fleishman, Tech. Phys. Lett., **50** (4), 71 (2024). DOI: 10.61011/PJTF.2024.08.57518.19785.

[4] K.R. Efferson, Adv. Cryog. Eng., **15**, 124 (1995). DOI: 10.1007/978-1-4757-0513-3_18

[5] E.P. Volkov, L.S. Fleishman, V.S. Vysotsky, A.A. Nosov, V.V. Kostyuk, V.P. Firsov, S.F. Osetrov, A.N. Kiselev, in *Innovatsionnye tekhnicheskie resheniya v programme NIOKR PAO „FSK EES,“* Ed. by A.E. Murov (AO „NTTs FSK EES," M., 2016), pp. 32–49 (in Russian).

[6] O.A. Koval'chuk, G.V. Murav'ev, V.I. Nikishkin, V.S. Ovsyannikov, I.Yu. Rodin, D.B. Stepanov, M.V. Dubinin, A.V. Kashcheev, V.E. Sytnikov, Sverkhprovodimost: Fundam. Prikl. Issled., № 2, 14 (2024). DOI: 10.62539/2949-5644-2024-0-2-14-30

[7] Y. Yue, G. Chen, J. Long, L. Ren, K. Zhou, X. Li, Y. Xu, Y. Tang, Superconductivity, **4**, 100028 (2022). DOI: 10.1016/j.supcon.2022.100028

[8] Yu. Larin, Yu. Smirnov, Pervaya Milya, No. 1, 16 (2011) (in Russian). https://www.lastmile.su/files/article_pdf/1/article_1992_588.pdf

[9] X. Li, C. Qian, R. Shen, H. Xiao, S. Ye, Opt. Express, **28**, (6), 8233 (2020). DOI: 10.1364/OE.384994

[10] S. Samoilenkov, A. Molodyk, S. Lee, V. Petrykin, V. Kalitka, I. Martynova, A. Makarevich, A. Markelov, M. Moyzykh, A. Blednov, Supercond. Sci. Technol., **29** (2), 024001 (2016). DOI: 10.1088/0953-2048/29/2/024001

[11] V.A. Malginov, L.S. Fleishman, Tech. Phys. Lett., **49** (6), 50 (2023). DOI: 10.61011/TPL.2023.06.56380.19579.

[12] S.V. Pokrovsky, A.Yu. Malyavina, R.G. Batulin, I.A. Rudnev, Kabeli Provoda, No. 6, 14 (2023) (in Russian). http://www.kp-info.ru/node/221

[13] *Kabeli, provoda, materialy dlya kabel'noi industrii. Tekhnicheskii spravochnik* (NKP „Ellips," 2006), p. 86 (in Russian). https://diext.ru/wp-content/uploads/2019/06/Kabeli-provoda-materialy- dlya-kabelnoj-industrii.pdf

Translated by D.Safin