Published in AIP Conference Proceedings 1218, pp. 461-468 (2010).

Cryogenic and Electrical Test Results of a 30 M HTS Power Cable

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***Abstract* - In the framework of the Russian R&D Program for high-temperature superconducting (HTS) power devices, a three-phase, 30-m-long cable carrying a current of ~1.5-2 kA under the 20 kV operating voltage was delivered by the Russian Scientific R&D Cable Institute as the first stage of the HTS power cable project. Various basic HTS materials, cryostats and current leads were incorporated into the cable design in this essentially research part of the project. The cable is being tested at the special test facility for superconducting power devices developed at the R&D Center for Power Engineering. The cryogenic system for the test facility was delivered by Stirling. The basic cryogenic system was equipped with a specially developed flow distribution unit. This unit permitted variation and control of liquid nitrogen flows, pressure and temperatures in all three cable phases. Dependencies on temperature of critical currents of each phase were measured during the cable test. The results of this project's first stage were used to develop and produce a 3x200m cable system for the Moscow distribution grid. In this paper, results of cryogenic system tests and cable electrical tests are presented.**

Submitted July 9, 2009. Accepted July 29, 2009. Reference No, ST117; Category 6
A quite similar paper was simultaneously submitted to the CEC/ICMC 2009 Proceedings. If accepted, the CEC/ICMC published version should be referenced (the reference will be displayed here once available).

***Keywords* - superconducting power cable, HTS, cryogenic systems, cable test**

I. INTRODUCTION

In the Russian R&D Program on superconducting power devices, HTS power cables are considered as most advanced and close to commercialization. During the program completion extensive technological experiments were performed to develop an industrial cable manufacturing technology, and a 5m piece of the full-scale power cable has been developed and tested as the first prototype [1]. On the basis of these developments and tests, an experimental 30 m HTS power cable has been produced as a prototype for longer cables [2,3]. Three 30 m phases carrying currents of ~1.5 kA (nominal operation) and 2 kA (30% overload operation) under the 20 kV operating voltage were delivered as the result of the project. The Various basic HTS materials, cryostats and current leads were incorporated into the cable design in this essentially research project. The cable is being tested at the special test facility for superconducting power devices developed at the R&D Center for Power Engineering.

Before the full scale 30 m cable test, a 5m witness sample has been cut from the full length cable, heavily instrumented and extensively tested at the low voltage – high current test facility at the Russian Scientific R&D Cable Institute (VNIIKP) [2-4]. The witness-sample test confirmed that design methods and cabling technology are properly developed to make full use of the superconducting properties of HTS tapes used for the 30 m cable.

The cryogenic system for the test facility was delivered by Stirling Cryogenics & Refrigeration BV (The Netherlands). The basic cryogenic system was equipped with specially developed flow distribution units. These units permitted variation and control of liquid nitrogen flows, pressure and temperatures in all three cable phases. Dependencies on temperature of the critical currents of each phase were measured during cable tests. In the paper the results of cryogenic system tests and cable electrical tests are presented

II. EXPERIMENTAL CABLE AND TEST FACILITY

A. Experimental Three–phase 30 m HTS Power Cable and Current Leads

The cable design was described in details in [2, 3]. The basic design of the cable consists of a central former, 2-layers of HTS tapes, cold paper insulation, and a non-superconducting copper shield. The photo of the cable is shown in Figure 1. The non-superconducting shield design has been accepted due to the limited budget of this project. We considered the 30 m cable development as mainly a research project necessary to work through the technology and production issues of HTS power cables. That is why we varied basic HTS materials, cryostats and current leads in the cable design.

The former was made of stainless steel spiral covered by two layers of copper wire bunches to provide HTS protection at fault. A copper cross-section of about 220mm^2 has been selected after the fault behavior analysis [2]. The superconducting cable layers were made of two types of first-generation (1G) HTS BSCCO-based tape. For one phase the CT-OP™ tapes from Sumitomo Electric Industry Co (Japan) were used. Two phases were made of American Superconductor Co. (USA) Hermetic™ wires. Different tapes were used to verify the survival of superconducting properties of different HTS tapes during all technology routes for the power cable production.

The central former and the HTS layers cabling were fabricated using the especially upgraded cabling machines at the VNIIKP workshop. The insulation of the cable core by the conventional cable paper has been done at the cable factory “Kamskii Kabel” at the city of Perm (some 1500 km from Moscow). The non-superconducting copper shield from copper tapes has been made at the “Kamskii Kabel” factory as well.

The three flexible cryostats, each 30 m long, were produced by Nexans Deutschland Industries, Hannover (Germany). We used two of three cryostats with an O.D. of 110 mm and one with an O.D. of 92 mm to compare the heat losses in cryostats [2, 3]. The inner diameters of all cryostats were the same.

Fig. 1. Photo of the 30 m experimental cable model.

Fig. 2. Two types of current leads connected to the cryostats and electrical system.

Three pairs of current leads were developed and produced by two different Russian institutions [2, 3]. The current leads were developed for a 4 kA maximum current and 20 kV nominal voltages. The photo of the current leads connected to cryostats and electrical system is shown in Figure 2.

B. Electric System and Cryogenic System

The experimental cable has been installed at the special test facility for tests of HTS power devices at the R&D Center for Power Engineering in Moscow. This test facility is connected to the substation "Yuzhnaya" of the Moscow Energy Grid and it can perform tests with step-like voltage regulations (6 kV, 10 kV, 19 kV, 33 kV, 66 kV, 110 kV, 183 kV) and with AC currents up to 3 000 A. The important thing about the test facility is that there are installed electrical reactors as loads *that permit testing of different superconducting power devices under the full load*. It means the possibility to model the power devices behavior in real conditions of a grid. The general arrangement of the test facility is shown schematically in Figure 3.

The cryogenic system for the test facility has been delivered by the Stirling Cryogenics and Refrigeration BV, The Netherlands. The standard system LPC 4 was adapted for the needs of our test facility. The cryogenic block is able to use two cryocoolers that permits to increase the cryogenic power if necessary. Right now one cryocooler SPC 4 is used with the cryogenic power up to 3.4 kW at 77 K. Two cryocoolers would allow a possible future upgrade up to 7 kW cooling power.

An important part of the cryogenic system is a specially developed flow distribution and control unit. This unit permits to distribute flows of subcooled pressurized liquid nitrogen between the three phases of a cable. It also has pressure and flow meters and temperature sensors installed at the inlet and outlet of each phase of the cable. The cryogenic system permits to cool LN_2 down to 66K, with a flow up to 100 liter per minute. Maximum pressure at the outlet is up to 6 bar, minimum pressure at the inlet 2 bar. The cryogenic system permits cooling power variations from 660 to 2800 W at 72 K and from 840 to 3400 W at 77 K. A photo of the cryogenic system with the flow distribution unit is shown in Figure 4.

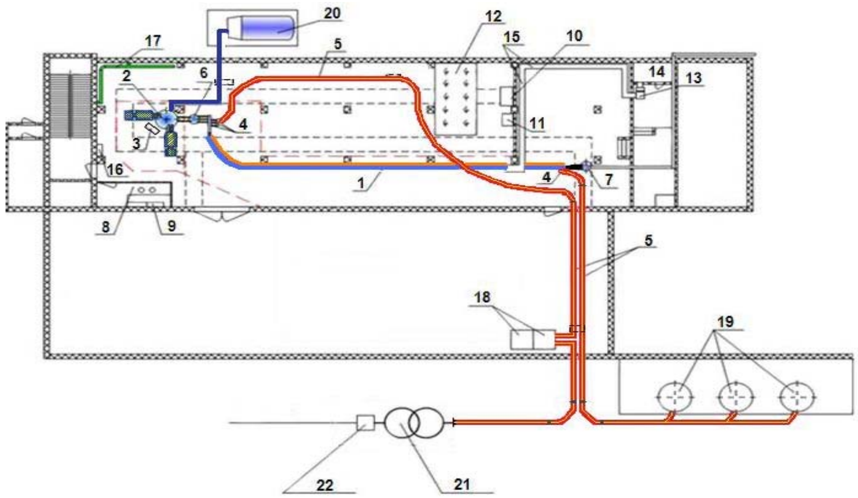


Fig. 3. Test facility for HTS power devices scheme. 1- HTS cable, 2, 3, 6, 7, 17, 20 – Cryogenic system, 4 – Current leads, 5, 11, 12, 16, 18, 21, 22 – Facility power system, 8, 9 – Facility control center 10 – DC current source, 13, 14, 15 – Air compartment, 19 – Electrical load.

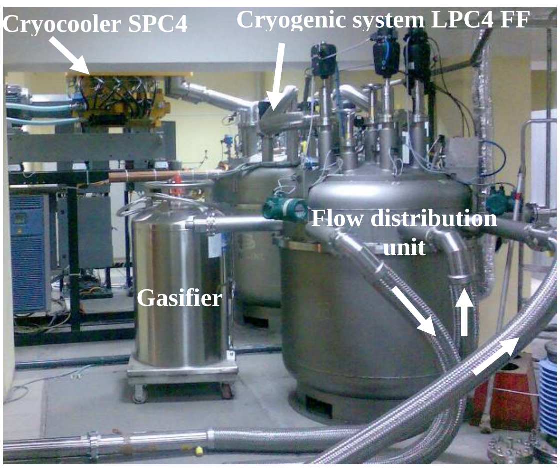


Fig. 4. Cryogenic system with flow distribution unit. Directions of LN_2 flows are shown.

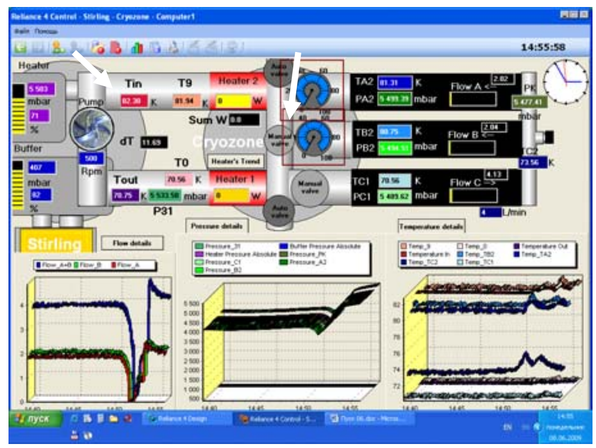


Fig. 5. Example of a screen shot from the control panel of cryogenic system.

The computerized control system allows one to record in real time temperatures, flows and pressures within the cryogenic system and in the three phase cables as it is shown in Figure 5. A measuring system for electrical parameters, which is certified by the State Standard Committee is used as well.

The test facility permits to test powerful HTS electro technical devices in wide ranges of cryogenic and electrical parameters.

III. CRYOGENIC SYSTEM TEST

Before the cool-down starts, a pressurizing leak check should be performed. Subsequently, drying of the cable should be done by use of warm nitrogen gas at ~ 50-60 ^{0}C from gasifier and flow distribution unit.

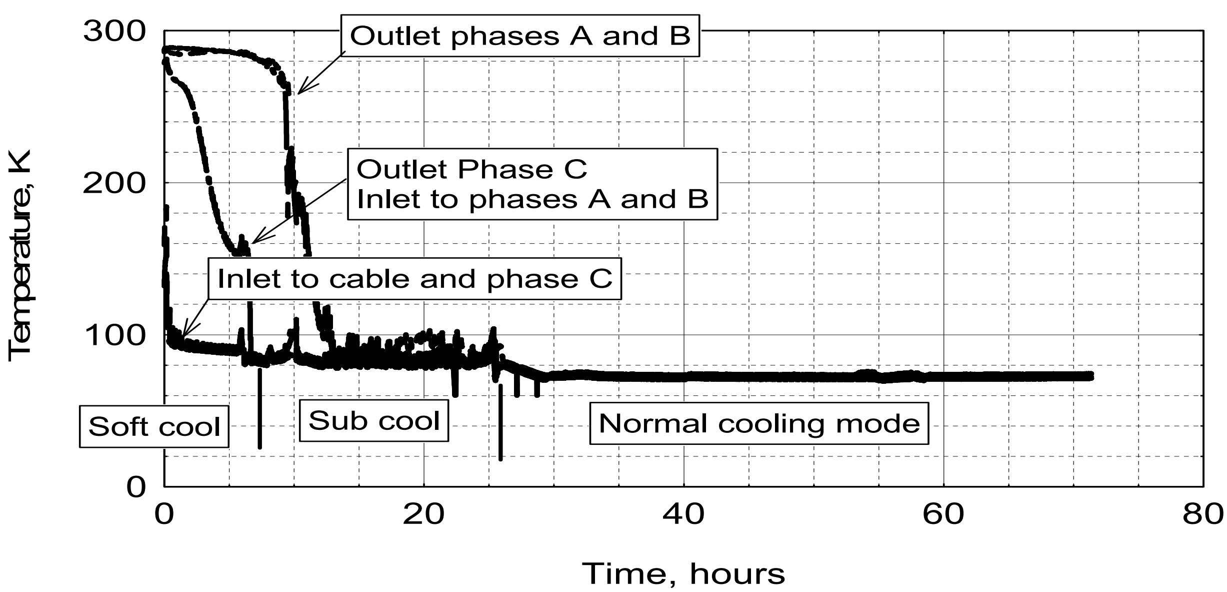
The cryogenic system permits several operational modes. This is illustrated in Figure 6, where examples of temperature *versus* cool-down time of the cable (first, upper diagram) and flows of nitrogen versus time (the next diagram down) are shown. The soft cool mode starts after drying the cables. Cold gaseous nitrogen is going to phase C fist and is returning via phases A and B to the cryogenic system. The temperature is decreased during 7-10 hours. The sub-cooling mode starts once portions of liquid nitrogen are sprinkling to the three cable cryostats (3 phases) continuing their cool-down. After the temperature reaches ~80K at cable's inlet and ~85K at cable's outlet the LN_2 pump starts operating and high flow of nitrogen under pressure is pumping through the three cable phases.

In all cooling modes mentioned, the cryogenic system is working fully automatically. Switching between modes is performed by an operator. In Figure 6 one can see that it takes about 30 hour to cool down our cable to its nominal operational temperature (below 77K). After cooling down below 77 K, the cryogenic system permits to perform all necessary electrical tests of HTS power cable.

During the normal operational mode, several cryogenic tests have been performed with inlet temperature as low 66K and with a LN_2 flow from as low as ~370 kg/hour to as much as 2400 kg/hour. During tests, the cable was working both with and without currents and under full loads. The data about thermal losses during these tests are analyzed and will be published later.

Warming test has been performed to check how long the cable can work under condition of the cryogenic system stalled. With cable current $1500A_{rms}$, inlet temperature about 70.7 K, and outlet temperature about 72 K, the cryogenic pump has been stopped manually by closing the LN_2 flow. During the first hour this test, temperatures slowly reached ~90K at inlets and outlets. No thermal runaway has been detected. It means that the cable's enthalpy is sufficient to keep the cable working during at least 1 hour without LN_2 flow.

Generally, the cryogenic system demonstrated full operability and good flexibility to perform tests under different cryogenic conditions.



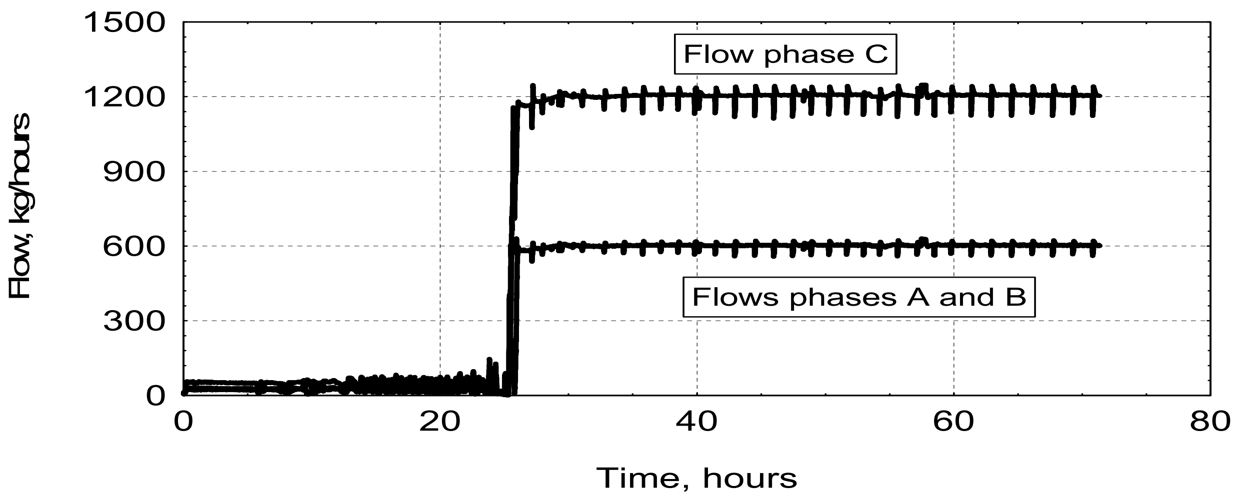


Fig. 6. Cooling modes of the cryogenic system and cable. Temperatures and flows are shown.

IV. THE CABLE ELECTRICAL TEST

A. Cable Tests

Electrical tests of the 30-m three – phase experimental cable included:
- Dielectric strength test;
- DC critical current measurements of each phase;
- Full AC current and working-under-load tests;
- Fault current test.

B. Dielectric Strength Test

The dielectric strength test has been performed at temperatures 70 to77 K. A maximum DC voltage of 70 kV was applied between current terminal and ground during 15 min to each of three phases sequentially. Measured leakage currents at 70 kV were less than 150 μA, and the insulation resistance measured at the voltage of 2.5 kV was larger than 10 GOhm. The cable passed the dielectric strength test well.

C. Critical Current Measurements

The cryogenic system permitting temperature variations made it possible for us to perform measurements of critical current dependence on temperature with 30 m superconducting sample, which each phase of our cable is. To measure critical current, we used voltage taps attached to current leads at room temperature. Thus, during measurements of DC voltage current characteristics (VCC), when we fed DC current to the cable we recorded a bias voltage from normal resistance of current leads as shown by Figure 7. To determine the critical current of each phase, we digitally subtracted the bias voltage from initially measured VCCs and obtained the VCCs shown in Figure 8. From these characteristics we determined critical current of each phase of our cable using the standard 1μV/cm criterion. For our cable it corresponds to 3mV over entire cable phase. Critical current dependencies on temperature for all three phases are shown in Figure 9. Temperatures are changing along the cables, so Figures 7 and 8 show average temperatures. In Figure 9, temperature variations are shown by error bars. Estimated errors in critical current determination due to measurements via current leads are shown a well.

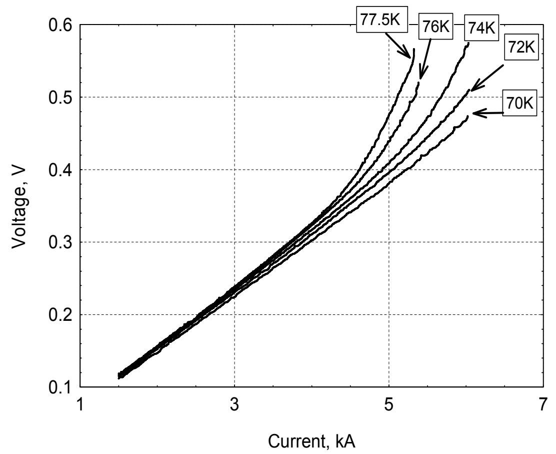


Fig. 7. Measured voltage-current characteristics during DC critical current measurements.

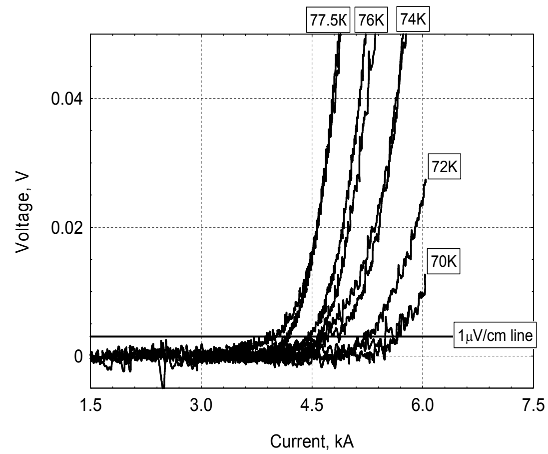


Fig. 8. Reduced voltage-current characteristics during DC critical current measurements.

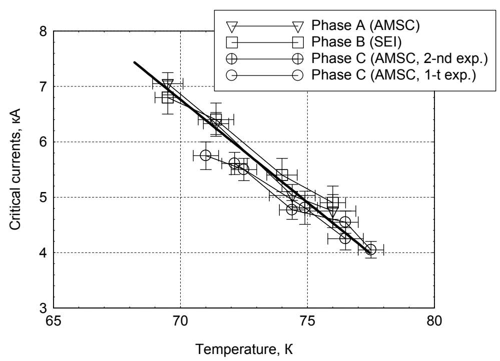


Fig. 9. Critical current dependence on temperature for all three phases of the 30-m HTS power cable. Solid line - I_c(T) dependence from producer's specifications [5,6].

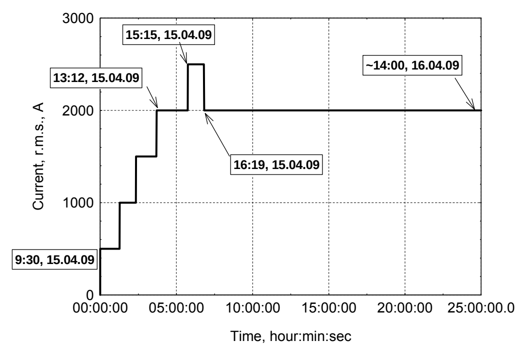


Fig. 10. Example of a full current test.

Critical currents of all phases exceed 4200A even if the temperature is slightly above 77 K. At ~77 K, the critical current of all phases is equal to the sum of critical currents of all HTS tapes used, as we determined earlier during our tests of the 5-m prototype [1] and of the 5 m witness sample [2]. This clearly signifies that the superconducting properties of the HTS tapes are fully (100%) used in our cable.

The dependencies on temperature of the critical currents of our phases coincide well with the data presented by producers of the HTS tapes we used [5,6].

D. Full AC Current and Working-Under-Load Tests

There were several tests performed under full AC current and full AC voltage. These tests were performed mostly with non-superconducting shields disconnected from ground at one end of a cable. Would the non-superconducting shield be grounded at both ends of a cable, extra eddy losses could be generated at shields demanding higher cooling power and limiting the maximum AC current achievable.

An example of one of the full AC current test is shown in Figure 10. One can see that the cable has been working about 24 hours with 30% overload current and ~1 hour with 67% overload (2.5 kA). Long time tests at a nominal load ~20 kV, 1500 A or ~50 MVA transporting power through three phases were performed as well. Operation under load has been conducted during several days; these tests are also continuing at this writing.

E. Fault current test

Our cable was tested for its tolerance to fault overload currents. Before the test, the DC critical current of the cable was determined. Subsequently, a voltage pulse from a powerful LC circuit has been applied to each cable phase with control of current and temperature.

The pulse with the highest current is shown in Figure 11. The maximum overload-current amplitude reached 28 kA, which is 10 times more than the nominal current amplitude. In Figure 12 the measured temperatures of LN_2 are shown inside the SS tube and between the non – superconducting shield and the inner tube of the cryostat. One can see that the temperature rise is quite small, ~0.15-0.35 K. The delay in reaching the maximum temperature is caused by the delay in the heat transfer from the cable and the former to the LN_2 flow. We made estimations of the temperature rise by using the computer model described in [2]. They provided a maximum temperature rise for this fault current test of ~ 0.2-0.3 K that is coinciding with the experimental data.

DC VCC measurements after a fault test showed no change of cables' critical current. This demonstrated a proper cable protection against faults.

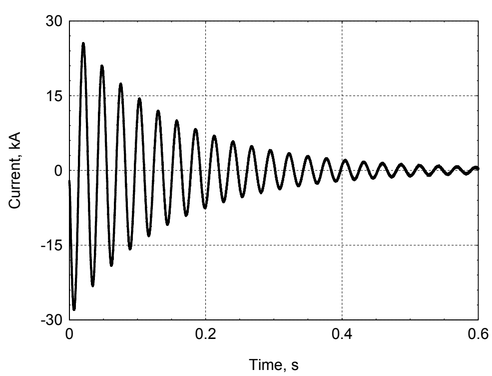


Fig. 11. Current in a cable *versus* time during fault tests. Maximum current amplitude is 28 kA.

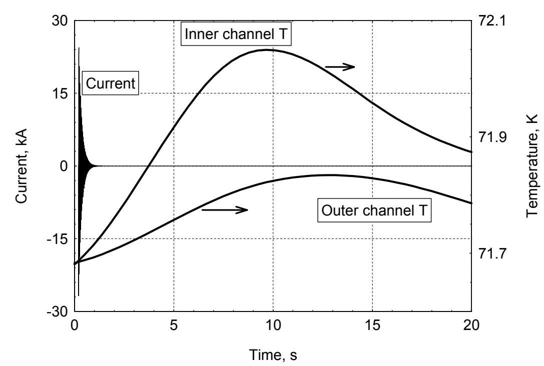


Fig. 12. Temperatures rise *versus* time during fault current test in inner channel (SS spiral) and outer channel – between shield and inner tube of the cryostat.

V. CONCLUSIONS

The first Russian experimental three-phase 30-m HTS power cable has been delivered and is tested at this writing. Special test facilities has been developed permitting tests of powerful HTS power devices at full load and within a voltage range from 6 kV to 183 kV and with AC currents up to 3kA. The available cryogenic system permits tests of HTS devices with subcooled, pressurized (up to 6 bar) liquid nitrogen at temperatures as low as 66 K with liquid nitrogen flows up to as much as 100 l/min with full control and measurement of temperatures, flows and pressures in the system. Both cryogenic and electrical systems of the test facility demonstrated their availability for full use.

Electrical tests of the 30-m HTS power cable demonstrated its full working capacity at rated parameters: 20 kV and 1.5kA (nominal load) and 2 kA (30% overload) or up to 50MVA (or 70MVA) transporting power. Critical current dependencies on temperature for each phase of the cable were measured and confirmed the full use of the superconducting properties of the basic HTS tapes. The cable survived without any problems a tenfold overload-current at fault-current test. Tests of the cable under nominal load are continuing.

ACKNOWLEDGEMENTS

This work is supported by the Federal Grid Company United Energy System and in part by the Ministry of Science and Education of Russian Federation.

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