

## First Russian Long Length HTS Power Cable

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**Abstract** — The Russian R&D Program for superconducting power devices is underway, supported both by government and electric power companies. In this program R&D on HTS power cables is considered as most advanced and close to commercialization. In the framework of the Program, several heavily instrumented 5 m cables have been tested followed by the 30 m - 3 phase experimental power cable development and testing in 2008-2009. The latest achievement is the development and testing of the first long length 3x200 m power cable with rating 1.5/2kA – 20 kV. In parallel with the cable development an innovative cryogenic system has been also developed for the cable cooling. The system is using neon as the working substance and radial turbo-machines in the refrigerator. Cooling power is up to ~8 kW at 65K, the inter-maintenance time ~30 000 hours. The cryogenic pump with superconducting motor can be used to provide subcooled liquid nitrogen flow of ~0.1 to 1.5 kg/sec at 0.1 to 2.5 MPa pressure. After extensive tests at a special test facility, the HTS power cable and its cryogenic system should be installed at some substation in the Moscow utility grid. In this review, we present some details of the Russian HTS power application program, the 200m cable and its cryogenic system design. Tests results are also presented.

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### I. INTRODUCTION

In our previous presentations [1, 2] we reported on the Russian R&D Program for superconducting power devices supported both by government and electric power companies. In this program, the development of high- $T_c$  (HTS) power cables is considered as the most advanced and closest to commercialization. In the framework of this Program, several, heavily instrumented, 5 m long cables have been tested. Both 1G and 2G (first and second generation) HTS wires were used for 5 m cables [3-5]. As the second step, a 30 m long, 3 phase experimental power cable with rated parameters 1500/2000A and 20 kV has been developed, produced and successfully tested [2,6]. During this cable tests, critical current dependencies on temperature were measured for all 3 phases [2, 6]. The cable underwent high voltage, full load and fault current tests, which all passed successfully.

The following step has been the development and test of 3x200 m power cable with same rating: 1.5/2kA – 20 kV. This cable has a superconducting shield and is made of 1G DI-

BSSCO™ HT-CA wires from Sumitomo Electric Industry Co. This cable is the first long-length and full-size HTS power cable in Russia, and the biggest HTS power cable developed so far in Europe. The cable successfully passed acceptance test and is being prepared for reinstallation in the Moscow utility grid.

Along with this cable, an innovative cryogenic system has been developed for cable cooling. The system is using neon as the working substance and radial turbo-machines in the refrigerator to cool liquid nitrogen for the cable.

In this review we are presenting more details about our 200 m cable and cryogenic system. The details about the test facility with capability to test HTS power devices under full load have been presented in [1,2,7].

## II. THE RUSSIAN PROGRAM

The Russian program for introduction of superconducting devices to electric power industry has been officially launched on May 16, 2007, by Mr. A. Chubais – at that time the Head of the Russian company “United Energy Systems”. The program includes both the R&D and introduction into real grids where HTS power cables are of the first priority as the most advanced and closest to commercialization.

The Russian Scientific R&D Cable Institute (known by its Russian abbreviation: “VNIKIP”) is the major performer of the R&D effort in HTS cables. The HTS cable development path at VNIKIP can be divided into three phases: *Science* → *Technology* → *Production*. In each phase the research and developments were completed, sometimes in parallel [1]:

### *Science*

- Incorporation of previous experience in LTS and HTS cable developments at VNIKIP [8, 9];
- Theoretical fundamentals [10-12];
- Basic HTS wire studies [13, 14];
- Test facility development and model/prototype/witness samples with 5 m length studies [3-5];
- Experimental test facility for power devices development [1,2,7];
- Experimental 30 m cable test [2, 6].

### *Technology*

- Technological experiments [3];
- Development of fabrication machines and equipment [1];
- Development of current leads (terminations) [1,2,6]

Upon completion of all tasks above it was possible to start the *Production* phase that eventually led to the production of 3x200 m HTS power cable described here. Along with VNIKIP responsible for HTS cable development, three more teams participated in the 3x200 m project, namely:

- The Moscow R&D Center for Power Engineering as the major test site permitting test of different HTS superconducting devices under full load [2, 7];
- The Moscow Aviation Institute – Technical University (MAI) as a developer of cryogenic cooling system and current leads;
- The Krzhizhanovsky Energy Institute as a system integrator and general management of the project.

The synergy in the collaboration of these teams led to the successful completion of the first

stage of the project: the HTS power cable development, fabrication and its acceptance test. The funding of the project was split 50/50 between the Federal Grid Company “United Energy System” and the Ministry of Science and Education of the Russian Federation.

### III. THE 3x200 M HTS POWER CABLE

The cable nominal rating is the same as that of the 30 m cable: 20 kV – 1500A with possible 30% overload, *i.e.*, 2000A at 20kV. This means 50 MVA to 70 MVA of transmitted power. Many the design features of this cable are similar to those of the 30 m cable described in [2, 6]. For example, three separate phases placed in three different cryostats. The significant difference is that a superconducting shield is used in the 200 m cable. Other features of the 200 m cable are as follows:

- Basic wire: Sumitomo Electric DI-BSCCO™ HT-CA 1-G tapes with Cu alloy lamination;
- Design: Central spiral, copper former, two layers of the cable core and one layer for the superconducting shield, copper protection for superconducting shield.
- High voltage insulation made from a standard cable paper;
- Cryostats: NEXANS flexible cryostats with 92 mm outer diameter, with PE protection cover extending up to the diameter of 102 mm.

Figure 1 shows the artist’s conception of the cable (left), a photo of the cable model (center) and the cross-section of the cable (right).

Several technologies have been developed to produce the cable, as mentioned before. The cable has been produced at VNIKP facilities on the fully industrial basis, as it is shown in Figure 2. All operations but insulation have been made in VNIKP. Cable’s insulating has been made by the standard method the at the Russian Kamkabel factory in the Perm city, some 1500 km from Moscow. Assembling into three flexible cryostats via the pulling-through method has been made in VNIKP facilities at Protvino city as shown in Fig.3.

In collaboration between MAI and VNIKP the highly effective high voltage current leads have been developed and produced. The current leads produce connection of superconducting shields and liquid nitrogen level. The artist’s conception of current leads and their photo are presented in Figure 4. The cable produced has been installed at the test facility of the Russian R&D Center for Power Engineering as shown in Fig.5.



**Fig.1.** Artis’s conception (right) , photo of the cable model (center) and cross-section of one phase of the 200 m cable (right). 1-Former- a spiral of stainless steel, surrounded by a bundle of wires made of copper and stainless steel, wrapped in copper tape - 2 and 3; 4 - Two layers of HTS tapes; 5 - high-voltage paper insulation; 6 - HTS shield -7- flexible copper strips to protect shield, wrapped by tapes of stainless steel; 8- flexible cryostat, 200 m long.

The test of the witness sample demonstrated full compliance with rated parameters; the critical current at 77.4 K was 4.2 kA, as designed (Figure 6). Current distribution between layers and AC losses were also measured in this sample [5]. In the AC mode the difference between currents per layer was less than  $\pm 0.5\%$  [5].

In December 2009, the acceptance test of the full length cable has been performed. The primary goal of the tests was to ensure that the cable does work. During testing, we found that the cable has a cooling time of about 30 hours (Figure 7). DC critical currents for all three phases are more than 5.2 kA at about 74 K. 50 kV DC voltage test has been passed successfully. Energy transfer of 50 MVA (1500 A and 20 kV for three phases) has been performed for a 72 hour period.

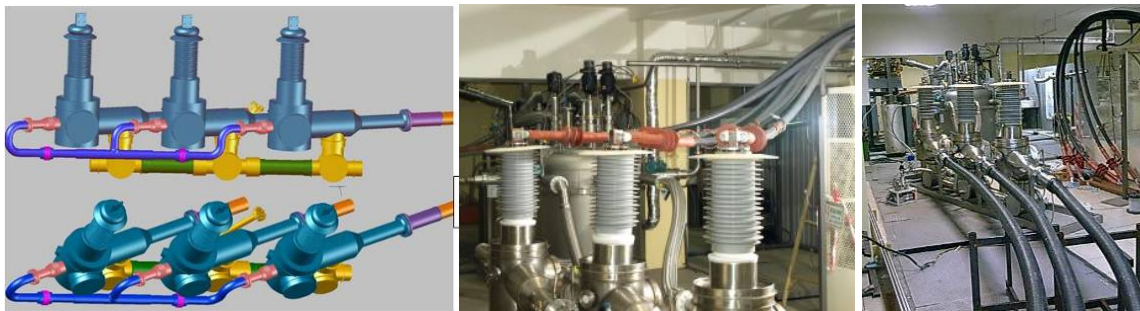
At present, more extensive tests of the 200 m cable are underway. The 30% overload test, the fault current test, the new cryogenic system test, *etc.*, are being performed to ensure the cable reliability before its installation in the power grid. Some test results are presented at this conference [15]. Examples of the fault imitation tests are shown in Figures 8 and 9. One can see that at ~44 kA maximum current with effective time ~0.4 s the cable and shield temperature increases do not exceed 2K. That means that cable is well protected against fault.



**Fig. 2.** Production of the 200 m HTS cable. From left to right: layer's twisting, superconducting shield's twisting, cable on a take-on drum.



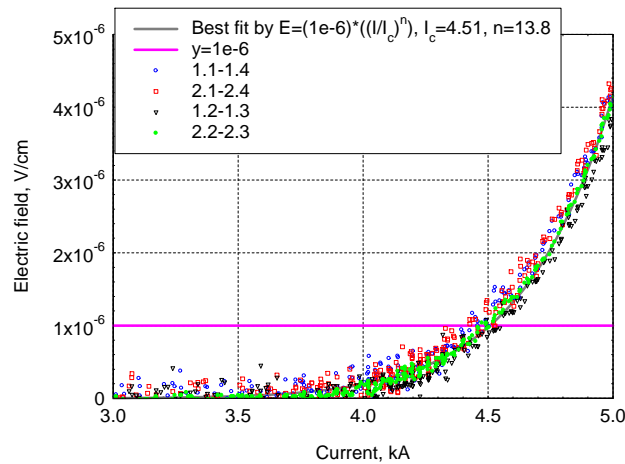
**Fig. 3.** Insertion HTS cable into cryostat by pulling through method.



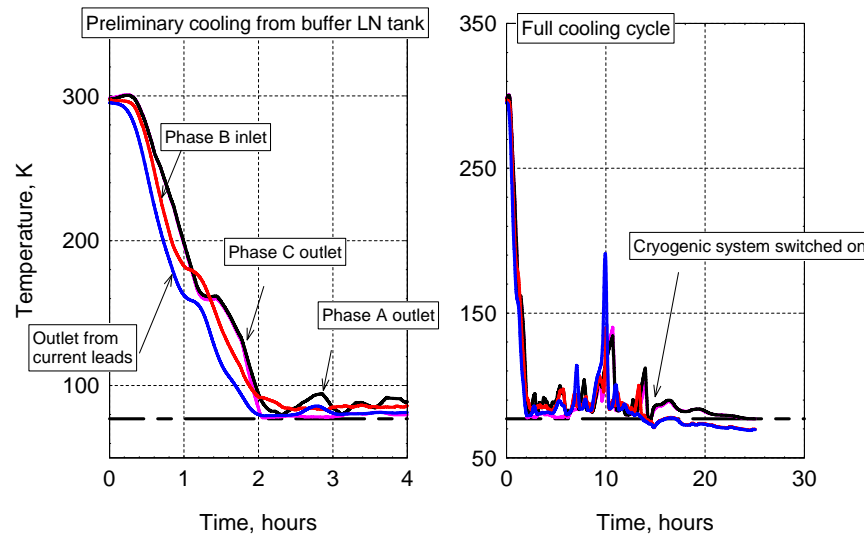
**Fig. 4.** Current leads artist' conception (left) and their photos as installed at the test facility.



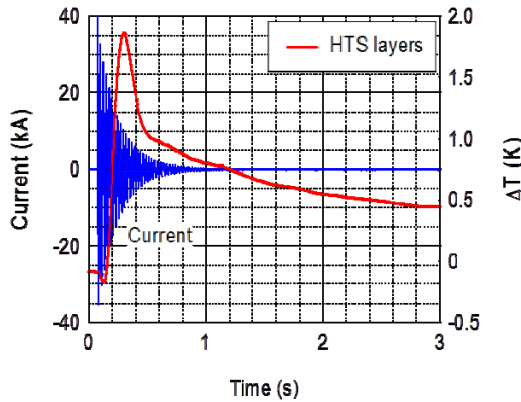
**Fig. 5.** The 200 m cable installed at the test facility in Russian R&D Center for Power Engineering.



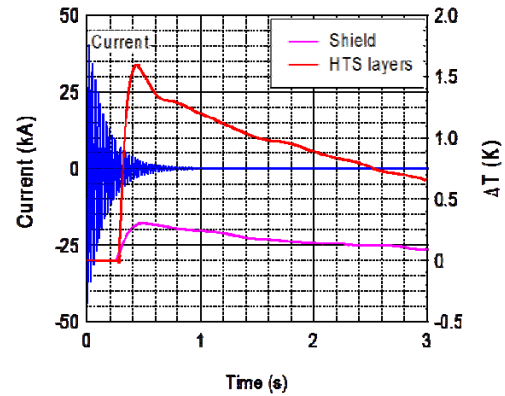
**Fig. 6.** Critical current tests of witness sample of 200 m cable. Symbols – data from different voltage taps set [5].



**Fig. 7.** Cooling down of the system using of a Stirling cryogenic system at the Russian Center for Power Engineering [1,2,7].



**Fig. 8.** Current during fault imitation (blue trace) and temperature rise  $\Delta T$  of the cable core when the HTS shield is shorted outside the cryostat (red trace) [15].



**Fig. 9.** Current during fault imitation (blue trace) and  $\Delta T$  of the cable core (red trace) and shield (pink trace) when the HTS shield is in series connection with a cable core [15].

After more tests, particularly with the new cryogenic system, the cable will be installed at some Moscow substation to be tested in a real utility grid.

As the 200m cable and all its components were fabricated by fully industrial technologies, we demonstrated readiness for the real commercial HTS power cable production.

#### IV. THE CRYOGENIC SYSTEM

Cryogenic cooling system is one of the most crucial sub-systems necessary for implementation of HTS power devices into real-life applications. The level of cooling power at temperatures  $\sim 66\text{-}77$  K is necessary at levels from 5kW to about 50-100 kW, in order to provide the flow of sub-cooled liquid nitrogen at pressures above 2 bars. So far such systems were mainly developed as “one of the kind” for each HTS power device project. Among the most known are cryo-refrigerators produced by the Stirling company (the Netherlands). Such 3.5 kW machine we used in the test facility in Russian R&D Center for Power Engineering [1,2,7]. However, while being quite good, these piston-based machines, demand maintenance every 6000 hours. That may be too often for HTS power devices installed in a grid.

Longer inter- maintenance time could provide machines based on rotating turbines. No such liquid nitrogen machines are produced in Russia. That is why for the 200 m cable project the Moscow Aviation Institute (MAI) team developed and constructed the special cryogenic system for cooling of HTS power devices.

Basic features of the cryogenic system developed are:

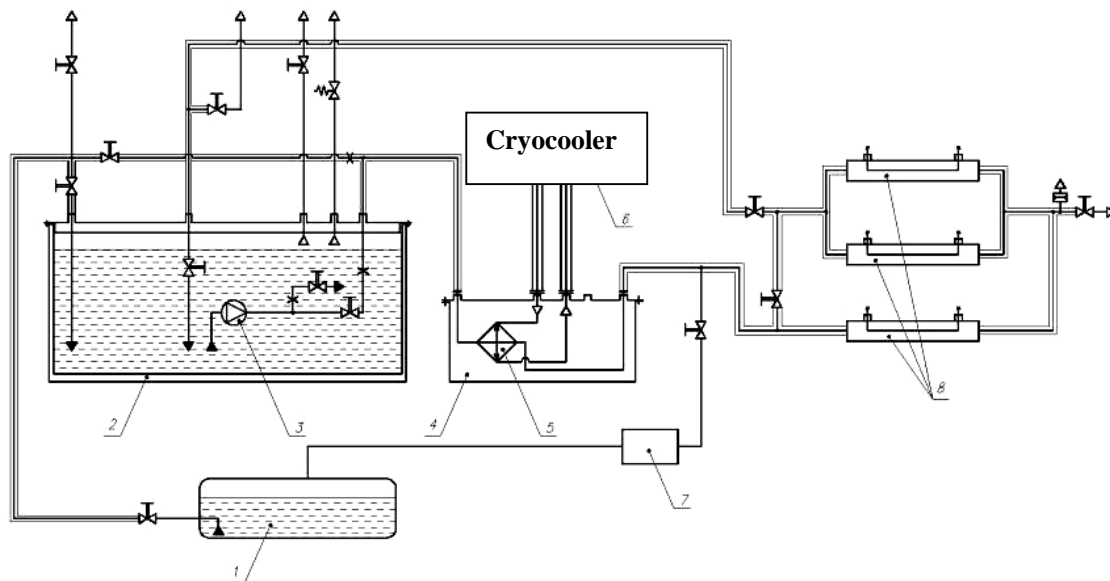
- Cryo-refrigerator with *neon* as a working substance;
- Radial turbo-machines with long inter – maintenance time in refrigerator;
- Cryopumps with an HTS motor.

The parameters of the cryogenic system are:

- Expected inter–maintenance time not less than 30,000 hours;
- Operation pressure (in cable’s cryostat) up to 20 bar;
- Operating temperature 65-75 K;
- Mass flow from 0.1 to 2 kg/s;
- Cold power 8 kW at 65 K;
- Electric power consumption – up to 100 kW at three phase 380 V.

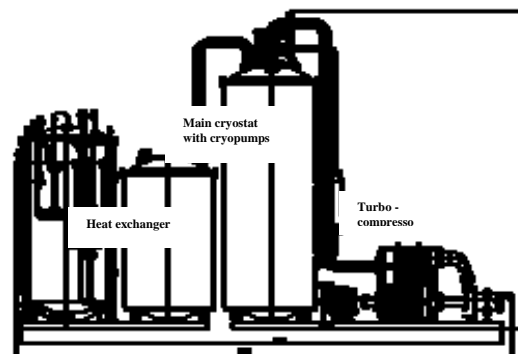
The system has no water cooling, which makes it easy to install in any conditions. It has relatively small mass and size. General schematic arrangement of the system is shown in Figure 10, the cryo-refrigerator arrangement is shown in Figure 11. An important feature of this cryogenic system is the use of liquid nitrogen pump driven by HTS motors. Two immersed cryogenic pumps shown in Figure 12 have been developed with HTS motors rated 12 and 30 kW. The tests of these cryogenic pumps with HTS motors demonstrated that their efficiency is 52-54% at 12000 turns per min thus agreeing with the design value. Its hydraulic measured head is 190 m.

The assembled cryogenic system has been tested with a phantom of the long length cryostat at the test facility of MAI: Major system parameters have been thus determined. Right now the system is being upgraded. After final acceptance test it will be installed at the test facility at the R&D Center for Power Engineering to be tested together with the 200 m cable. After the completion of all tests, the whole system (cryogenics + cable) will be moved to and installed at a Moscow grid substation for field tests.



**Fig. 10.** Schematic of the cryogenic system for long HTS power cables.

1 – buffer LN tank (6 m<sup>3</sup>), 2 – 1m<sup>3</sup> cryostat for LN storage, 3 – cryo-pump with HTS motor, 4 – cryostat of the heat exchanger, 5 – heat exchanger, 6 – cryocooler, 7 – heat exchanger for heating of nitrogen gas during auxiliary works, 8 – HTS cables' cryostats.



**Fig. 11.** General view of the cryorefrigerator arrangement: the photo (left) and the schematic drawing (right).



**Fig.12.** Cryogenic pumps with HTS motor. Left – 30 kW and 12KW pumps, right – the HTS motor during preliminary tests.

#### IV. CONCLUSIONS

The development and acceptance test of the first long length 3x200 m power cable with the rating of 1.5/2kA – 20 kV demonstrated readiness for industrial production of HTS power cables in Russia. The innovative cryogenic system has been developed for the cable cooling. The system is using neon as working substance and radial turbo-machines in the refrigerator. Cooling power of ~8 kW at 65K and inter-maintenance time of ~30 000 hours are acceptable for long time operation at utilities grid. After full testing at the experimental facility, the cable and cryogenics are to be installed in the Moscow utility grid.

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