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Russian Development Program on HTS Power Cables

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***Abstract* —Russian R&D Program for superconducting power devices is underway, supported by both government and electric power company funding. Within this program, the development of HTS power cables is considered to be most advanced and close to commercialization. The scientific background was established and several, heavily instrumented, 5 m long cables have been tested. As the second step, the 30 m long, 3-phase experimental power cable with rated parameters 1500/2000A and 20 kV has been developed, fabricated and successfully tested. The following step has been the development of a 3-phase 200 m power cable with same rating: 1.5/2kA at 20 kV. The cable is at first installed at the experimental test facility to undergo extensive tests; subsequently, it will be reinstalled into the Moscow utility grid. In the framework of the Program, a special test facility has been developed permitting to test different HTS electrical power devices at voltages up to 110 kV and currents up to 3000 A (rms) under full load. In this paper, we overview the whole program and present some details of the cable development and tests.**

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***Keywords* — High temperature superconductivity, Power cables, Experimental test facility**

I. INTRODUCTION

The Russian R&D Program for superconducting HTS power devices is underway, supported both by government and electric power companies. In this program, the development of HTS power cables is considered as the most advanced and close to commercialization. In the framework of this Program, several, heavily instrumented, 5 m long cables have been tested. Both 1G and 2G (first and 2nd generation) HTS wires were used for 5 m cables. 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. During experimental cable tests, critical current dependencies on temperature of all phases were measured. The cable underwent high voltage and full load tests, which it 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 BSSCO wires from Sumitomo Electric Industry Co. The cable is first installed at the experimental test facility to undergo extensive tests, than it will be reinstalled into the Moscow utility grid. Also in the framework of the Program, a special test facility has been developed permitting to test different HTS electrical power devices at voltages up to 110 kV and currents up to 3000 A (rms) under full load.

II. THE 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 of the following devices:

- HTS power cables – as the first priority.
- HTS fault current limiters rated 10-20kV to 110 kV–220 kV.
- HTS transformers 20/0.4 kV 2500 kVA; 110/20kV 50 MVA.
- HTS generators and other machines (including synchronous compensators).
- SMES (LTS) rated 30-60 MJ.

The program funding was suggested to occur on year by year basis. So far, the real funding has been obtained for HTS power cables only as the most advanced and close to commercialization. In Figure 1, we show the roadmap for HTS power cable development.

The Russian Scientific R&D Cable Institute (JSC "VNIIKP") is the major performer of the HTS cable R&D. The HTS cable development path at VNIIKP can be divided into three phases: Science → Technology → Production. In each phase the following studies and developments were completed, sometimes in parallel:

Science

- Incorporation of previous experience in LTS and HTS cables developments at VNIIKP,
- Theoretical fundamentals,
- Basic HTS wire studies,
- Test facility development and model/prototype/witness samples with 5 m length studies,
- Experimental test facility for power devices development,
- Experimental 30 m cable test.

Technology

- Technological experiments,
- Development of fabrication machines and equipment.
- Current leads (terminations) development.

Upon completion of all tasks above it was possible to start the *Production* phase.

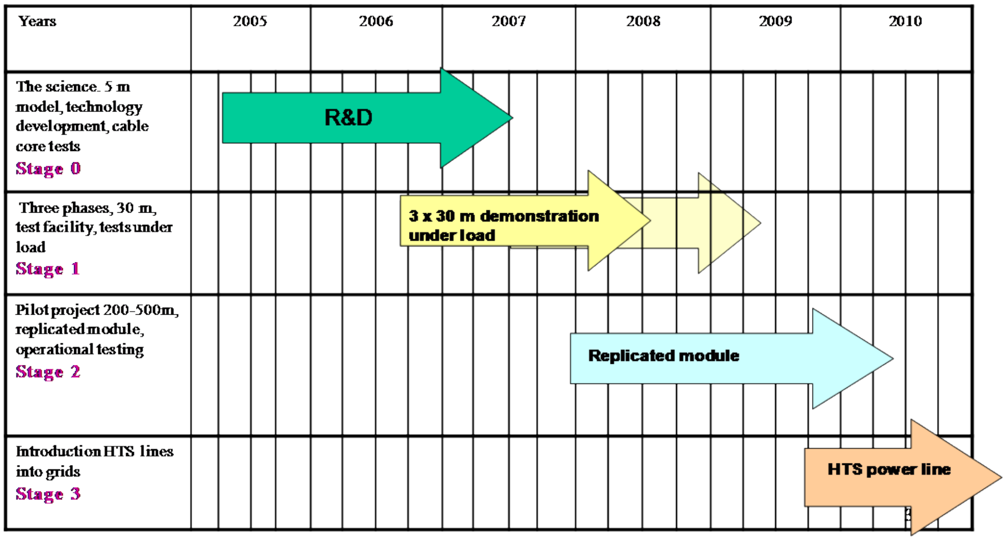


Fig.1. The roadmap for HTS power cable development. Parameters of cables: 10-20kV, 2-3kA, 35-100MVA.

III. SCIENCE

A. Previous Experience in LTS and HTS Cables

VNIIKP has long experience in power cables R&D. In 1970s, several LTS power cables were developed [1], one of them shown in Figure 2 (a). In 2000-2001 the first 5 m model of HTS power cable was developed in collaboration with Condumex Co (Mexico) with current above 10,000A, the world record at that time and until 2009 [2], Figure 2 (b). In 2005, this experience permitted VNIIKP to give a good kick-start to the Russian HTS power cable program development.

Fig. 2 (a). LTS power cable 50 m long developed at VNIIKP.

Fig. 2 (b). HTS power cable model with 5 m length and 10 kA current, developed at VNIIKP and tested in Mexico.

B. Theoretical Fundamentals

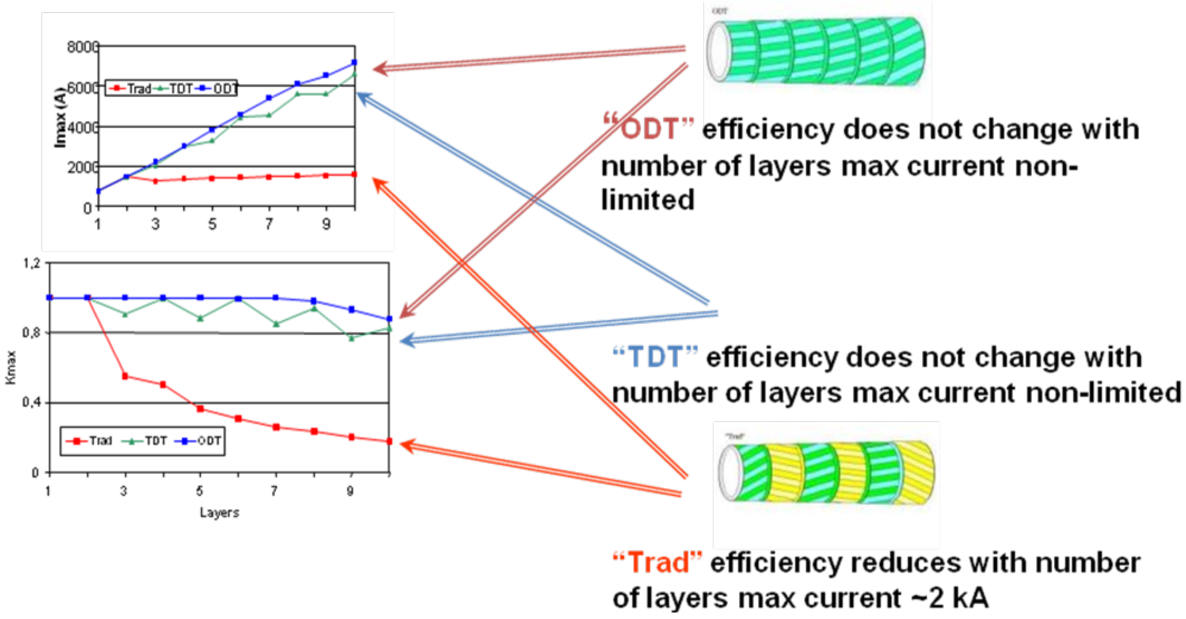
Theoretical developments include basic analyses of cable design optimization, cable (and other HTS devices) behavior at fault conditions, AC losses analysis, etc.

In an optimal HTS cable design one of the major demands is the full use of superconducting properties of basic HTS wires. This can be achieved when the transport AC current is distributed uniformly among conductor layers. We performed an analysis of current distribution in HTS power cables with different twisting directions and angles and showed that only two styles of twisting can provide uniform current distribution [3]: all layers should be twisted in one direction (One Direction Twist – ODT) or twist direction can be changed only once (Two Direction Twist – TDT) as it is shown in Figure 3. Traditional cabling approach (Trad) when at each layer twist direction is changing cannot provide uniform current distribution, because AC current will concentrate in two upper layers only, limiting the total cable current.

The developed VNIIKP computer codes and analysis methods permitted us to optimize cable design, twist pitches and directions. Comparison of our theoretical calculations with independent experimental results [6] confirmed the adequacy and accuracy of theory.

Our methods of optimization of cable design permitted us to develop a six-layer HTS cable with uniform current distribution among layers and to obtain 10 kA transport DC current in 5 meter cable model [2]. This current was below critical, it was limited just by the power supply.

HTS power cables are electrotechnical devices, like fault current limiters, transformers, *etc*. All these devices must have one general feature – they must withstand fault currents over an order of magnitude higher than their operating currents (for cables up to 30 times of the nominal current). The fault currents may forcibly go into superconductors, leading to overheating and possible destruction of the device. It is important to this take into account, especially in HTS power cables design. For FCLs, overload is just one of the operational modes.



"ODT" efficiency does not change with number of layers max current non-limited

"TDT" efficiency does not change with number of layers max current non-limited

"Trad" efficiency reduces with number of layers max current ~2 kA

Fig. 3. Analysis of optimal cable design to achieve uniform current distribution among layers [3-5].

We have been studying current overloading conditions in basic HTS wires, cables and other HTS devices, both theoretically and experimentally [7-11]. For example, we showed theoretically that the, so called, "blow-up" regimes are possible in HTS cables with heat localizations that are due to strong nonlinearity of HTS. The left graph of Figure 4 illustrates an example of the local temperature distribution around a "hot spot" at current densities *J* between 40 and 60 A/mm^2, while in the right graph the temperature rise *T*(*t*) is plotted for several *J* values between 40 and 100 A/mm^2.

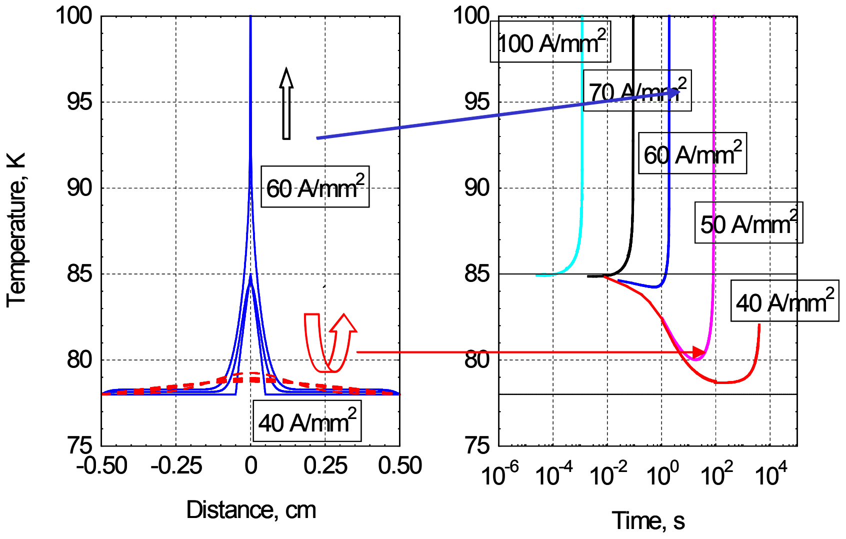


Fig.4. Example of "blow up" regime possibility in HTS devices [7-9].

Experimental study of overload conditions in HTS tapes and their theoretical analysis [10, 11] permitted us to understand the change of cooling regimes in liquid nitrogen at current overloads, which is important for overload analysis, particularly for HTS FCL. The example of Figure 5 (a) shows plots of temperature increase with time, Δ*T*(*t*) at various overload currents when the tape is not insulated. In Figure 5 (b), resulting overload current - voltage characteristics are plotted for HTS tape without and with Kapton™ insulation.

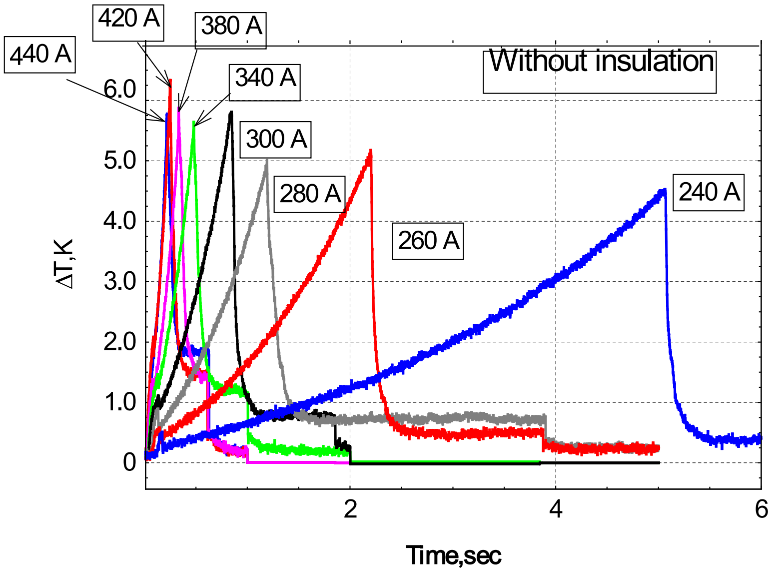


Fig. 5 (a). Temperature increase with time at various overload currents.

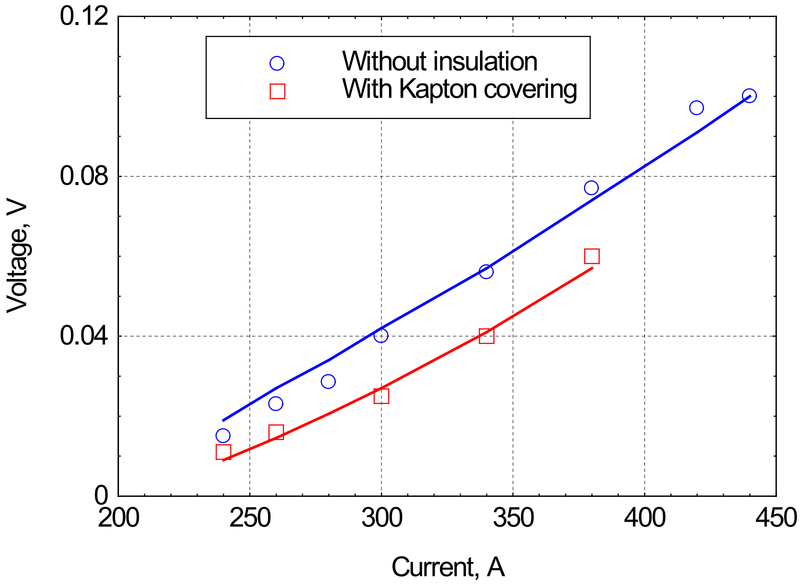


Fig. 5 (b). Voltage versus overload current curves without and with kapton insulation.

Theoretical analysis of fault conditions in HTS cables [12] indicated that the presence of inner bore in a cable former reduces the recovery time after a fault.

We also developed a novel approach to analyze stability and heating at quench in HTS devices [13-15]. Depending on HTS material parameters, size of the device and cooling conditions, two regimes are possible: stable and unstable ("thermal runaway"). The regime change occurs at the threshold current I_q that should replace critical current I_c of HTS. Depending on conditions, I_q may be higher than I_c (in small devices with good cooling) or less than I_c (in large devices with inadequate cooling). This approach is rather convenient for analyzing stability and quench in HTS devices.

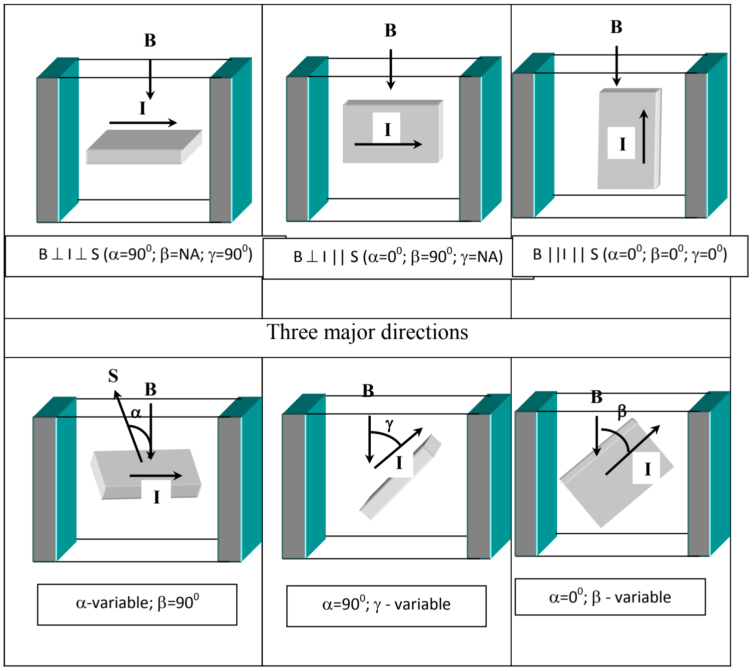
Our fundamental studies provided a good basis for experiments and the development work.

C. Basic HTS Wire Studies

Any superconducting device starts from basic superconducting wire. The knowledge of basic wire properties is important for any HTS device development. At VNIIKP we have a standard test program for testing of basic HTS wires. This program includes (but is not limited to) the following:

1. Evaluation of critical current anisotropy in magnetic field at any thinkable angle between critical current, the magnetic field direction and tape surface plane *S*. Figure 6 illustrates six typical orientations evaluated. Comparison of $I_c(B)$ anisotropy of 1G and 2G HTS tapes led to the conclusion that 1G tapes could be in some sense better for HTS power cables where magnetic field parallel to the tape surface is dominant [16]. Figure 7 shows $I_c(B)$ plots in *B* perpendicular and parallel to *S* for 1G and 2G tapes of various manufacturers.
2. Thermal cycling sequence 273K-77K-273K with checking superconducting properties after several dozens of cycles [16].
3. Modeling of mechanical behavior of HTS tapes in power cables [16]. As an example, Figure 8 shows compares the dependence of the normalized critical current on the twist pitch (I_c is normalized to the value in absence of twisting).
4. Magnetization measurements to analyze AC losses.
5. Overload testing [9, 11, 17, 18] to model fault conditions and to study change of HTS device cooling regimes in liquid nitrogen bath (Figures 4 and 5 above are examples of the behavior in fault conditions).

Eventually, we collected a data base of tape properties from all major HTS wire providers over the world and we do our best to keep it updated.



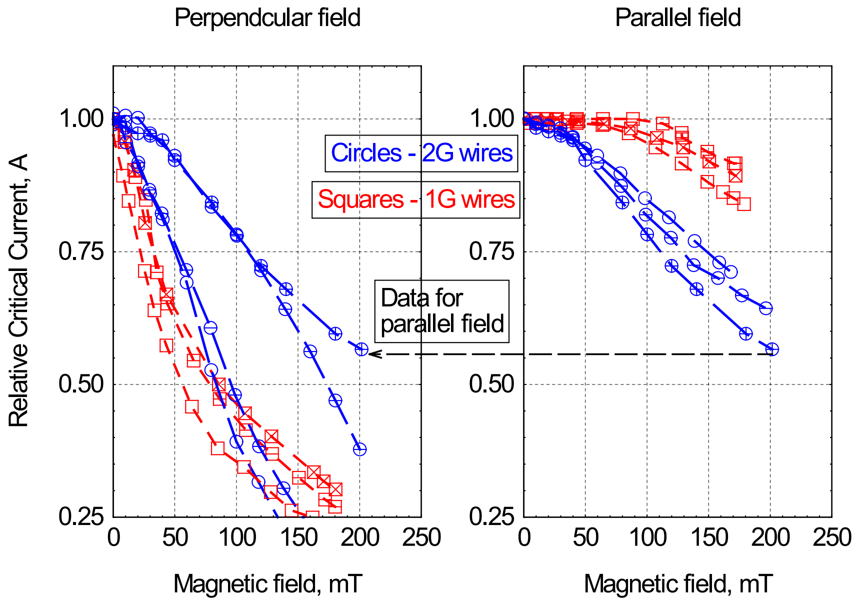


Fig.7. Comparison of critical currents of various 1G and 2G HTS conductors in magnetic fields parallel and perpendicular to the tape surface. In a weak parallel field 1G tapes demonstrated better behavior.

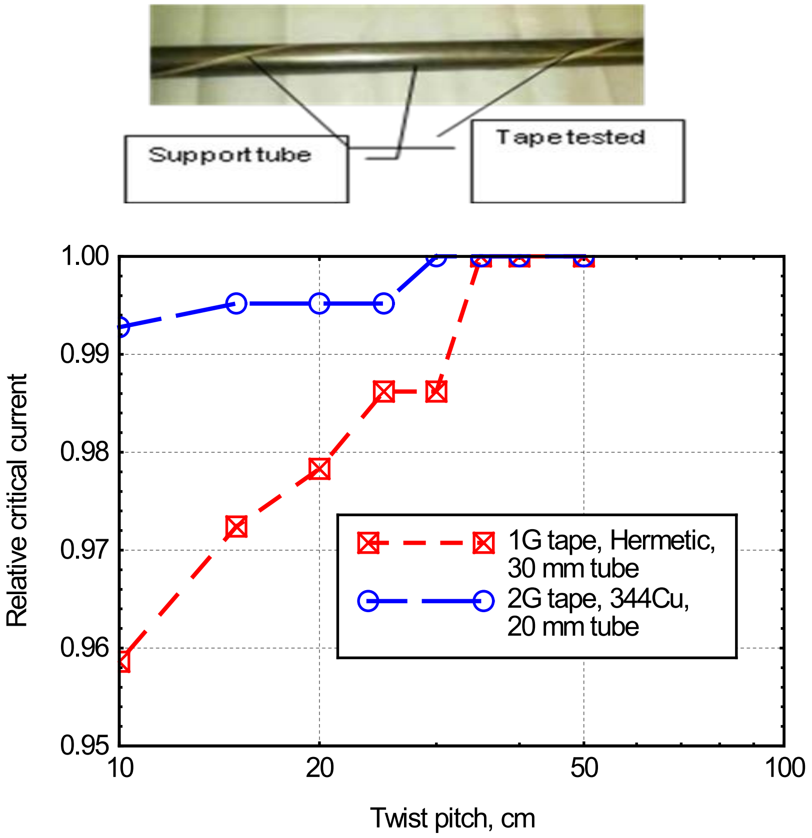


Fig.8. Studying of mechanical properties of HTS tapes by modeling the cabling operation. The I_c of 2G tapes demonstrates lesser dependence on twist pitch.

D. VNIIKP Test Facility and Model/prototype/witness Samples of 5 m Length

To test properties of HTS power cables especially in the AC mode one has to use long enough cable model. Current distribution among layers in the AC mode is determined by the inductive impedance of layers. Its value exceeds the joint and termination resistance if the cable is long enough. According to our estimations, the length should be not less than ~3 m. At shorter model lengths, edge effects will foul the current distribution among layers.

In our own test facility (photo is shown in Fig.9) we use a 5 m flexible cryostat from Nexans Co (Hannover, Germany) to test 5 m HTS cable models. The test facility is equipped with a DC power supply with maximum current of up to 6.5kA and an AC power supply with current up to 3.6kA$_{rms}$. The test facility is equipped with digital Data Acquisition System from Yokogawa Co., with up to 1MHz sampling rate that provides high accuracy in digital measurements, especially of AC losses [19]. Modern measuring devices: amplifiers, flow meters, *etc*., are at our disposal as well.

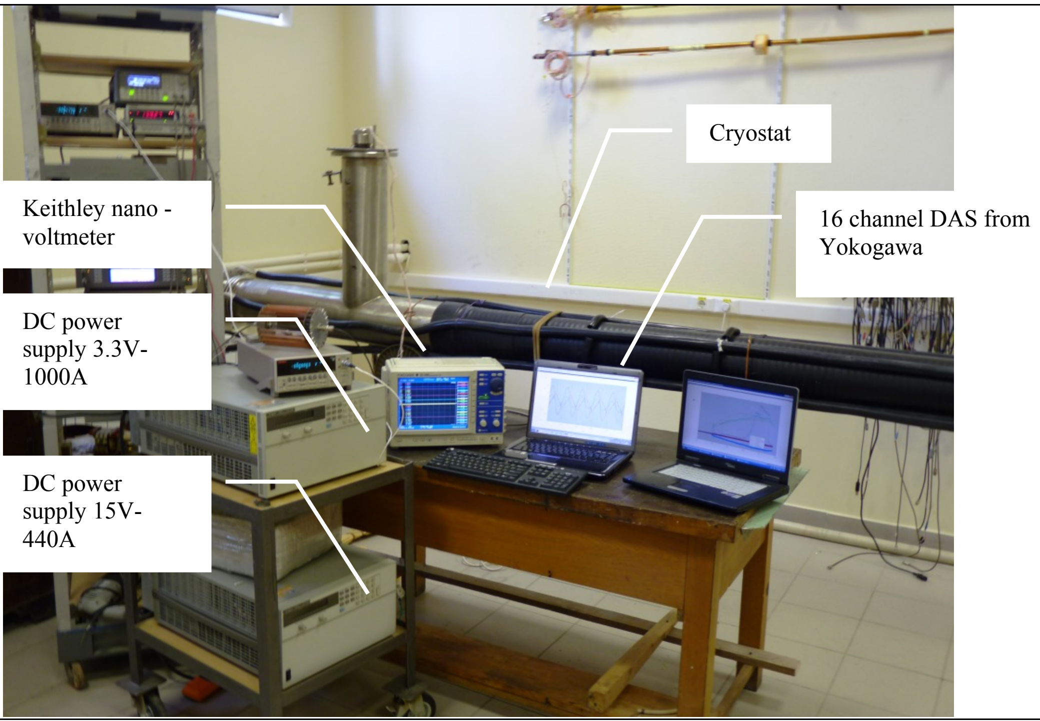
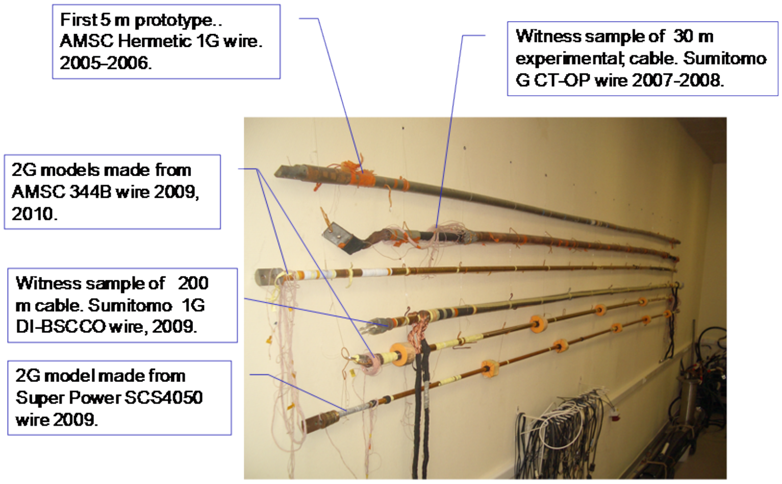


Figure 9. General view of the facility for testing 5 m HTS cables

Several 5 m cable models (witness samples) were tested at this test facility, some of them are shown in Figure 10. First 5 m model made from 1G HTS wire was developed and tested in 2006 [20]. A witness sample of 30 m cable was tested as well [21]. Test results from a witness sample of the 200 m HTS power cable are shown in Figure 11. The 2G model cables tested were made of wires from American Superconductor Corp [22] and from SuperPower [23].

Before testing our 5 m cables we equip them with many sensors and probes [21-23]. Handmade calibrated Rogowski coils are used to measure current distribution among layers, Hall probes are measuring magnetic field in different directions inside and outside of a cable. Thermocouples permit to check temperature of a cable and sometime to calibrate AC loss measurements [21]. Voltage taps are used to measure critical currents and AC loss.

The standard test program of 5m cable equipped with all probes usually includes (but is not limited to) DC current distribution and critical current measurements, AC current distribution and AC loss measurements. In a separate paper we described in more details our tests of 5m cables [23]. We are now ready to develop, produce and test 5 m cables on order.



First 5 m prototype.. AMSC Hermetic 1G wire. 2005-2006.

Witness sample of 30 m experimental; cable. Sumitomo G CT-OP wire 2007-2008.

2G models made from AMSC 344B wire 2009, 2010.

Witness sample of 200 m cable. Sumitomo 1G DI-BSCCO wire, 2009.

2G model made from Super Power SCS4050 wire 2009.

Fig. 10. Samples 5 m long of various experimental cables tested at VNIIKP.

Fig. 11 (a). Witness sample of the 200 m long cable tested at VNIIKP.

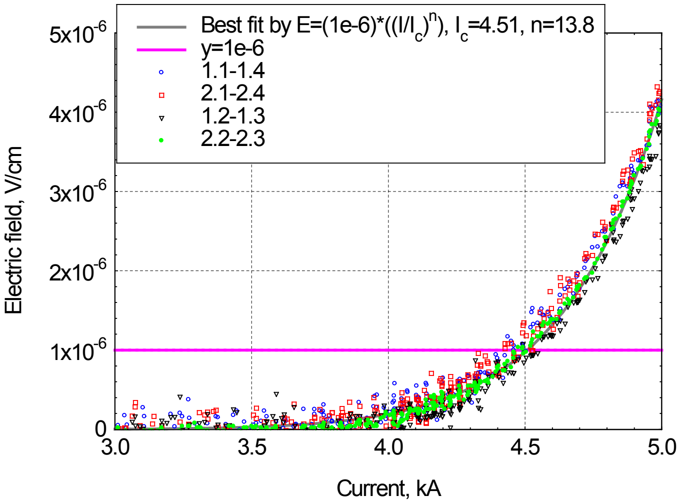


Fig. 11 (b). Critical current test *E*(*I*) data of the sample of Fig. 11 (a).

E. Experimental Test Facility for High-power Device Development

To test HTS power devices to be developed in the framework of the Russian program for such devices, a special test facility has been developed in the Moscow R&D Center for power engineering. This test facility is connected directly to the substation “Yuzhnaya” of the Moscow Energy Grid. The facility permits to perform testing at voltages: 6 kV, 10 kV, 19 kV, 33 kV, 66 kV, 110 kV; at AC currents up to 3kA$_{rms}$ and DC currents up to 6.5 kA. It has inductive electrical reactors as loads up to 70-100MVA (see photos of Fig.12). There is modern certified testing laboratory with highly experienced staff. The test facility is equipped by Stirling LPC-4FF machine with cooling power variations from 660 to 2800W at 72 K and from 840 to 3400W at 77 K. Cooling with pressurized (up to 6 bar) liquid nitrogen at flows up to 100 l/min is possible. Upgrade to 7 kW at 77K is possible as well. A special cryogenic load distribution unit permits to distribute and control liquid nitrogen flow while measuring its parameters (flow rates, temperature, and pressure).

The test facility will be able to test experimental, pilot and commercial samples of superconducting power devices *UNDER FULL LOAD.*

The test facility is open to users interested in testing HTS power devices.

Fig. 12 (a). Active load at the test facility in R&D Center for Power Engineering.

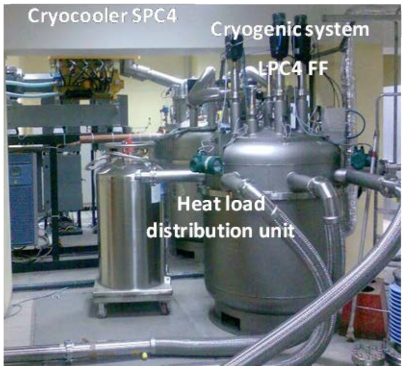


Fig. 12 (b). The cryogenic system at the test facility in R&D Center for Power Engineering.

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F. The 30 m HTS Cable Development and Test

The 30 m, three phase (3x30m) HTS power cable has been fabricated during the second stage of the program as a prototype for longer cables (see Figure 1). We considered the 30 m cable development mainly as a research project necessary to work through the technology and production methods of HTS power cables. That is why variations were introduced in basic HTS materials (wires from American Superconductor and Sumitomo Electric), cryostats (two diameters) and current leads (two designs from two suppliers). The basic design of the cable is 2 layers of HTS tape, cold insulation, and a copper, non-superconducting shield. The non – superconducting shield design has been accepted due to limited budget in this project. The design of the cable and results of its tests are described in more detail in [21, 24].

The tests of the 30 m HTS power cable [24] demonstrated its full working capacity at rated parameters: 20 kV and 1.5kA (nominal load) and at 2 kA (30% overload) corresponding to 50MVA or 70MVA of transported power. Critical current dependencies on temperature for each phase of the cable were measured and confirmed the full use of the superconducting properties of basic HTS tapes. The cable survived without any problems the more than tenfold overload-current during the fault-current test [24]. The successful and extensive test of 30 m HTS cables, along with technological experiments, paved the way to longer cables. Figure 13 (a) shows the three-phase terminations of the cable, while Figure 13 (b) is the photo of the cable, both photographed at the test facility.

Fig. 13 (a). The 30 m cable: terminations of three phases at the test facility.

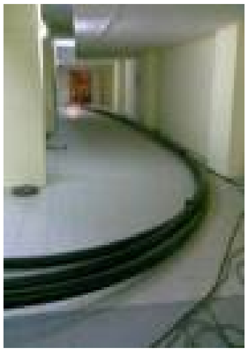

Fig. 13 (b). The 30 m long three-phase cable at the test facility.

IV. TECHNOLOGY AND CURRENT LEADS

A. *Technological Experiments*

As it is well known, the basic HTS tapes are rather fragile materials. So, the technology to produce HTS power cable in industrial scale is a difficult task. Before starting long cable production effort, the following technology experiments were performed [20]: cabling on the former → extraction of superconducting tapes and testing their properties → change of the technology → new testing. Our cabling workshop and test facilities are in the same building, so this iteration process is very easy. Permanent control of all technological steps is possible. After several iterations of the technology, the superconducting properties of tapes did not change after the cabling process.

B. *Technology Development*

We developed several technological steps used generally in superconducting cables production, both HTS and LTS. In the HTS case this included the fabrication of the central spiral and of the former, the HTS layer cabling with strict control of twist pitch and direction, and the copper shield production. Figure 14 (a) shows the equipment fabricating the central spiral, while Figure 14 (b) is a photo of the former twisting machine. Figure 15 shows (a) the cabling machine and (b) the cable fabrication.

The only technological operation that was performed outside of VNIIKP was insulation by cable paper. It was made at the cable plant "Kamskii Kabel" some 1500 km east from Moscow.

Fig. 14 (a). Central spiral fabrication equipment.

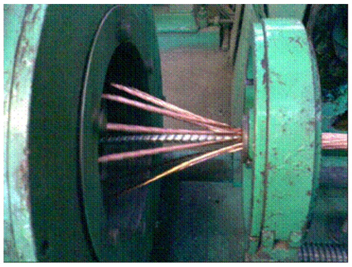

Fig. 14 (b). The former twisting machine.

Fig. 15 (a). The cabling machine for HTS cable.

Fig. 15 (b). The HTS cable fabrication.

C. *Development of Current Leads*

Current leads (terminations) are one of the most important and most complicated parts of any HTS power cable system. Their purpose is to interface the cryogenic system and HTS power cable with the electric grid. The first types of current leads were developed by two different Russian institutions for the 30m experimental cable project [21, 24]. With these current leads, seen in Figure 13 (a), basic principles of current lead design were verified and tested.

For the 200 m project, the current lead should connect to the superconducting shield, which is carrying current equal to the transport current. Superconducting shields of each of three phases have to be connected and grounded. If current leads for shields are at room temperature, the heat load of the cryogenic system by current leads will double. That is why the current leads for 200 m cable have superconducting connection of shields in the cold zone and have only one output for grounding (Fig. 17).

These current leads demonstrated excellent performance during acceptance test of the 200 m cable, with a total heat load from all six current leads at nominal current not exceeding 1200W. The leads were developed by the Moscow Aviation Institute – Technical University (MAI). Their artist's conception is shown in Figure 16.

Thus, we can state that basic technologies for HTS power cable production have been developed, including the cabling technology, current leads technology and the production workshop. VNIIKP and collaborating teams became ready for industrial production of HTS power cables.

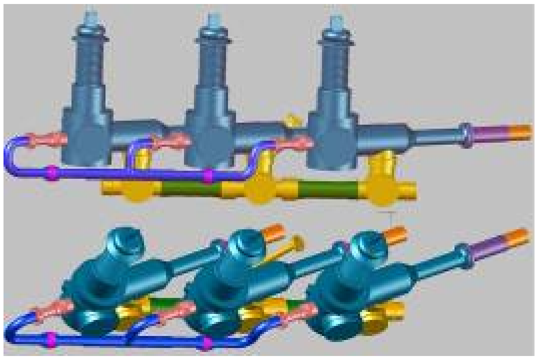

Fig. 16. The artist's conception of current leads.

V. PRODUCTION

A. *3x200m Power Cable Project*

The scientific and technological developments described above permitted us to start pre-industrial and pre-commercial fabrication of the 200 m cable project. We consider this 200 m cable project as Stage 2 of the roadmap shown in Figure 1.

The organization of this project has been as follows. General management was performed by the Moscow Krzhizhanovski Power Engineering Institute (ENIN). The three-phase cable was developed and produced by VNIIKP. Cable testing was performed at the test facility of the Russian R&D Center for Power Engineering in Moscow - with participation of both, VNIIKP and MAI. 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 Russian Federation.

The cable nominal rating is similar to 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 [21, 24]. 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 tapes with Cu alloy lamination;
- Design: Central spiral, copper former, copper protection for superconducting shield.
- High voltage insulation made from cable paper at the Russian Kamkabel factory in Perm;
- Cryostats: NEXANS flexible cryostats with 92 mm outer diameter, with PE protection cover extending up to the diameter of 102 mm.

Three phases of 200 m cable have been produced, assembled into three flexible cryostats via the pulling-through method, delivered to the test facility in early September 2009 and laid on the ground at the test site. In parallel, the 5 m witness sample equipped with many probes and voltage taps has been produced as well and tested (see Fig.11) [23]. Figure 17 shows the installation at the R&D Center for Power Engineering test site: (a) the three cable terminations, and (b) the three phases of the cable on the ground.

The test of the witness sample demonstrated full compliance with rated parameters; the critical current at 77.4 K was 4.2kA as designed. Current distribution among layers and AC losses were measured as well in this sample [23]. In the AC mode difference of currents per layer was less than ±0.5% [23].

In December 2010 the acceptance test of the full length cable has been performed. The primary goal of the tests was to ensure that the cable works. During testing, we found that the cable has a cooling time of about 30 hours, and DC critical currents for all three phases are more than 5.2 kA at about 74 K. Energy transfer of 50 MVA (1500 A and 20 kV for three phases) has been performed for a 24 hour period.

At present, more extensive tests of the 200m 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. After these tests, in 2011, the cable is to be installed at the Moscow “Dinamo” substation to be tested in a real utility grid.

As the 200m cable and all its components were fabricated by fully industrial technologies, we completed the implementation of Stage 2 of the roadmap for HTS cable technology and demonstrated readiness for the real commercial HTS power cable production.

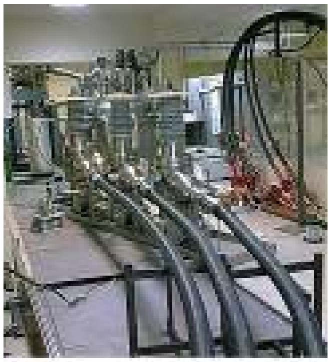

Fig. 17 (a). Terminations of the 200 m long cable installed at the test site in R&D Center for Power Engineering.

Fig. 17 (b). Three phases of the 200m long cable installed on the grounds of the test site.

B. *Future Plans and Ideas*

There is no definite decision on the future cable development, subsequent to the installation of the current cable in the Moscow grid. In planning and discussion stage are longer and higher voltage models. Actually, all components of the 200m cable, including current leads, could be easily upgraded to higher voltages (110 kV for example) that are important to the Federal Grid Company, which is a distribution utility. Some 1 to 1.5 km cables with the same voltage rating are considered both in the DC and AC version. There has been also talk of future commercial projects involving similar cables.

In any case, our 200 m project will represent the first cable to be installed in the Russian electricity grid. The outcome of work we are performing should be a wide implementation of superconducting cables in the future Russian and not only Russian electric grid. We are ready for any collaboration. We can state that VNIIKP, together with collaborating teams, is ready for industrial production of HTS power cables for any customer.

VI. CONCLUSION

Russian program on HTS power cable development and introduction is underway. In-depth theoretical scientific studies, basic material studies and 5 m cable tests provided the base of HTS power cables development. Test facilities for 5 m cables and for high-power HTS devices were developed and are ready for collaborative studies. Experimental 3 x 30 m cable has been successfully tested under load at the special test facility for HTS power devices. The test facility with voltage up to 110kV, DC - 6.5kA, AC - 3kA (rms) with cryogenics and measuring devices is available for tests of HTS devices under load. After the 30 m cable test, our 3x200m cable has been produced, passed acceptance test and is now under extensive full scale testing. After the completion of these extensive tests, the 200 m cable will be installed in the Moscow distribution grid. VNIIKP with collaborating teams is ready for industrial HTS cables production.

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