Electrical and cryogenic tests of the 1200 m HTS DC cable system

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Abstract. Comprehensive tests of all the components of the HTS DC line were carried out as a part of the project to create a superconducting cable line with a capacity of 50 MW for the power system of St. Petersburg. HTS DC cable line will connect two substations of different voltage in the center of the city. The experimental stand included several cable lengths with joints and current leads, a reverse cryostat, a two-circuit cryogenic system with a capacity of 12 kW at 77K, a converter station and a control and monitoring system. The total length of the cryogenic line exceeded 1200 meters. The report presents the results of vacuum, cryogenic and electrical tests carried out over several months. The electrical and hydraulic characteristics of the HTS cable line were determined. Some emergency modes of the cryogenic system were studied. The possible time of cable operation in various accidents in the cryogenic system was estimated.

1. Introduction
Superconducting cables are the most developed and advanced area of superconductivity application in electric power industry in current time. Superconducting cables have evident benefits when transmitting large power flows through electrical networks in comparison with traditional ones. This fact stimulated the development of a large number of designs of cables for the transmission of tens to hundreds of megawatts. A large number of experimental cable lines was created with a length reaching hundreds of meters [1]. Two types of cryostats are basically applied to create a circulation of liquid nitrogen in those projects: the flexible corrugated cryostats[2, 3] and systems with rigid pipes [4].

Recently, superconducting DC cables have attracted increasing interest. They are designed to create powerful long transmission lines of electrical energy [5] and HTS cable lines to connect substations at distribution voltage [6, 7]. This leads to the need to solve such problems as: the reliability of the cryogenic system of the cable line, maintaining the specified parameters of the liquid nitrogen, maintaining the parameters of vacuum insulation, monitoring the level of heat load and control of the pressure drop. In the framework of HTS DC cable line project for the St. Petersburg power system, electrical and hydraulic characteristics of the line were determined and the most credible emergency modes and accidents of the cryogenic system were analyzed. As a result the hardware and software complex with a system of interlocks and protection of the HTS DC cable line was developed.
2. Superconducting cable lines in a power system

High-temperature superconducting cable lines (HTS CL) are an innovative development that allows solving a significant part of the problem of energy supply to consumers. In electrical networks, it is possible to create a circuit with the use of AC and DC superconducting cables. However, long-distance cable transmissions are possible only with the use of DC lines, since any, including superconducting, AC cable lines have a length limitation, due to the occurrence of charging currents ($I_c$), which lead to a decrease in power at the far end of the line.

$$I_c=U\omega C_0 L,$$

where $U$ is phase voltage, $\omega$ is circular frequency, $C_0$ is capacitance, and $L$ is line length.

As a result, the length of AC cable lines does not exceed several tens of kilometers. For this reason, HTS DC cable was chosen for the St. Petersburg project. The cable includes three layers of HTS tapes – two layers for direct conductor and one layer for reverse conductor.

3. The project “HTS cable line for the St. Petersburg power grid”

The St. Petersburg HTS DC cable project is designed to connect “Tsentralnaya” 330 kV Substation and “RP-9” 220 kV Substation. The cable length is about 2500 m, and the liquid nitrogen cryogenic circuit is 5000 m. By using HTS DC cable line for interconnection of two substations allows implementation of reversible power mode and provides an increase of reliability of power supply to consumers without the occurrence of unacceptable (emergency) electric regimes and without increasing the fault-currents levels. The cable line consists of six cable lengths (figure 1), two end joints (current leads), five coupling joint, two converter substations, one cryogenic system, control, monitoring and protection systems. The content and objectives of the project have been described in sufficient detail in the references [8, 9]. General characteristics of the cable line are shown in table 1.

| Table 1. The main characteristics of HTS cable line. |
|---------------------------------------------------|
| Transmitted power | 50 MW |
| Rated voltage | 20 kV |
| Rated current | 2500 A |
| Working temperature | 66-80K |
| Length of cable | 2500 m |
| Type of converters | 12-pulse |
| Possibility of reverse | Provided |
| Cooling capacity of cryogenic plant | 12kW @ 70K |
| Pressure of liquid nitrogen | up to 1.4MPa |
| Flow rate of liquid nitrogen | 0.1 ÷ 0.6 kg/s |

*Figure 1. Scheme of laying of cable lines in St. Petersburg.*
3.1. Electrical diagram of the line and the results of electrical tests
As shown in figure 2, the HTS cable connects a 220 kV substation “RP-9” and a 330 kV substation “Tsentralnaya” at the medium voltage level.

![Figure 2. Electrical scheme of superconducting connection.](image)

The cable line is a DC link. The transmission of a large flow of energy at the distribution voltage is carried out by a superconducting cable, and the AC-DC-AC conversion, the fault-current limitation and the power flows regulation are carried out by Converter substations. The DC link provides mutual reservation of two power districts powered from substations "RP-9" and “Tsentralnaya” and, consequently, the increase of power supply reliability for consumers.

Detailed results of the whole complex of electrical tests are presented in ref. [10]. The current voltage characteristics (CVC) of the forward and reverse conductors for 860 meters line are shown in figure 3. Point "B" in the figure shows the value of the critical current determined by the criterion $E = 1 \mu V/cm$. Point "A" shows the value of the critical current, defined as the beginning of the deviation from CVC linearity.

![Figure 3. The current-voltage curves for forward and reverse conductor of 860 meters HTS cable.](image)

In our cable the forward conductor consists of 22 G-1 HTS tapes with a critical current of 160 A, and the reverse conductor 19 of the HTS tapes with average critical current of 190 A. The coordinates of the points "A" in figure 3 corresponds to the sum of the critical currents of the original tapes within 6%. The coordinates of the points "B" in figure 3 are more than the sum of the critical currents of the original tapes by 12-20%. This result confirmed the achievement of design characteristics of HTS cable line and also the perfection of its design and manufacturing technology.

When varying the temperature within the range from 67K up to 81K the critical current varied from 5700 A to 3200 A (figure 4).
Figure 4. Critical current temperature dependence for 60 meters cable sample, where Tin – temperature of LN2 at the HTS cable inlet and Tout – LN2 temperature at HTS cable far end.

Taking into account that the operating current of the line is 2500 A, the above results show a large margin of reliability for HTS cable line in terms of current. The cable line has successfully passed high voltage tests with a constant voltage of 60 kV for 30 minutes.

As a result, the reliability of the cryogenic system becomes a determining factor for the overall reliability of the entire cable system.

4. Cryogenic circuit pattern

The principle of cryogenic system operation is the supercooling of the liquid nitrogen circulating in the HTS cable line due to heat exchange with cold gaseous helium. A schematic diagram of the closed circuit is shown in figure 5. The scheme includes two circuits.

Figure 5. Cryogenic system principal diagram.

where, 1 - 9 – Measuring points with temperature and pressure sensors; TE - turbo-expander unit; MCS - modular compressor stations; P10 and P20 - cryogenic pumping station (CPS); HE – heat exchanger; TLS – heaters.
The structure of the first main circuit includes:
- Liquid nitrogen cryogenic pumping unit;
- Heat exchanger “gaseous helium - liquid nitrogen”;
- Supercooled nitrogen storage;
- Liquid nitrogen tank;
- HTS cable cryostat;
- Reverse cryostat.

Cryogenic pumping unit includes two cryogenic pumps (one – in operation, the second – backup) and switching valves. Heat exchanger is designed for supercooling of liquid nitrogen with gaseous helium to a temperature of 65–66K. Direct-flow heat exchange scheme is applied in order to avoid liquid nitrogen freezing.

The second main circuit – where gaseous helium is compressed and cooled. Gaseous helium is supplied to compressor units at suction pressure of 3-4 bar where it is compressed to a discharge pressure of 13 bar. Then gaseous helium at 13 bar is supplied to turbo-expander where it is cooled to 46K with pressure drop to 3-4 bar. Cooled gaseous helium at 46K is supplied to helium-nitrogen heat exchanger inside liquid nitrogen supercooling unit. The circuit includes:
- Two modular helium compressor station (one – in operation, the second – backup)
- Switching valves for automatic switch between compressors in case of failure of primary compressor.
- Helium turbo-expander.

In addition to the above mentioned units, the cryogenic system includes a system of initial refill and recharge with liquid nitrogen and gaseous helium purification system.

The cryogenic system operation is automated, including stages of initial cooling, cable thermal condition maintenance, liquid nitrogen discharge from the cryostat and reheating, with the possibility of switching to manual remote control and the autonomous automatic control circuits enabling from the control panels.

Automatic process control system (APCS) of the modular compressor stations (MCS) and cryogenic pumping station (CPS) enables automatic switch of Cryogenic System operation to a backup helium modular compressor station and a backup liquid nitrogen cryogenic pumping station.

4.1. Cryogenic tests

The main purpose of cryogenic tests was to check the cooling capacity of the cryogenic system and to estimate the pressure drop at the length of the cryogenic loop. Cryogenic experimental bench include two construction cable length reverse cryostat with total cryogenic loop length about 1200 meters. The difference in height along the length of the cable was 8.2 meters. HTS cable with an outer diameter of 40mm was placed in flexible corrugated cryostat of Nexans company with inner diameter 64 mm. Reverse cryostat has inner diameter of 39 mm. The liquid nitrogen flow varied between 20 - 65 l/min. The temperature and pressure sensors were installed at the inlet and outlet of the cryogenic system, the forward and reverse cryostats as shown in figure 5. Two heaters were installed in a cryogenic loop to simulate the full thermal load in a full-scale cryogenic loop of 5 km long.

Assessment of thermal loads was carried out using following source data:
- Temperature was measured at the points of inlet and outlet of the cryogenic system, each cryostats and heaters.
- The current is not supplied to the cable. Heat input through one current lead (at zero current) was estimated at 90 W.
- Flow rate and pressure were kept constant;
- For the calculations, the temperature at the return point has been fixed only after a “control volume” passed entire cryogenic loop and the temperature remained stable.
- The readings were taken every second.
The obtained heat load data is shown in figure 6. The average value of heat load into the cryogenic environment was 2.82 kW. It should be borne in mind that this amount includes heat leakage through the cryostats, current leads and the interconnecting piping between the cryogenic system and the current leads. During the experiments, the cryogenic system showed a stable value of cooling capacity at the level of 12 kW. It provided a temperature at the outlet of the cryogenic system within the 66 K - to 68 K at a nitrogen flow rate of 20 - 65 l/min.

When steady flow conditions in a corrugated cryostat is developed into turbulent regime, the value of the Reynolds number was about Re = 30000.

![Figure 6. Heat inflow through two cryostats with connecting fittings and pressure drop in cable cryostat.](image)

One of the main objectives of experimental research is to obtain data on the value of the hydraulic resistance of corrugated cryostat and assess the appropriateness of the proposed theoretical calculation of the pressure drop [2]. The thermally stable area with constant pressure drop and mass flow-rate was selected to reduce the impact of external factors in determining the value of the hydraulic resistance.

Hydraulic resistance coefficient of rigid pipe in turbulent mode is determined in accordance with the Blasius law:

\[ \lambda = 0.3164 \cdot Re^{-0.25} \]  

In turbulent flow the coefficient of hydraulic resistance depends weakly on the Reynolds number [11] and significantly depends on the ratio of the corrugations length step to its height [12]. The average value of the pressure drop was obtained from the experiment, which was 0.43 bar. for a cable length of 860 m (figure 6). The average friction coefficient for the inner diameter of the corrugated tube of the cryostat 64 mm and 40 mm cable was 0.0672. The presence of the corrugations in the cryostat increases the friction coefficient, that restricts the length of the cable line at a given allowable pressure drop. The friction coefficient rigid pipe with the same hydraulic diameter equals to 0.02405. The correlation coefficient for corrugated pipe to the coefficient of a rigid pipe in our case is 2.74.

The manufacturer of cryostats limited the maximum pressure in the cryostat as 10 bar. It is known that the pressure in the cryostat shows a power-law dependence on the flow rate. On the other hand, the flow rate determines the temperature difference along the cable length. A series of experiments was carried out to determine the dependence of the pressure drop on the flow rate. Figure 7 shows the experimental results are given to the full length of the cryogenic loop. As previously assumed [2], the reverse cryostat makes a significantly larger contribution to the pressure drop along the cryogenic loop. From the figure 6 it follows that the maximum flow rate of liquid nitrogen, not leading to exceeding the permissible pressure, is 47 l / min. The temperature difference at this flow rate along the superconducting cable will be 3.0-3.5 K. Thus, the previously selected operating nitrogen flow rate of
30 l/min provides acceptable operating parameters (temperature difference 4.0 -5.0 K and pressure drop about 4 bar).

**Figure 7.** The pressure drop in the cryogenic loop as a function of flow rate.

This mode also ensures that there is no gas phase when nitrogen is returned to the cryogenic circulation pump.

5. Emergency processes analysis, control and protection system

Emergency processes in HTS DC cable line cryogenic system can arise as the result of the occurrence of damage to the equipment, increase of level of leakage in the circulation loop of liquid nitrogen, the false alarm rate of devices and machines, incorrect human actions.

The main controlled parameters for each point were determined according to the developed scheme. The values of emergency operation modes obtained as a result of the tests were structured according to the significance for each of the fault or accident scenarios.

Table 2 contains indications of the normal operation of the system recorded during the tests on the Cryogenic System of HTS cable line.

During the experimental studies, the circulating cooling circuit of the cable included two cable factory lengths of 430 meters each with one coupling joint and two end joints, a 300 meters reverse cryostat, circulation pumps, “liquid nitrogen-gaseous helium” heat exchanger, interconnecting piping and a measuring unit. Thus, the length of the cryogenic circuit (without heat exchanger) was about 1200 meters.
Table 2. Steady-state mode parameters.

| No. | Parameter                                | Value          |
|-----|------------------------------------------|----------------|
| 1.  | Gaseous helium minimal temperature at turbo expander unit | 59.5 K          |
| 2.  | Turbine speed rev/min                     | 130000         |
| 3.  | LN2 temperature at HTS CL inlet          | 68.7 K         |
| 4.  | LN2 temperature at HTS CL outlet          | 70.63          |
| 5.  | LN2 temperature at reverse cryostat inlet | 73.00          |
| 6.  | LN2 flow rate                             | 36.6 L/min     |
| 7.  | Gaseous helium intake pressure            | 0.17 MPa       |
| 8.  | Gaseous helium discharge pressure         | 1.07 MPa       |

The following variants of emergency modes of the cryogenic system were investigated:
- Emergency shutdown of one/two cryogenic pumps.
- Emergency shutdown of the supercooling circuit.
- Emergency vacuum loss in one of cryostat shells of HTS cable line or in coupling or end joints.

At the time of emergency shutdown of active cryogenic pump, there was a response in the parameters of the heat-hydraulic mode of the nitrogen circuit associated with the of liquid nitrogen circulation loss in the HTS cable line. The diagram of the emergency mode is shown in figure 8. The mode is accompanied by liquid nitrogen temperature increase at the control points of the HTS cable line. The data obtained confirm the necessity to control the automatic failover switch regime of cryogenic pumps, since delays in switching between active and backup pumps can lead to the refrigerant circulation loss with consequent noticeable increase in the temperature of liquid nitrogen at current leads.

The critical influence of the cryogenic system on the transmission characteristics was observed due to the coolant temperature increase and a corresponding decrease in the critical current of the superconducting cable. Taking into account that the cryogenic station is located at one end of the cable line, the maximum temperature will be registered at the far end of the cable near the current lead. As follows from Fig 6 between the time of switching off the main pump, switching on and entering to the operating mode of the backup pump passes 1.0 - 1.5 minutes. Operating characteristics of liquid nitrogen during this time practically do not change. The failure of the working compressor and the switching on of the backup also occurs quickly enough and does not affect the performance of the refrigerant. This confirms the efficiency of the developed backup scheme.

As expected, of all emergency modes the most dangerous one is the circulation loss of liquid nitrogen in HTS cable line. In this case at nominal loading of a cable line the temperature near current leads reaches 77 K for 10-15 minutes. For this reason the Cryogenic System has a dual redundancy of circulation pumps.

When the supercooling unit fails and the circulation in the main circuit is maintained, the cable line can transmit a nominal capacity up to two hours. This time is allotted to the staff to eliminate the emergency mode or to make a decision to gradually reduce the load according to the temperature rise with the subsequent end of transmission.
**Figure 8.** The oscillogram of the emergency mode of HTS CL cryogenic system at the main cryogenic pump emergency shutdown.

Limiting the maximum temperature to 77K provides some safety margin to our estimates due to the fact that the current carrying capacity of the cable remains satisfactory up to 81K (see figure 4). The results obtained during the investigation of the emergency modes were obtained at two construction lengths of HTS cable and will be refined experimentally after the installation of the full 2500 m line at the facility in Saint-Petersburg.

6. **Conclusion**

Electrical and cryogenic tests of two factory lengths of the HTS cable line and 300 meters of reverse cryostat with a total cryogenic length of 1200 meters confirmed the achievement of all design characteristics.

The results of the analysis of emergency operation modes HTS DC cable line cryogenic system will ensure the safety of the technological process of cryogenic supply of HTS DC cable line, and enable necessary adjustments to the interlocking and protection system and automatic control of dual-circuit cryogenic system in given modes.

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