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Development, adjustment, and implementation of the HTS Transmission Cable Line (2.4 Km) in St. Petersburg

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SUMMARY

Development, adjustment, and implementation of the HTS Transmission Cable Line were carried out within the framework of the National project for the implementation of a superconducting DC cable line with a capacity of 50 MW, 20 kV in the power system of St. Petersburg. The HTS Cable Line was developed by Research and Development Center of Federal Grid Company of Unified Energy System and manufactured by Russian cable factory – JSC "Irkutskkabel". All the tests were carried out at dedicated premises of R&D Center in Moscow. The experimental stand consisted of six lengths of cables with five couplings and two current leads, return cryostat (no cable inside), dual-circuit cryogenic system with rated power of 14,5 kW at 77 K, the rectifier-inverter device and the automatic process control system. In accordance with the approved project for laying the HTS cable line in Saint Petersburg, the total cable length was 2400 meters. The cryogenic circuit total length is 5000 meters and includes cable in cryostat, return cryostat (2400 meters), thermal load simulator and measuring equipment. The report describes the scheme of a two-circuit cryogenic unit and presents the results of vacuum, cryogenic and electrical tests carried out over several months. The cable protection system and its test results are also described. The temperature of liquid nitrogen and its flow rate varied widely during the test. The electrical and hydraulic characteristics of the HTS cable line and reverse cryostat were determined. The HTS cable line implementation into St. Petersburg power grid is scheduled for the beginning of 2023.

KEYWORDS

DC power transmission, Superconducting transmission lines, Cooling system, conversion system, tests

I. INTRODUCTION

The current problems of the 21st century electric power industry require the creation of intelligent energy systems that ensure high efficiency of generation, transportation, and electricity consumption. At the same time, the requirements for the controllability of the power system, environmental and resource-saving parameters at all stages of electricity production and distribution are increasing. The development of power grid infrastructure and the creation of ring circuits of electric grids based on the implementation of cable lines with cross–linked polyethylene insulation (XLPE) that are traditionally used in the power systems of megacities increases the complexity of power flows management in power systems and can lead to unacceptable levels of fault currents in several electrical modes. The introduction of a new regulated electrical connection, devoid of these disadvantages, is possible through implementation of a high-temperature superconducting DC cable line, which can perform the functions of fault current limitation and power flows control. In addition, energy losses and transmission voltage can be significantly reduced when transporting energy via superconducting cables, which leads to simplification of the network architecture and reduction of alienated territories. The stability of the power system can be significantly improved due to the low impedance of superconducting lines. Beside that HTS cable lines are environment-friendly – no chemical, heat or magnetic contamination and they are fireproof.

Considering the obvious advantages of HTS DC power lines in many countries (Russia, South Korea, China, Japan, Europe), the current work is being carried out to create and introduce such lines into power transmission or distribution grids for various purposes [1-5]. Russia is approaching the final stage of work on creation and implementation of HTS DC cable line for the St. Petersburg power grid [6].

II. SAINT-PETERSBURG PROJECT

A. Overview

The first Russian HTS DC cable line will be installed in the power system of Saint Petersburg between 330 kV and 110 kV substations in the dense urban area. The cable Length is 2.4 km, and the liquid nitrogen pumping circuit is about 5.0 km. These parameters are a record among existing HTS cable line projects in the world.

The cable line is a DC-link. The transmission of a large flow of energy at medium voltage is carried out by a superconducting cable equipped with the AC-DC-AC device. Fault current limitation and the power flows regulation is carried out by Converter substations. The DC-link provides mutual redundancy of two power districts powered by the substations 330 kV and 110 kV substations and, consequently, increases the reliability of power supply to consumers. The content and goals of the project were previously described in detail [6-8]. The main characteristics of the cable line are shown in Table I.

TABLE I
HTS DC cable line parameters

Parameter	Value
Transmitted power	50 MW
Operating voltage	20 kV
Operating current	2500 A
Operating temperature	66-80 K
Cable length	2400 m
Converter device configuration	12-pulse
Reversable transmission	enabled
Cooling system capacity	14,5 kW@ 70 K
LN_2 pressure	Up to 1.4 MPa
LN_2 mass flow-rate	0.1-0.6 kg/sec

B. HTS DC cable line cooling system

The HTS DC cable is cooled with liquid nitrogen when it is pumped in the space between the outer surface of the cable and the inner surface of the cryostat

When designing long-length cryogenic systems, one of the main issues is the calculation of heat and mass transfer in the flow part of the system. This is due to the very narrow range of operating temperatures and pressures of the HTS cable. The operating range of liquid nitrogen is limited by the freezing point at the bottom and the boiling point at the top, making up only ΔT =77.4 K - 65 K = 12.4 K at atmospheric pressure. Although it can be expanded by increasing the pressure in the system (for example, 20.6 K at 2 ATM.). However, the range extension is possible only through the increase of upper range limit, which leads to a temperature rise at the outlet from the cryogenic pipe and therefore decreases the critical current of the cable, which is undesirable. The operating pressure range is limited to a lower value of 0.1 Bar. The safety valve is set to a maximum pressure of 13 Bar consequently for long lines there is a strong physical restriction on ΔT and some other values. For this project, it is assumed that $\Delta T_{max} \leq 12$ K for a length of 5.0 km and $\Delta T_{max} \leq 6$ K for a cable length (2.4 km). In this case, it is desirable to limit the pressure drop on the direct and reverse cryostats within 5-6 Bar on each cryostat. Results of calculating the differential pressure and temperature over a cable length of 2.4 km. and cryostats were presented earlier [9].

To verify that the characteristics of the HTS DC cable line correspond to the design values, we have conducted full-scale experiments. At the test site, the full length of the HTS DC cable was installed, consisting of 6 construction lengths of cable in cryostat, five connecting and two terminal joints, as well as 1000 meters of the reverse cryostat for refrigerant circulation. In addition, a thermal load simulator was introduced into the cryogenic loop, which allows simulating the full thermal load on the cryogenic system under the conditions of laying a cable line with a cryogenic loop length of 5.0 kilometers. It was also possible to increase the hydraulic resistance of the reverse cryostat to the value of its total resistance on implementation site, corresponding to the length of 2.4 km.

Thus, the assembled scheme allows to fully reproduce and study the electrical and thermohydraulic characteristics of a full-scale HTS DC cable line. As shown in Figure 1 HTS DC cable line is cooled by a cryogenic unit located at one end of the cable line. The cooling scheme includes two circuits: a nitrogen circuit (shown in blue) and a helium supercooling circuit. The scheme was described in detail in [10].

The superconducting cable is cooled in the nitrogen circuit. In the heat exchanger of the circuit, liquid nitrogen is supercooled to a temperature of 65K-67K, after it is heated during pumping through the cable line. Liquid nitrogen is cooled by cold gaseous helium with a minimum temperature of 47K. To avoid nitrogen freezing, a direct-flow heat exchange scheme is used.

The circuit contains a pumping unit consisting of two centrifugal cryogenic pumps (one in operation, the second one is backup) and an automated switching valve.

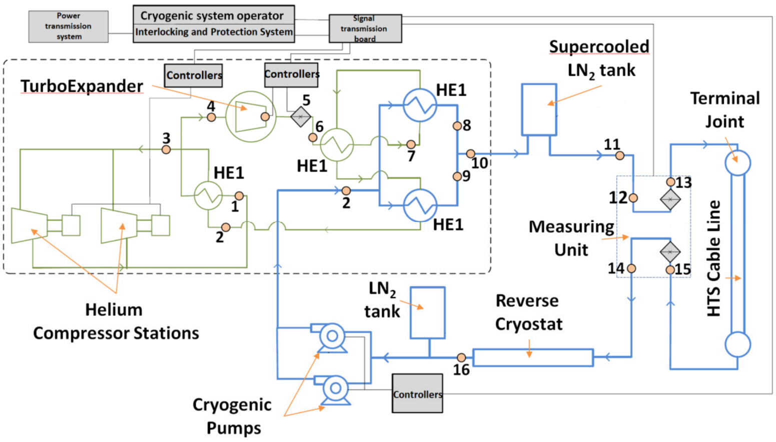

Figure 1. Schematic diagram of the cryogenic support system.
where, 1-9-measuring points with temperature and pressure sensors; TDA-turbo-expander unit; MKS-modular compressor stations; H10 and H20-cryogenic pumping stations; TA-heat exchanger; ITN-heat load simulator.

The helium circuit is a refrigerator designed for cooling helium gas by compressing it in a compressor, followed by expansion and operation in a turbo-expander unit. The main and backup helium compressors are provided in the circuit.

The automated process control system (APCS) of the compressor and pumping units enables automatically switching the operation of the cooling system to a backup helium compressor and a backup pump for pumping liquid nitrogen.

Two sessions of HTS DC cable line coolings were conducted, with electrical and hydraulic tests.

III. TESTS

A. Electrical tests

The initial electrical tests were conducted with two construction lengths with a total length of 860 meters assembled. The results were described in detail in report for e-CIGRE Session in 2020 [17].

In 2020 after a deep upgrade of entire Cryogenic system, dedicated electrical tests were carried out as a part of complex boundary functional tests on the test bench using a 3-pulse ring test circuit, as shown in Figure 2, because in our case it was quite risky to carry out this procedure in the existing electric network using 12-pulse circuit.

The peculiarity of this scheme is that one 6-pulse converter is divided into two 3-pulse unidirectional converters (two switching groups with a Mitkevich connection scheme each), one of which operates in the rectifier mode, and the second one – in the inverter mode. Because of common connection of switching connected to the same secondary winding of the converter transformer and a different delay angle for controlling the rectifier and inverter, this test circuit has unique characteristics.

The scheme can be used to carry out tests by periodic switching on and off.

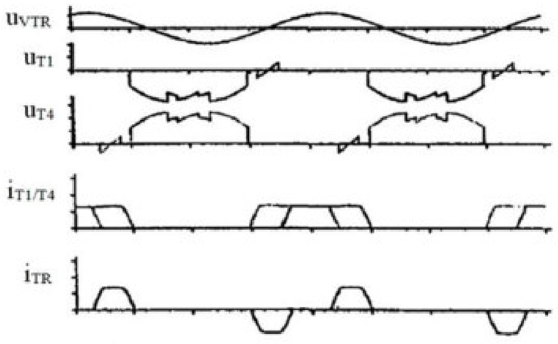

Figure 2. Characteristic shapes of voltage and current curves for 3 pulse test circuits, U_{VTR} – transformer voltage, U_{T1} – AC/DC voltage, U_{T4} – DC/AC voltage, $i_{T1/T4}$ – AC/DC/AC currents, i_{TR} – transformer current

In the case of a 3-pulse ring test circuit, the current curves of the valves (for example, T1 and T4) belonging to the same phase of the valve winding of the transformer overlap, and the corresponding phase does not carry current for this period. In this case, the circuit conducts current freely through the specified valves and the smoothing reactor(s) of the DC circuit. Due to the free flow of current, the current value of the transformer is reduced. The active and reactive power required from the AC grid is also reduced. With an increase in α, the transformer current increases, reaching its maximum at $\alpha = 90^{O}$, which corresponds to a 6-pulse ring test circuit.

When creating a test facility in the form of a 3-pulse ring circuit for the implementation of a comprehensive testing of the entire set of electrical equipment of the DC-link, smoothing and phase reactors, control system, regulation, protection, and automation were also used as components of the circuit in addition to valve blocks.

B. Cryogenic tests

The main purpose of cryogenic testing was to confirm the cooling capacity of the cryogenic system and evaluate the hydraulic characteristics of a full-scale cryogenic circuit.

On the first stage an assembly of 1200 m of HTS cable line was installed on testing site consisting of two construction lengths of cable, 300 m of reverse cryostat, one connection joint and two terminal joints carrying current leads. Details of 1200 cryogenic test were given in the report for e-CIGRE Session in 2020 [17].

In 2020 the second stage of Cryogenic tests was carried out with an assemble of full length of cable and 1000 m of reverse cryostat with 5 connection joints and two terminal joints was installed at testing site. The overall length of cryogenic circuit was 3 400 meters. The layout of testing site with full length of cable line assembly is shown on Figure 3.

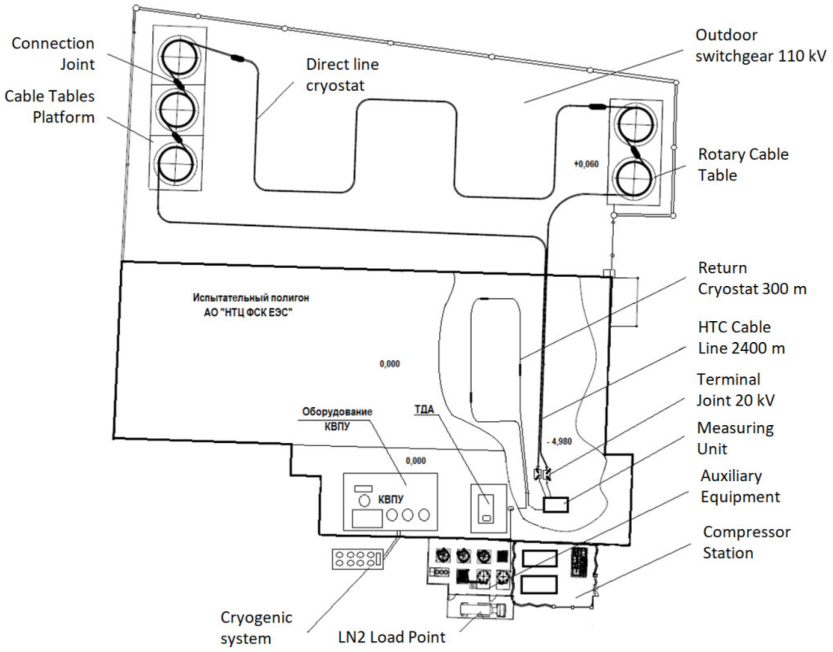

Figure 3. Full line assembly layout

Preliminary theoretical calculations were made for the cooling time of 2400 m of the cable line with nitrogen gas. To simulate non-stationary thermal processes in HTS DC cable line during cooling, a numerical model was developed. The initial model is a system of non-stationary energy conservation equations describing the heat exchange between the elements of the cable structure and the flow of liquid nitrogen in the flow path of the cable line. The graph of HTS DC cable line cooling for various lengths is shown in Figure 4.

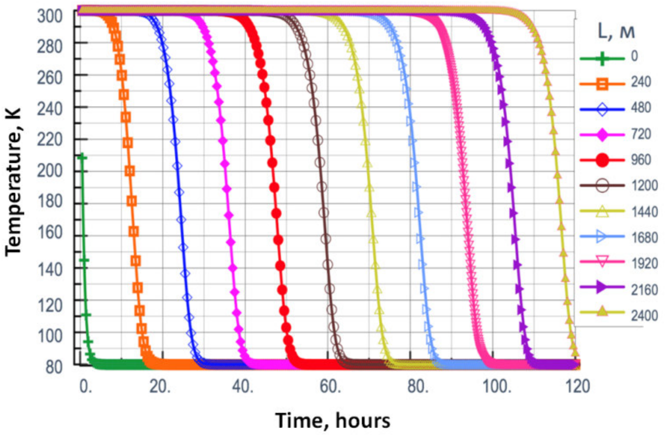

Figure 4. Calculation of the cooling time of HTS DC cable line 2400 m at a gas flow rate of 1500 l/m

Thus, the estimated cooling time was about five days. During the first session of cooling, the total time significantly exceeded the estimated time. This was because after a very rapid initial cooling of part of the cable line from the cryogenic system, the hydraulic resistance of the circuit then sharply increased, the cooling gas flow-rate decreased, and pressure pulsations appeared. After that, it took a considerable time to push the cold gas along the entire length of the nitrogen circuit. In addition, freezing of the end surfaces of the connecting coupling was detected because of insufficient thermal insulation. This led to the appearance of an additional local heat flow to the cold zone and the formation of a vapor-liquid phase.

To eliminate the difficulties encountered, it was decided to provide additional thermal insulation of the connecting couplings and to place relief valves on two couplings installed at 680 and 1540 meters of cable. The cooling mode itself was divided into three stages: the first stage was performed by cooling the HTS DC cable line 2400 m with cold gas until the minimum temperature difference at the inlet and outlet was reached; the second stage was the launch of the cryogenic support system along a small circuit (without HTS DC cable line), followed by re-cooling of liquid nitrogen to 70 K; the third stage was the supply of supercooled liquid nitrogen to the HTS DC cable line. The discharge valves were closed as liquid nitrogen appeared.

This solution allowed to increase the flow-rate of nitrogen gas in the cooling mode and reduce the time to enter the operating mode of the cryogenic system. The modified coupling is shown in Figure 5.

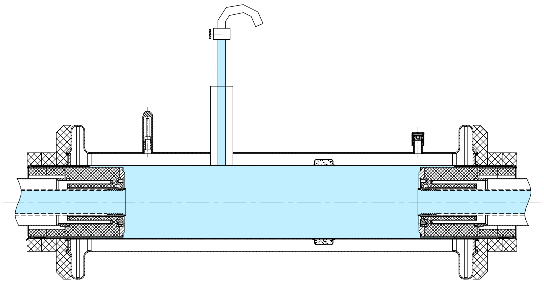

Figure 5. Modified HTS DC cable line coupling with relief valve

The second session of cooling was carried out in almost five days, which is well in line with theoretical estimates. First the experiment started with cooling of full-scale HTS cable line with gaseous nitrogen. The purpose was to cool the line before LN2 injection in order to shorten the overall cooling process. The Figure 6 depicts the process of cooling with gaseous nitrogen.

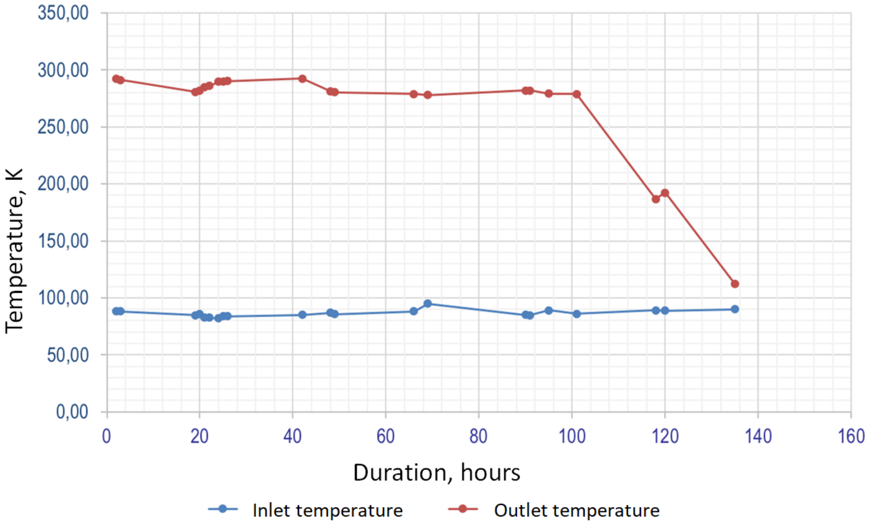

Figure 6. HTS DC cable line cooling with gaseous nitrogen

Then the system was switched to LN2 cooling mode. Figure 7 shows temperature changes at the inlet and outlet of the cable line including 300 meters of return cryostat during the second cooling session.

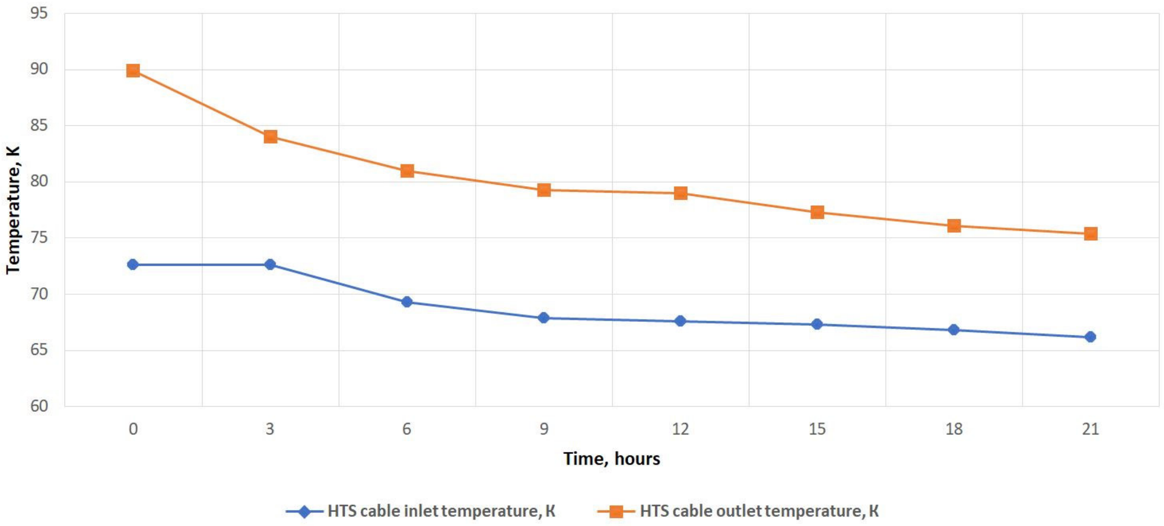

Figure 7. Temperature changes during second session

After line cooling and the inclusion of simulators, resulting in hydraulic characteristics and the total leakage to a value corresponding to the full line on the object has reached steady state.

C. Temperature and Hydraulic Tests

During the tests, the flow rate of liquid nitrogen varied from 19 to 40 liters per minute. The pressure drop was recorded on the cable length and back of the cryostat with the included imitation. The results from the data obtained clearly showed that when the refrigerant flow rate is up to 40 l/min, the pressure drop along the length of the superconducting cable does not exceed 0.2 MPa, which corresponds to previous estimates after studies conducted at a length of 860 meters [10]. The total pressure drop along the entire cryogenic loop did not exceed 0.4 MPa (Fig. 8).

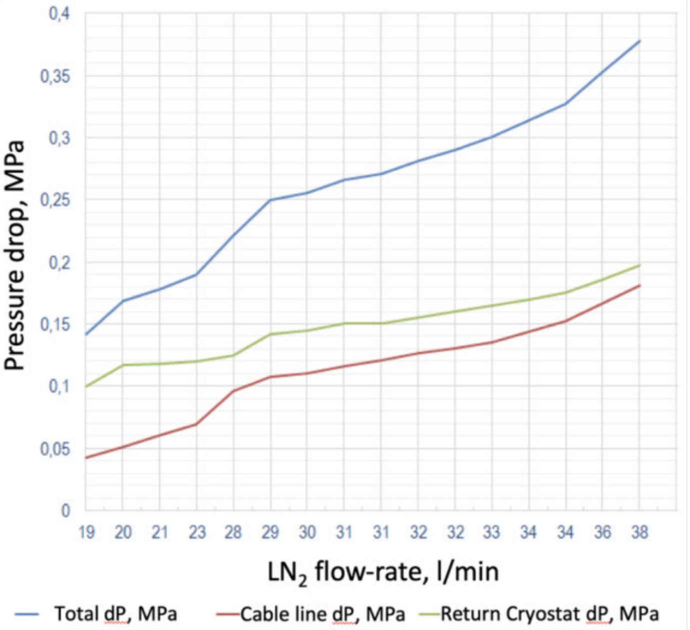

Figure 8. Pressure drop recorded on the cable and return cryostat lengths with the included simulation unit

It should be noted that for long-line tests, it takes a very long time to reach a steady temperature after each change in the refrigerant flow rate. So in the studied design of the cable line, it takes 3-5 hours to pass a fixed volume of liquid nitrogen along the line length of 2400 meters at a flow rate of 30-40L/min, and significantly longer time to stabilize the temperature field along the length. In our experiments, the temperature at the entrance of the HTS line was 67.5 K. At a flow rate of 30 l/min, the temperature at the output of the HTS line was 73.8 K, and at a flow rate of 43 l/min – 72.0 K.

IV. CRYOGENIC SYSTEM UPGRADE

Based on the results of tests in 2019 and February 2020, it was decided to thouroghly upgrade Cryogenic system.

Through 2020 a complex work was carried out and main technological equipment of the two-circuit closed-type cryogenic system was upgraded:

- The thermal capacity of helium-nitrogen heat exchangers was increased by 20%
- The capacity of helium compressor stations was increased by 10%
- The cooling capacity of the cryogenic system was increased by 30% up to 14,5 kW
- A system of automatic locks and protections of cryogenic system was developed and successfully implemented
- The technology of HTS DC Cable line cryo-cooling was upgraded:
- The period of HTS DC Cable line initial cryo-cooling was reduced from 14 to 6 days
- The total demand of nitrogen for initial cryo-cooling was decreased by 50%
- A complete local automation of the cryogenic support system was carried out
- Repair kits of a direct and reverse cryostats were developed, manufactured and tested

V. OPERATING MODES DETERMINATION

The analysis of the operational modes of the Cryogenic system is of interest from two points of view:

- Selection of the optimal mode for normal operating conditions;
- Selection of the mode for maximum heat flow into the nitrogen circuit of the Cryogenic system.

A. Normal operating mode

The main controlling factors in the HTS cable line are the helium flow-rate (operation of helium compressor) and nitrogen (operation of cryogenic pump). It is obvious that in the stationary mode of the Cryogenic system, the heat flows entering the nitrogen circuit are equal to the amount of heat transferred from nitrogen to helium in the LN2 Supercooling Unit. The heat input from the nitrogen pump depends on the nitrogen flow-rate. Accordingly, each nitrogen flow-rate value will correspond to its own operating mode of the helium compressor and/or the temperature regime of the nitrogen circuit.

To analyze the modes, we limited the range of nitrogen flow-rate between 25 and 40 l/min, since an increase in flow over 40 l/min leads to a significant heat flow from the nitrogen pump, which consequently leads to an irrational increase in the load of the helium compressor.

It is obvious that for each nitrogen flow-rate value it is possible to determine such a helium flow-rate value at which the temperature regime of the Ctyogenic system (for nitrogen) will be the same. However, it was far more important not only to accurately determine specific values, but to determine the optimal range of operating parameters.

A small change in the pressure drop of helium on the turboexpander leads to significant changes in its cooling capacity and the temperature of helium at the outlet. With low nitrogen flow-rate, a slight increase in the pressure drop can lead to a risk of local freezing of nitrogen in heat exchangers. With high nitrogen flow-rate, approaching the freezing temperature requires a much greater increase in the pressure drop on the turboexpander, which gives much greater opportunities for reliable control of the Cryogenic system equipment.

The analysys of the results let us conclude that the optimal nitrogen flow-rate in our case is in the range from 30 to 35 l/min. In this case the helium flow-rate will be about 430 kg/h, and the risk of nitrogen freezing will be minimal.

B. Maximum operating mode

With an increase in heat flows to the nitrogen circuit, an adequate response of the control system aimed at removing additional heat is be required.

From the point of view of temperature the critical conditions for the sustainable operation of the Cryogenic system are:

1) The temperature of nitrogen in the cryostat of the cable should not exceed 77 K to ensure its superconducting properties;
2) The temperature of nitrogen at the inlet to the circulation pump should not exceed 79 K in order to avoid boiling of nitrogen;
3) The temperature of nitrogen at the outlet of the Supercooling unit should be greater than 63.5-63.7 K, so that local freezing of nitrogen in heat exchangers does not occur.

Based on the nitrogen temperature of 79 K at the pump inlet and knowing the heat flow in the pump, it is possible to determine the nitrogen temperature at the Supercooling unit inlet. In the calculations, we proceeded from the parameters of the expander at a helium flow-rate of 500 kg/h. As a result, we are interested in such a nitrogen flow-rate at which it is possible to remove the maximum amount of heat from the cryostats of the HTS Cable Line (total heat input minus the heat input in the pump).

At a nitrogen flow-rate of 25 l/min and a helium flow-rate of 500 kg/h, nitrogen freezes in Supercooling unit heat exchangers. This is due to the reduction of helium flow-rate with low nitrogen flow-rate.

Based on the results of the experiments we conducted, it can be concluded that compensation of the maximum heat input into the cryostats of the nitrogen circuit is possible at a nitrogen flow-rate of 35 l/min.

VI. CONCLUSION

The tests of a full-scale HTS DC cable line demonstrated its operability and allowed choosing the modes of initial cooling and temperature stabilization along the length of the line. At the same time, the electrical characteristics did not change, and cryogenic tests made it possible to obtain information on the full length of the cable line and determine the operating modes of temperature stabilization on the full length of the line. Upon determination of normal and maximum operating modes of Cryogenic system the HTS cable line together with all auxillary equipment commisioned to next phase of the Project – construction in Saint-Patersburg which is scheduled for the beginning of 2023.

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