PROSPECTS OF USING HTSC CABLE LINES FOR LONG DISTANCES ENERGY TRANSFER

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The location of powerful electric power sources at great distances from large cities and electric power consumers, leads to the need to transport large energy flows over considerable distances. The use of superconducting cable lines will significantly improve the efficiency, reliability and environmental friendliness of long-distance transmissions.

Keywords: superconducting cable line; power bridge; transmitted power; cryogenic station; critical current; gigawatt.

General view of the cryogenic station with current inputs of the cable line

INTRODUCTION

More recently, the scientific community celebrated the 100th anniversary of the discovery of phenomenon of superconductivity and the 30th anniversary of the discovery of high-temperature superconductivity (HTSC), which has shown the world the possibility of transition from a costly cooling of low-temperature superconductors with liquid helium to a fundamentally new nitrogen temperature level [1]. Currently, there are several dozen experimental cable lines in the world designed to study the possibility of electricity transmission using the superconductivity effect, but their lengths do not exceed one kilometer. The use of superconducting cable lines will significantly reduce the voltage class and increase the unit transmission power due to the increase in operating currents. This opens up the possibility of transmission at reduced voltage, which significantly affects the cost of entire infrastructure of the cable line. In addition, there is no voltage drop along the line length in a superconducting line, which is important for long lines.

ELECTRICAL SCHEME OF SUPERCONDUCTING LINE (A) AND POSSIBLE SCHEMES OF COOLING WITH THE PLACEMENT OF CRYOGENIC STATION FROM ONE END OF THE LINE (B), AND ALONG THE CABLE ROUTE (C)

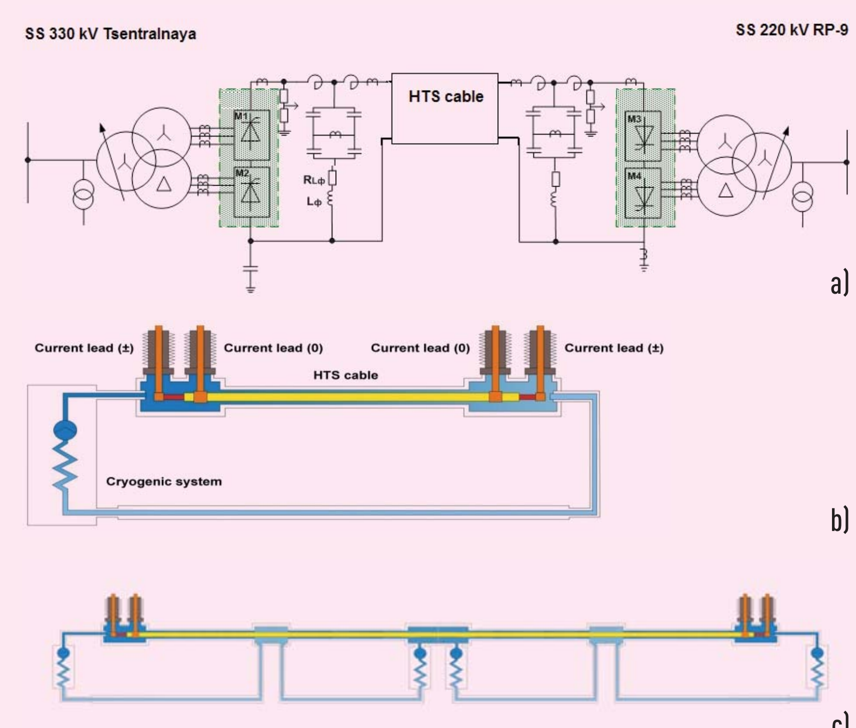

Fig. 1

SUPERCONDUCTING CABLE LINES IN A POWER SYSTEM

High-temperature superconducting cable lines (HTSC 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, which lead to a decrease in power at the far end of the line.

$$Ic=U\omega C_0 L, \qquad (1)$$

where U is phase voltage, ω 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.

ST. PETERSBURG PROJECT, RUSSIA

The Russian HTSC DC CL project, intended for connecting "Tsentralnaya" 330 kV Substation and "RP-9" 220 kV Substation in St. Petersburg power grid. The length of the cable is 2.5 km, and the loop of pumping with liquid nitrogen is 5.0 km. The introduction of HTSC DC CL into the power grid in this case allows implementing a reversible power mode and providing an increase of reliability of power supply to consumers without the occurrence of unacceptable (emergency) electric regimes and without increasing the short-circuit currents [9]. Design parameters of the line are presented in Table 1.

CONSTRUCTION OF SUPERCONDUCTING CABLE LINE

Fig. 2 shows the superconducting cable layout and its appearance. As a basic design, monopolar design with forward and reverse conductor in one cable was chosen. The cable consists of the following concentric layers. Stabilizing forming element is designed so as to provide the necessary mechanical strength and protection of direct conductor from overheating in emergency situations. Superconducting straight conductor consists of twenty-two tapes with a critical current of 160 A superimposed in two layers on the forming element. Diameters and layer twist pitches are designed for equality of their impedances, which ensures an equal distribution of current between the layers. High-voltage insulation is designed for rated voltage. Superconducting return conductor consists of nineteen tapes with a critical current of 180 A placed in one layer. Next are external stabilizer, external (screen) insulation, electrical (non-superconducting) screen. The cable is placed in a cryostat consisting of two corrugated pipes with vacuum thermal insulation between them and an external protective coating of cross-linked polyethylene.

High value of critical current density in superconductor allowed the placement of forward and reverse conductors in one cable, which leads to localization of magnetic field inside the section of return conductor of the cable. The absence of electromagnetic and thermal scattering fields and the use of liquid nitrogen for impregnation make such cables environmentally friendly and significantly reduce the requirements for cable routing.

Cable line is completed with the necessary fittings [10]. Current leads are used to connect superconducting cable wires to the network and for the entry/exit of liquid nitrogen into the cable. Temperature difference along the length of the current lead reaches 200 °C. The coupling is intended for joining sections of the cryostat and for connecting segments of the HTSC cable.

The general scheme of cryogenic-flowing part of the cable line is similar to that shown in Figure 1b. The cryogenic station is located on one side of the cable line. Liquid nitrogen is pumped through the cryostat with a high-temperature superconducting cable and returns through the cryostat of a smaller diameter. The total length of the loop is 5 km. Cryogenic station of a closed type is made according to a two-circuit scheme. The cooling circuit includes HTSC cable in a cryostat, circulation pump, heat exchanger and tank with supercooled nitrogen. The gas (helium) supercooling circuit consists of primary coil of heat exchanger, compressor and expander. This circuit provides lowering of temperature of nitrogen after heating it while passing the cooling circuit.

CHARACTERISTICS OF THE HIGH-TEMPERATURE SUPERCONDUCTING LINE

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

Table 1

SUPERCONDUCTING CABLE DESIGN

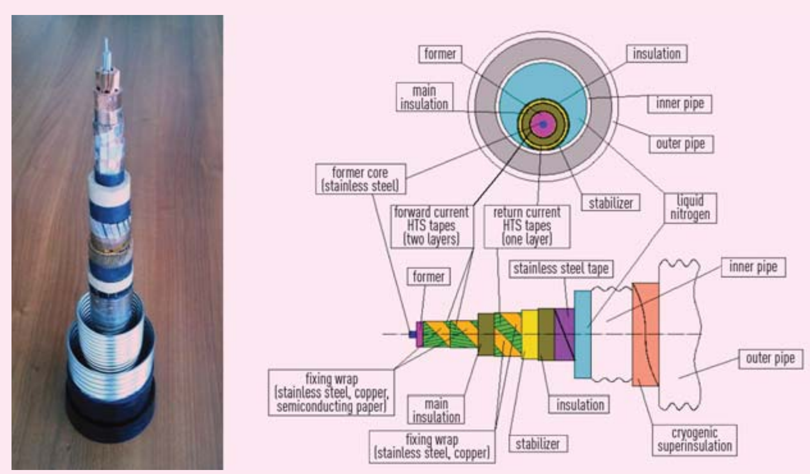

Fig. 2

GENERAL VIEW OF 860 M HIGH-VOLTAGE SUPERCONDUCTING CABLE AT THE TEST SITE

Fig. 3

CURRENT-VOLTAGE CHARACTERISTIC OF THE 860-METER LINE AND TEMPERATURE DEPENDENCE OF CRITICAL CURRENT ON TEMPERATURE FOR THE 60-METER LINE

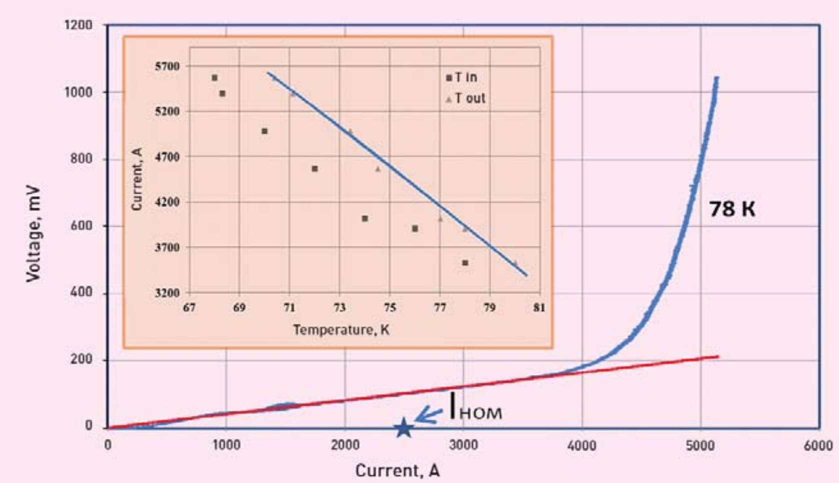

Fig. 4

RESULTS OF TESTING OF HIGH-TEMPERATURE SUPERCONDUCTOR CABLE LINES

HTSC CL and its elements were tested in accordance with the developed program. When compiling the test program, the requirements of Russian GOST for testing of similar traditional-type cables [11] and CIGRE recommendation for testing superconducting cables [12] were taken into account. Two 30-meter cable samples, two full-scale lengths (430 + 430 m), three pairs of current leads, and three couplers were tested.

Full-scale tests were carried out on two cable lengths assembled with two current leads and one coupler [13]. The total length of the line was 860 meters. Its general view is shown in Fig. 3. Current-voltage characteristic of the line and the critical current are shown in Fig. 4. The inset to the figure also shows the dependence of critical current on the temperature at inlet and outlet of the cable line.

The electrical resistance of the coupler was less than one microohm. The resistance of current inputs (including the "warm" part) was 20–21 μΩ at 80 K, which corresponds to heat generation of not more than 140 W at a nominal current. The resistance of current inputs remained stable up to a current of 5000 A. Measurements were made of critical current in temperature range 68–78 K and high-voltage tests. The critical current of two HTSC conductors was in the range of 3420 to 3550 A at 78 K. When the temperature was lowered to 68 K, the critical current increased to more than 5000 A (Fig. 4) [13]. Critical current of the cable was almost equal to the sum of critical currents of original superconducting tapes, which indicates the development of reliable design and manufacturing technology for HTSC cables.

VIEW AND LAYOUT OF 1000-METER EXPERIMENTAL CABLE LINE OF THE ISHIKARI PROJECT

Fig. 5

Hydraulic tests were carried out with a steady flow of refrigerant equal to 30 liters per minute. In this case, pressure drop along the length was 0.43 atm, which corresponds to 1.25 atm for linear approximation to a length of 2.5 km. The coefficient of hydraulic resistance was 0.0672.

All cables and fittings successfully withstood vacuum, cryogenic and electrical tests.

ISHIKARI PROJECT, JAPAN

HTSC cable was mounted in a U-shaped line (Fig. 5) with a length of 1000 meters with two couplings [14, 15]. The direct and reverse flow of liquid nitrogen is organized inside a common cryostat, as shown in Figure 6. The main goal of the project is to carry out researches and obtain basic knowledge for the development of longer lines.

The goal for design of the high-temperature superconducting line was to obtain best performance in the main parameters critical for design of long length HTSC power transmission lines. Smooth cryostats are used instead of traditional corrugated ones to reduce the hydraulic resistance of the flow channel and, therefore, to reduce the energy loss for circulation of liquid nitrogen. The greatest attention is paid to reducing the heat input into cryogenic volume.

Two cryostat designs, shown in Fig. 6, were used to study the possibility of reducing external heat input in the project. The best results were obtained at the 482-meter section of cryogenic pipe with the cable protected by a radiation shield, which are in thermal contact with the liquid nitrogen return pipe (Fig. 6a). This allowed to reduce heat input to the pipe with the cable to an extremely low value of 0.034 W/m [15]. This construction is considered as base for the next generation of HTSC lines. The structure of screen-vacuum thermal insulation has also been optimized by the criteria of cost and efficiency. To improve conditions for evacuation, external large diameter pipes were used. To prevent the occurrence of large mechanical stresses due to changes in the HTSC cable length upon cooling, a new technique has been developed for preliminary spiral laying of the cable in a cryostat pipe.

As a result, at the temperature of liquid nitrogen, the cable is straight, and at room temperature, it is arranges spirally along the walls of the pipe. In addition, to compensate for residual stresses, the terminal cryostats are mobile. All these solutions are extremely important in design of the cryogenic part of long HTSC lines.

ON THE POSSIBILITY OF CREATING LONG-LENGTH HTSC CABLE LINES

Based on results obtained by research groups in implementation

CONSTRUCTION OF TWO ISHIKARI CRYOSTATS

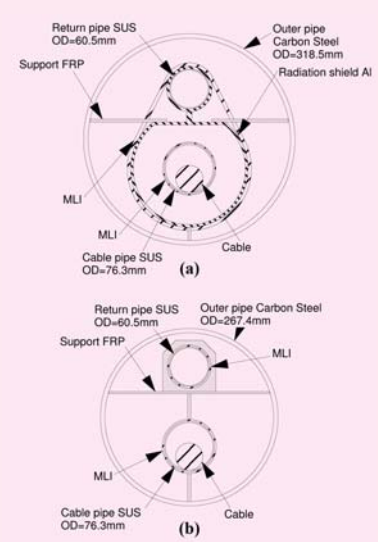

Fig. 6

TRANSMITTED POWER IN HTSC DC LINE (IN MW)

Transmission voltage, kV	Monopolar transmission		Bipolar transmission	
	One line	Two lines	One line	Two lines
50	750	1500	1500	3000
100	1500	3000	3000	6000
200	3000	6000	6000	12000

Table 2

of these two projects, we will make a preliminary assessment of the possibility of creating long HTSC cable lines. We will evaluate the following parameters:

- possible levels of transmitted power;
- amount of energy loss in the line;
- organization of a cooling system.

High-temperature superconducting cable lines are an innovative development that allows solving a significant part of the problem of energy supply to consumers

POSSIBLE LEVELS OF TRANSMITTED POWER OVER HTSC DC CABLE LINE

We estimate a possible level of transmitted power at various voltages based on achieved characteristics of superconducting materials. With design critical current density of 200 A/mm^2 [16], it is realistic to create direct current cables with a rated current of 10.0-20.0 kA. Cables with a working current of 10.0 kA have already been created [2, 17]. For the estimates given in Table 2 below, we used the rated current equal to 15.0 kA.

To increase the reliability of transmission, it is advisable to consider transmission along two parallel lines, i.e. in a two-circuit design. As it can be seen from the table, the power of the order of 6000 MW can be transferred to the network already at a voltage of 100 kV with bipolar transmission or 200 kV with monopolar transmission. In this case, only 2–4 cables are required for transmission.

LOSS OF ENERGY IN SUPERCONDUCTING LINE

The energy losses in a high-temperature DC superconducting line are composed of:

1. Converters energy loss of about 2 % of the line power.
2. Heat input through current leads (unities of kW).
3. Losses associated with heat input into cold zone through the cryostat, multiplied by the refrigeration ratio.

The first two quantities do not depend on the length. For long lines, heat inflow through the current leads can be neglected. Let's take into account the length-independent component of the energy loss equal to 2 % of transmitted power. There are no electrical losses in superconducting DC cable.

Heat transfer through the pipes of modern flexible corrugated cryostats is (1.0–1.5) W/m. The refrigeration ratio is 12–18, then the power loss per meter of line length will be 12–27 W/m. We take an average value of 20 W/m. Let's limit total loss in 3 % of transmission power. In this case the losses in superconducting line, taking into account energy consumption for cooling, should not exceed 1 %. The results of calculating maximum length of a high-temperature superconducting line, whose total losses are no more than 3 % of its nominal power, are presented in Table 3.

LENGTH OF THE HTSC DC LINE THE TOTAL ENERGY LOSS IN WHICH IS EQUAL TO 3 % OF TRANSMITTED POWER

Capacity in MW	100	300	500	1000	3000	6000
Length in km	50	150	250	500	1500	3000

Table 3

From the above table it follows that the use of high temperature DC superconducting line will significantly reduce energy losses during long distance transmission. For long lines, it is most expedient to use smooth cryostats by analogy with those developed in Ishikari project, which will lead to decrease in energy losses from external heat input and friction losses. Then total losses in the line will be less than 2 % of transmitted power.

COOLING THE LINE WITH DETERMINATION OF THE MAXIMUM DISTANCE BETWEEN THE CRYOGENIC STATIONS

When calculating cooling of the line, we proceed from the following initial data:

- Maximum temperature of superconducting cable cooled by liquid nitrogen should not exceed 78–80 K, which leads to an allowable temperature difference along the length of the order of 10 K.
- Permissible pressure drop along the length is determined by characteristics of cryostat and for flexible cryostats based on corrugated pipes is 10–15 atmospheres. For smooth pipes, the allowable pressure can reach several tens of atmospheres.
- Minimum nitrogen pressure and maximum nitrogen temperature in high-voltage application area should ensure that gas bubbles cannot form which substantially reduce the electrical strength. This corresponds to the following conditions: the pressure is not less than 1.0 atm, and the temperature is not higher than 78 K.

The first condition is a consequence of the fact that the range of existence of liquid phase of nitrogen is limited from below by freezing point and from above by boiling point,

OPERATING TEMPERATURE RANGE OF LIQUID NITROGEN DEPENDING ON THE PRESSURE (RED LINE IS BOILING POINT, BLUE LINE IS FREEZING TEMPERATURE)

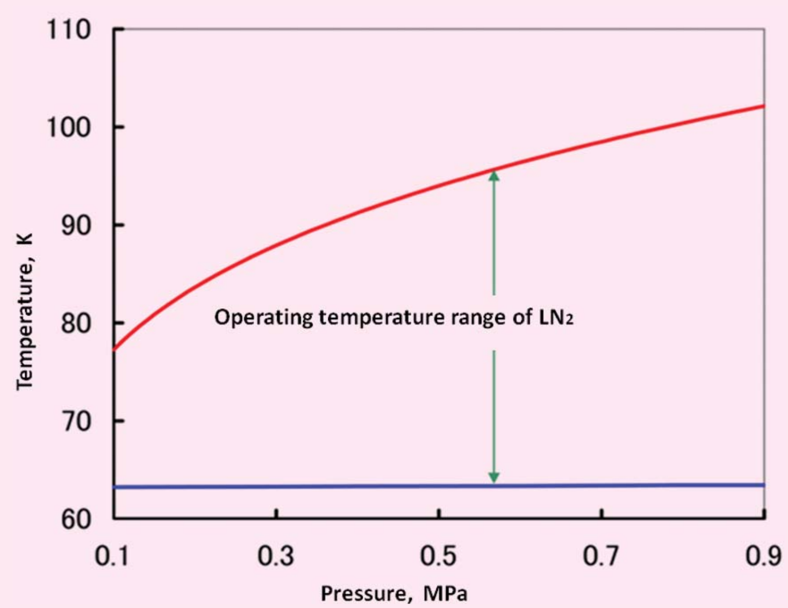

Fig. 7

and is only 77.4 K – 63.2 K = 14.2 K at 1 atm (Figure 7). Although it can be expanded by increasing the pressure in the system (making, for example, 20.6 K at 2 atm.), but the lower temperature limit (freezing point) remains practically unchanged.

Consequently, expansion of the range leads to an increase in temperature at the exit from the cryostat and, therefore, to a decrease of superconducting material critical current.

In order to ensure the predetermined temperature drop ΔT along the length of cable line, it is necessary to pump a certain amount of coolant to remove the heat supplied to the cryostat [18]. If the concentrated thermal load at the line ends is neglected, the mass flow of liquid nitrogen necessary to remove incoming heat and heat generated by friction will be determined as

$$\dot{m} = \frac{L(q + q_f)}{C_p \Delta T} \qquad (2)$$

where: $\dot{m}$ is consumption of liquid nitrogen, kg/s; L is length of the cryostat, m; q is specific heat load through thermal insulation, W/m; q_f is specific heat release from friction, W/m; C_p is specific heat of liquid nitrogen, J/kg·K.

Mass flow is related to the flow rate by expression

$$\dot{m} = \rho v A \qquad (3)$$

where ρ is density of liquid nitrogen, kg/m^3; v is flow velocity, m/s; A is cross-sectional area of the channel, m^2.

Typical values of external heat input for modern corrugated cryostats are 1.0 to 1.5 W/m. Using the foregoing relationships, we estimate the heat and mass transfer characteristics for HTSC cable with external diameter of 39–40 mm placed in cryostats with internal diameter of 60, 66, and 84 mm. The results of calculations are summarized in Table 4. From Table 4 it follows that pressure drop can be easily regulated by increasing the diameter of the cryostat. However, as the diameter of the cryostat increases, external heat input into the cold zone increases.

Another way to reduce the pressure drop (not less than 2 times) is the use of smooth tubes with bellows interconnections as the inner tube of a cryostat, as shown in Fig. 6.

The main limiting factor for increasing the distance between cooling stations is the temperature drop along the length of the cable. However, as it can be seen from Table 4, for a cryostat with internal diameter of 84 mm this distance may be 10 km. Unfortunately, the flow rate cannot be increased indefinitely, since at high flow rates, in accordance with formula 2, additional heat generation occurs due to dissipation of energy as a result of friction of the coolant in the cooling channel and the pressure drop along the length increases dramatically.

The main way to reduce the temperature drop is to reduce heat input to the cold zone. This can be done both by improving thermal insulation of a cryostat and by lowering temperature difference between the outer and inner shells of the channel in which HTSC cable is located.

A radiation shield can be a promising solution. This design was worked out in Ishikari. Cryostat has a relatively large diameter, and a pipe with cable and a return pipe are placed into it. The cryostat circuit shown in Figure 6a allows to significantly reduce the heat input to the cable channel by placing the screen cooled by reverse flow of liquid nitrogen between the outer shell of the cryostat and the cable pipe. The results of measuring heat inflows [14,15] allow us to estimate the length of the cable line at which the temperature difference along the length does not exceed a given value. Table 5 presents the results of the estimated calculation for the cryostat with Ishikari-2 radiation screen.

As it follows from the comparison of Tables 4 and 5, with an increase in length of the cable line to 10 km or more, it is necessary to use rigid cryostats with a smooth tube. The distance between cryogenic stations can reach 10 km for lines based on flexible cryostats, and when switching to smooth pipes, the distance between cooling stations can be increased to 30–80 km.

Long lines can be created by replicating pumping areas, as shown in Fig. 1c.

Of course, the calculations presented above are of an evaluation nature and require experimental confirmation. However, the results obtained during the implementation of the two above-mentioned projects inspire confidence in possibility of implementing a line with length of about 10 km as the next stage in development of high-temperature superconducting technologies for transmission of energy over long distances.

CONCLUSION

With the current level of development of superconducting and cryogenic technology, it is possible to create long superconducting cable lines for transmission of energy over distances of tens of kilometers. Then, the power of a single line can reach several gigawatts, and the energy losses in it will be significantly lower than in traditional lines. The electrical voltage on the line and the converter station can be reduced to 200 kV or less. Cryogenic stations for line cooling can be located at its ends with a line length up to 20 to 40 km (in perspective up to 80 km). When creating longer lines, cryogenic stations should be located along the route in distances of 20–60 km. The maximum length of a line with this approach has no technical limitations.

With design critical current density of 200 A/mm^2, it is realistic to create direct current cables with a rated current of 10.0-20.0 kA

There is every reason to hope that in foreseeable future, powerful DC superconducting cable lines will allow to optimize electric networks of megacities and form a global energy network with transfer of electric power to long distances, to make interconnecting links, to connect unsynchronized power systems, to build long underwater lines, etc. All this will significantly increase efficiency and reliability of electrical networks.

TEMPERATURE AND PRESSURE DROP ALONG THE LENGTH OF HIGH-TEMPERATURE SUPERCONDUCTING LINE

Internal diameter of the cryostat, mm	Cable length, km	Flow rate of l. nitrogen, l / min.	Temperature difference, K.	Difference of pressure, atm
60	2.5	40	4.0	4.8
	5.0	40	7.5	14.0
66	2.5	40	4.0	3.0
84	2.5	40	4.0	0.4
	5.0	40	8.0	1.1
	10.0	60	11.0	4.5
		80	8.4	8.0

Table 4

ESTIMATED LENGTH OF THE HIGH-TEMPERATURE SUPERCONDUCTING LINE

Temperature difference, K	Consumption of liquid nitrogen, l / min	Temperature difference of 1 km, K	Length of the line, km
8	10	0.122	66
	5	0.244	33
10	10	0.122	82
	5	0.244	41

Table 5

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