Prospects of long-distance HTS DC power transmission systems

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Abstract. Continual improvement of technologies for the safe use of power resources is a key to sustainable development of a human society. In particular, high-temperature superconductivity (HTS) should be used to meet the growing needs of the electric-power industry. It is known that HTS power cables allow us to increase the level of transmitted energy to several GW at voltage of 66-110 kV. HTS power cables of a coaxial design are almost ideal non-polluting system shielding electromagnetic field. In the present work we have tried to analyze various configurations of HTS power transmission systems, estimate the cable transmission capacitance depending on distance, and characterize reliability and efficiency of the systems.

1. Introduction

Efficiency of power production, transmission, and distribution, improvement of energy quality become priorities in the field of electric power industry in the 21st century. Requirements to ecological and resource saving aspects at all phases of power production and distribution are simultaneously raise. Advanced technologies including superconducting one should be used to satisfy the growing needs of the people. Intensive research and development programs are supported to create different kinds of HTS electrical devices such as transformers, current limiters, engines and generators, and power cables. In fact, HTS power cables now are the most developed application of superconductivity in electric power industry. Using power cables made of the traditional materials (copper, aluminium), high voltage has to be applied in order to increase the transmitted power and reduce power dissipation. The maximum achieved voltage is at the level of 500 kV and does not exceed level of 1150 kV for systems under development. Therefore, transmitted power is limited at the level of 0.5-1.5 GW. A number of environmental problems such as ground currents, ground heating up, electromagnetic pollution, dielectric oil pollution, etc. raise, even if special conditions to be observed during cable installation. In this context, HTS power cables allow increasing the level of transmitted energy to several GW at voltage of 66-110 kV. The power transfer efficiency of the cable can be increased to 95-98%.

In the world, there are a large number of experimental cable facilities constructed to explore the efficiency of HTS electric power transmission [1]. Two DC HTS cable lines being under construction in Russia [2] and Japan [3] have record length of 2.5 km. The construction will be completed in the next 2-3 years. Therefore, the problems of short-distance superconducting power transmission are close to be solved. However, estimates show that the benefits of HTS power cables will fully manifest

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in long-distance transmission lines. The development of intermediate-distance (10 km class) and long-distance (100-1000 km class) power transmission technologies demand high investments and intensive researches in order to solve technological problems, generally related to HTS cable cooling system. Long-distance power transmission is especially important owing to non-uniformity of distribution of power resources on a planet. Megacities accumulate powerful energy consumers, but territory where electric power stations can be built are usually at considerable distances from consumers. It is possible to remember as an illustrative example the project of construction of solar batteries in the Sahara Desert and transmission of energy to Europe. The embodiment of the above project entirely depends on feasibility of long-distance HTS power transmission lines. Furthermore, DC HTS lines are well suited for collection of large amounts of electricity from renewable sources of different types, such as solar, wind and geothermal power plants, and so on [4].

2. DC HTS cable line length limitations

Let us estimate the possible level of transmitted power at different voltages, based on the achieved performance of superconducting materials. When the value of the working critical current density is 200 A/mm², the creation of DC cables with a rated current of 10-20 kA is real. Experimental cables with the operating current of 10 kA are already constructed. We assume working current of 15 kA to achieve 6 GW transmitting capacitance of two DC HTS cables at 100 kV bipolar voltage.

Let us determine the maximum theoretical length of the DC HTS line in terms of power losses. We can assume for estimations that the energy loss in the line depends on the following factors:

- Energy losses in the converters;
- Heat leakage through the current leads;
- Heat leakage through the cryostat;
- Heating due to hydraulic friction in the cryostat.

The first two quantities are independent of the cable length. The heat leakage through the optimized current leads in the case of long line will be comparatively small, which makes it possible to ignore this value. Losses of energy in the converting equipment may be assumed to be 2 % of the transmitting power. Heat leakage through the thermal insulation of the modern cryostats is at the level of 1.0-1.5 W/m (if the inner diameter is 50-75 mm), and the frictional heating is estimated to be 0.1 W/m. The sum of the last two values should be multiplied by the refrigerating factor, which is equal to 12-18 at the given temperature range. Therefore, the power loss in the range of 13-29 W per one meter should be considered. We assume an average value of 20 W/m. For a more efficient energy transfer let us limit the total loss at the level of 3 %. In this situation the loss in the cable line should not exceed 1 %, and then the total amount of specific losses is about 30 W/m. This value is comparable to the average annual loss due to corona discharge at 750 kV [5]. Results of calculations are summarized in the table 1.

| Transmitting capacitance, MW | 100 | 300 | 500 | 1000 | 3000 | 6000 |
|-----------------------------|-----|-----|-----|------|------|------|
| Length, km                  | 50  | 150 | 250 | 500  | 1500 | 3000 |

Let us now consider the limitation on the length of the line originates from the cooling system. Typically, liquid nitrogen (LN₂) pumping in the space between the cable jacket and the inner surface of the cryostat is used to cool HTS cable. It should make maximum use of the working temperature range of LN₂. Because temperature range is limited from below by the freezing point and from above by the boiling temperature and the critical temperature of HTS used, the temperature difference between the inlet and the outlet, ΔT, in practice will be equal to approximately 10-15 K. In this case it is easy to show [6] that under the condition of ΔT = const the dependence of the pressure drop Δp on the length L is close to a cubic, and on the specific heat load q is close to a quadratic:
where

\[ n = 1.75 - 2 \]  \hspace{1cm} (1)

or, more conveniently,

\[ \frac{\Delta p}{L^{n+1}q^n} = \text{const} \]  \hspace{1cm} (2)

The same relationship holds also for corrugated cryostats. In principle, there is no limitation on the transmission range originated from the cryogenic system, but long line will have to include a large number of intermediate pumping/cooling stations. This can raise the cost to an unacceptable level. Therefore, it is basically need to achieve greater length of each segment of the line, not only in terms of the economy, but also for the laying out in inaccessible locations, such as the sea bed. The pressure drop of the cryogen is the limiting factor if the thermal insulation quality is unchanged. On the one hand, the flow area should be increased in order to facilitate circulation. On the other hand, the diameter of the cryostat must be as small as possible to minimize the heat leakage. Increasing the diameter will also result the loss of benefits of the flexible cryostat because of it can not be wound on a reel and delivered to the construction site. These considerations lead to the conclusion of the need to carefully examine the possibility of using cryostat composed of straight pipes for the construction of HTS transmission lines.

To define the maximum length that can be achieved between two intermediate pumping/cooling stations using both flexible cryostat and straight cryopipes of the same diameter we can take as a basis the geometry of the real project to be embodied in Russia [2]. Namely, the diameter of the corrugated cryostat is 60/66 mm, and the diameter of the HTS cable is 40 mm. The method of calculating the pressure drop in the straight pipe with the cable placed inside is described in [7], and in the corrugated pipe with cable inside – in [8]. The cryogen flow rate increases with the cable length under the fixed temperature difference. It will cause additional frictional heating, which should be compensated by additional amount of the circulating cryogen. A kind of positive feedback forms and at certain length the abrupt unlimited growth of \( \Delta p \) will be observed. The calculated dependences are given in figure 1.

To determine the maximum possible length of the segment it is necessary to define the maximum allowable pressure drop, which to a large extent be determined by the mechanical performance of the cryostat. Table 2 lists the maximum length of the corrugated and straight cryostats at \( \Delta p = 1.5 \) MPa.

| Temperature difference, K | 4   | 6   | 8   | 10  | 12  | 15  |
|---------------------------|-----|-----|-----|-----|-----|-----|
| Length, km (straight)     | 5.59| 7.67| 9.47| 11.1| 12.6| 14.7|
| Length, km (corrugated)   | 3.46| 4.83| 6.03| 7.12| 8.13| 9.54|
| Frictional heating, W/m   | 0.35| 0.21| 0.15| 0.12| 0.10| 0.08|

The data show that the conventional corrugated cryostat is more convenient in the case of several kilometers line, since the cryogenic system can eliminate the intermediate pumping/cooling stations. However, if the length of the line will be a few tens of kilometers, it is preferable to use straight cryostat in order to significantly reduce the number of expansive intermediate pumping/cooling stations.

As may be seen from table 2, various practical problems of the energy transfer can be solved using two or three intermediate stations. These problems include the transfer of electricity from the nuclear power plants located at large distances from cities and consumers, resulting in the need for high voltage converters leading to the energy losses of 6-8 %.
power plant can be transferred to the customers at the voltage of 50-100 kV using DC HTS power cable, and from one nuclear unit at generator voltage without step-up substations.

![Graph showing pressure drop and frictional heating as functions of cryostat length](image)

**Figure 1.** Behavior of pressure drop (left) and frictional heating (right) as a function of cryostat length in case of $\Delta T = \text{const}$, namely 1, 2, and 3 K. Straight cryostat I.D. is 60 mm, corrugated one is 60/66 mm. Cable O.D. is 40 mm in both cases. Heat leakage through thermal insulation is 1.2 W/m.

One more of the advantages of the DC HTS power cables is the possibility of doubling the existing lines capacitance without making capital expenditures in transmission infrastructure. This is due to the fact that the cooling system requires a closed loop of cryogen circulation consisting of two cryostats for forward and return flows. Since DC HTS cable does not practically produce heat, the additional cable can be laid in return cryostat as may be necessary without significant impact on the system. It is only required to foresee this possibility and choose the appropriate flow area of the cryostat.

3. **Conclusion**

   It was shown that several kilometers' distance DC HTS power transfer can be embodied using conventional corrugated cryostat. However, it is necessary to apply straight cryostat in order to achieve best hydraulics of the long transmission system. Increasing diameter of the cryostat bring to nothing all advantages basically because of problems with transportation. Losses in HTS lines, in general, do not depend on the length and the transmitted power. The main limiting factor that requires attention in the construction of HTS lines is the design of cryosystem. The use of corrugated cryostat requires 50% more intermediate stations, which significantly raise the price of the system.

4. **References**

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