Low voltage and large current DC superconducting power cable designs for 10 km to 100 km transmission line using experimental data of Ishikari project

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Abstract. Main merit of the DC superconducting power transmission line is low loss even in low voltage power transmission. It should be realized when the transmission length is long. Therefore, we discuss and analyse an aspect of thermo-hydrodynamic performance of Ishikari project, and show one design of 100 km transmission line. At the same time, we also discuss the cable design and the rated voltage of the cable is lower than 50 kV for 500MW transmission. This is one of the most important advantages to make the DC power grid because we can omit an ultra-high voltage substation, the primary and the secondary substations and we can connect the power stations to the distribution stations directly. Finally, we may be able to reduce the construction and operation costs of the power grid.

1. Introduction

Main merit of the DC superconducting power transmission line is low loss even in low voltage power transmission. It should be realized when the transmission length is long. Therefore, the engineering objective is how to design, construct and operate a long transmission line. It is related with the performance of thermo-hydrodynamic parameters, such as the heat leak of the cryogenic pipe, the flow rate of the liquid nitrogen (LN2), the flow resistance of the pipe, the LN2 temperature from the refrigerator, the LN2 pressure of the cryogenic pipe, the LN2 temperature profile along the transmission line, the pressure-drop of the cryogenic pipe for the circulation of the cryogen and the output pressure of the circulation pump and so on. These parameters are related with each other, and we should keep the temperature of the high temperature superconducting (HTS) cable below the design value, such as 77K. Finally, the distance between the refrigerators along the transmission line is the key to realize an actual transmission because if the refrigerator should be installed for a short distance along the transmission line, we cannot construct a long transmission line. The similar system is the natural gas pipeline, and the pump-station is installed along the pipeline. The average distance between the gas-pump stations is 5 km to 20 km inside Japan, and 100 km for the intercontinental pipeline. Therefore, we can adopt these values for the superconducting power transmission line, and this is a goal of the design and performance of the superconducting power transmission line. In order to keep the economy of the superconducting
power transmission line, lower electric power loss should be realized from the lower heat leak of the cryogenic pipe and the higher COP of refrigerator system.

In order to solve the problem, we developed the radiation shield structure [1] in Ishikari project. The cross-sectional view is shown in Figure 1. There are two internal pipes. One is called as the cable pipe that the superconducting cable is set inside, and the other is called the return pipe for the circulation of the liquid nitrogen (LN2). They are made of the stainless-steel. The radiation shield is covered and connected to the return pipe thermally, and surrounded the cable pipe. Therefore, the heat flux from the outer pipe comes into the return pipe mainly, and the heat leak of the cable pipe is very small. The LN2 from the refrigerator flows into the cable pipe, then LN2 goes out from the cable pipe to the return pipe and finally goes back to the refrigerator. The cable pipe is supported by the FRP (fiber-reinforced plastic) legs from the radiation shield. Therefore, we should consider the thermal conduction of the support legs. However, the thermal conduction is very low in our design, and thus the temperature rise of the cable pipe is very low. This structure is important to make a long transmission line. If the temperature rise of the cable is high, the critical current of the HTS cable is lower along the temperature rise, and therefore we set the rated current of the HTS cable should be lower. Finally, we need many cooling stations along the cable if we keep the rated current high.

The other aspect of the Ishikari project is to use the straight pipes in order to reduce the pressure drop of the cryogen circulations. Usually the corrugated pipe [2] is used in many superconducting cables, but we think its pressure drop is too high to construct a longer cable. This is discussed in the next section. We discuss and analyze the experimental data of Ishikari project, and we describe the thermos-hydrodynamic designs of 50 km to 100 km transmission line under the reasonable assumptions. The present power grid uses high voltage transmission lines in order to reduce the loss of electricity, and we need many substations in the grid. However, if we can use the HTS cable, the resistance of the cable is zero basically, and therefore we do not need to use high voltage grid. The voltage of the generator is ~ 20kV, and if we can connect the DC HTS cable directly after rectification, we can save the substations of the grid. Finally, we discuss the grid system using low voltage cable in the paper.

2. Experimental data from Ishikari Project and scale law for the circulation
Thermo-hydrodynamic experimental data [3] in Ishikari project are shown in the first column of the Table 1. Its length is 474 meters, and the flow rate is 30 litter/min. We can estimate the thermo-hydrodynamic data for 5 km and 10 km cables from the experimental data, such as pressure drops, the temperature
rises, and the output temperature of the system, where the inlet temperature is set to be 70K. The design of the cryogenic pipe is completely the same. They are shown in the second and third columns [4].

The estimation results show that we can construct 5 km to 10km transmission line to use almost the same parts of present cryogenic system, such as the pipe, the circulation pump, but we need high refrigeration power for long transmission line. It is important that the flow rate is only 25 litter/min for the 10 km transmission line, and therefore the pressure drops of the cable and return pipes are lower than the maximum output pressure of the present circulation pump, which is 1MPa. In addition, the liquid power, that is the product of the circulation pressure and flow rate, is one of the heat-loads to the low temperature system. In case of the 10 km transmission line, the liquid power is calculated as 8.33mW/m which is much smaller than the heat leak of the cryogenic pipe. It means that we can neglect the liquid power because the total heat leak of the cryogenic pipe is ~ 1.0 W/m. Usually when the transmission line is longer, the flow rate should be high in order to keep the temperature rise of the superconducting cable. However, if the flow rate is high, the output pressure of the circulation pump is high. Therefore, we should consider the liquid power because it is one of the heat-loads for the cryogenic pipe, and if it is high, the economical efficiency of the superconducting cable would be worse because of high electric power consumption of refrigerator.

Table 1. The original data from Ishikari project, and the extended data for 5 km and 10 km transmission line.

| Radiation Shield | Original data |
|------------------|--------------|
| Length [m]       | 474          |
|                  | 5,000        |
|                  | 10,000       |
| Flow Rate [L/min]| 30           |
|                  | 20           |
|                  | 25           |
| ΔP [kPa]_cable [K]| 5.20         |
|                  | 24.4         |
|                  | 76.2         |
| ΔP [kPa]_return [K]| 8.50        |
|                  | 39.8         |
|                  | 124.5        |
| Cable ΔT [K]     | 0.019        |
|                  | 0.30         |
|                  | 0.48         |
| Return ΔT [K]    | 0.46         |
|                  | 7.2          |
|                  | 11.5         |
| Outlet temp [K]  | 70.5         |
|                  | 77.5         |
|                  | 82.0         |
| Total Pressure [kPa]| 13.7       |
|                  | 64.2         |
|                  | 201          |
| Heat Leak [W/m]_cable | 0.034   |
|                  | 0.034        |
|                  | 0.034        |
| Heat Leak [W/m]_return | 0.85   |
|                  | 0.85         |
|                  | 0.85         |
| Total Heat Leak [kW]| 0.42       |
|                  | 4.4          |
|                  | 8.9          |

This engineering aspect is sometimes serious, and therefore we should discuss the scale law of the thermo-hydrodynamics of the cryogenic pipe. One example of the scale law for the length of cryogenic pipe is shown in Table 2.

Table 2. Thermo-hydrodynamic parameters to keep the temperature rise of the cryogenic pipe for 1 km and 10 km cables.

| Distance [km] | 1.0 | 10.0 |
|--------------|-----|------|
| Temperature rise [K] | 3.0 | 3.0 |
| Flow rate [L/min] | 30  | 300 |
| Output pressure [MPa] | 0.1 | 100 |
| Liquid power [kW] | 0.05 | 500 |

We assume the parameters for 1 km transmission line in the left-hand side column of Table 2. Then, in order to keep the temperature rise of the cryogenic (cable) pipe, the flow rate, the pressure and the liquid power are estimated for the 10 km transmission line as shown in the right-hand side of Table 2. The flow rate is proportional to the length, and therefore it is 10 times higher than the value of the 1 km system because the heat leak is constant for length. Since the pressure is proportional to the square of
the flow rate, it is 100 times higher for the same length, but its length is 10 times longer, therefore it is 1000 times higher for the same design of the cryogenic pipe. Since the liquid power is the product of the pressure and flow rate, the total heat load for the 1 km transmission line is 50W, and it corresponds to 50mW/m. This value is lower than usual experimental heat leaks for unit length. Therefore, it is acceptable. However, when the length is 10 km, the liquid power is 500kW, and its heat leak per length is 50W/m. We cannot accept this level of the heat load and it is higher than the heat leak of the cryogenic pipe. This kind of the analysis had been discussed in Ref. [5]. In this meaning, if we get the experimental data for 1 km transmission line shown in Table 2, we cannot extend the cable length up to 10 km.

3. Thermo-Hydrodynamic Analysis for 100km cable
It is necessary to extend the cable length longer than 10 km when we consider the present electric power grid. Therefore, after we estimated the thermo-hydrodynamic parameters for 10 km transmission, we try to extend the cable length longer using the experimental data from Ishikari project. Figure 2 shows the 50 km superconducting transmission line under the several reasonable engineering assumptions. The inlet temperature of LN2 is 70 K and the temperature rise of the cable pipe is 1 K for 50km, where the flow rate is 60 litter/min using the same heat leak for the cable pipe in Ishikari experimental data. But since the heat leak for the return pipe is high, the temperature rise is 2.5 K for 50km and the same flow rate.

Figure 2. A design of 50 km superconducting transmission line using the experimental data from Ishikari project.

In order to reduce the pressure drops of the cable and return pipes, we will use large pipes. The size of the new large cable pipe is designed to be smaller than the radiation shield’s, we can put into the cable pipe inside the radiation shield. The size of the new return pipe is also larger than the size of the pipe in Figure 1, but because it is covered by the radiation shield, the area of the radiation shield is the same area of the Ishikari design of Figure 1. Therefore, we assume that the heat leaks of the cable and return pipes are the same as the Ishikari experimental data. The new inner diameters of the cable and return pipes are 84.9 mm and 97.4 mm, individually, and we can estimate the pressure drop of the pipes, which is proportional to the fifth power of the pipe diameter using the experimental data of Table 1 and Figure 1. Finally, the pressure drops of the cable and the return pipes are 0.486 MPa and 0.495 MPa for 50 km, individually. Therefore, the liquid powers of the cable and the return pipe are 8mW/m, and lower than the heat leak, and they can be negligible like the present experimental data. The outlet temperature of the LN2 from the return pipe is 96 K. The saturation pressure at that temperature is lower than 0.5 MPa. The design basis for the 50 km transmission line is almost the same as the design basis of the Ishikari project, and therefore we can use many same cryogenic parts, such as the pipe, bellows, pump and so on. This is an important to estimate the construction cost of the 50 km transmission line. Furthermore, we can use a turbo-Brayton refrigerator of 50kW at 70K in Figure 3, the COP of the refrigerator is ~ 0.12 including the water chiller and the control system of the refrigerator. It is almost 1.5 times improvement compared with the COP of the small present refrigerators.
T. Yamada et al presented the design of 100 km transmission line [6] in the annual domestic conference of Japan, 2018. They used the flush refrigerators for the return pipe in order to keep the internal pressure of the return pipe. However, if we use the flush refrigerators, the energy loss of the flushed nitrogen gas to the air is high because the temperature of the nitrogen gas is still low, and we lose a fundamental merit of the HTS cable. Figure 3 shows the different design of the 100 km transmission line without the flush refrigerators. This design does not lose the energy loss come from the liquid nitrogen loss from the flush refrigerators.

Figure 3. A design of 100 km superconducting transmission line using the experimental data from Ishikari project.

This system is combined with two 50 km systems in Figure 2. But the cable is laid through 100 km. Each return pipe is connected to the cable pipe at 50 km from each terminal cryostat. The LN2 flow is the counter flow in the cable pipe from each terminal cryostat. Two return pipes are not connected each other, but connected with the cable pipe. LN2 flows back to each terminal cryostat, and the length of the return pipe is 50 km. Therefore, we do not need to use the flush refrigerators. In order to control the flow rate of each return pipe, the valve and the circulation pump are used for each side as shown in Figure 3. Finally, the thermo-hydrodynamic parameters of the 100 km transmission line are the same as the parameters of the 50 km transmission line shown in Figure 3.

4. Electrical design of Superconducting cable

The voltage from the power station (generator) is AC 22kV, and the transformer is used to step up the voltage to AC 500kV in the ultra-voltage substation, and its high power is transmitted for a long distance in Japan. The voltage is step down from 500kV, 275kV to 66kV, 22kV in the primary and the secondary substations, finally the electric power is sent to the distribution substations, and its voltage is step down from 22kV and/or 66kV to 6.6 kV, and its power is distributed to many customers in Japan. The voltage is different from the foreign countries slightly, but the grid system is similar all over the world now.

The second merit of the superconducting power transmission line is to be able to use the low voltage system even for high electric power transmission line. The present AC power grid needs to use many step-up and step-down transformers to minimize the losses. Figure 4 shows the cross-sectional structures of the superconducting power cables, and their voltage, current and diameters.

We designed several cables to find the optimum design of the DC superconducting power transmission, and we choose that their voltages are from ±25kV to ±50kV for 500MW power transmission. The reason to choose these voltages is to pass through the ultra-high voltage substation, the primary and secondary substations of the power grid mainly. It may be effective to reduce the total cost of the grid, and we can install the HTS cables into the grid even if the cost of the HTS cable system is expensive. One is the single core cable shown in right-hand side of Figure 4, and the other two are co-axial cable structures, with (center) and without (left) the earth-ground layer. The voltage of the 500
MW transmission line is 500kV in Japan, and 400kV in EU for usual AC transmission line now, and the voltage of 50kV to 25kV is not used for large electric power. But if we can use this level of the voltage, we may be able to omit an ultra-high voltage substation, the primary substation and the secondary substation from the present grid, and we can connect to the power station to the distribution substation directly. The co-axial structure is not good for an AC cable because the cable capacitance is high, and the reactive power will increase even if for a short distance, but the reactive power is almost zero because of the DC transmission. Therefore, we can use the co-axial cable for a long distance, and it should be installed underground for safety reasons mainly.

![Figure 4](image.png)

**Figure 4.** A design of 100 km superconducting transmission line using the experimental data from Ishikari project.

If we can omit the high voltage substations from the present grid, we may have merit to reduce the operation and the construction costs of the grid even if we should use the power converters. This cost reduction is not small. Moreover, if the voltage is ±25kV, we can avoid the corona (= electric breakdown of air at 1 atm), and the substation will be smaller. These are the second merits.

5. **Summary and future plan**

Before we will construct a 100 km superconducting power transmission line, we should consider to construct a 10 km-class transmission line and it should be used as the commercial system. We will be able to test and check the parameters of the superconducting power transmission system, and the technology will be completed by the construction and operations of the 10 km transmission line through these tests. All kinds of the technologies, such as the low heat leak of the cryogenic pipe, will be improved by the construction and the operation of the 10 km transmission line. The experience of the 10 km transmission line will be useful to construct the 100 km transmission line as a commercial transmission line.

On the other hand, the authors and colleagues believe that it is important to realize the 100 km transmission line significantly. Because natural-gas pipeline is one of the major energy transmission lines in the world now and its length is extended to 1000 km to connect the different countries. Many pump-stations are used to transfer the natural gas (NG) for each 100km usually. The pump stations consume an electric power to compress and transfer the NG because of its viscosity. This structure is
similar to the superconducting power transmission line. When we operate the long power transmission line, the security is important and therefore the underground cable will be chosen. Low DC voltage system is also important for long operation time. After we will construct and operate the 100 km transmission line, we will be able to apply the HTS cable system to the international power grid, and connect all countries by the HTS power grid.

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6. References
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