A Proposal for DC Superconducting Power Transmission Line

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***Abstract*—DC Superconducting Power Transmission Line (DCSC-PT) is proposed for the next generation power transmission system. Because the resistance is almost zero for DC system completely, DCSC-PT will be able to use a low voltage system in order to reduce the cost of the inverter, and it will be planed from 10 to 30 kV. Instead of the low voltage, the magnitude of the current is high as 10 kA to 30kA. High current system can store high magnetic energy in the transmission line like the superconducting magnetic energy storage system (SMES). We will use the Peltier Current Lead (PCL) at the both of the ends in order to reduce the heat leakage to the cryogenic system. We also focus to develop a low pressure-drop system for cryogenic coolant circulation system, and the structure of the cryogenic pipe and the superconducting cable is simple as compared with the ac cable system. Therefore, it will be useful for long and short distance transmission line.**

***Index Terms*—DC power transmission, low voltage inverter, HTS power cable, Peltier current lead.**

I. Introduction

THE many applications of the high temperature superconductor (HTS) had been developed for various fields, and one of the major fields is the power transmission line. Several projects were focused to develop the AC power cable [1]-[3] for past 10 years. One of the key issues of the ac applications is to reduce the AC losses of the HTS tape conductor [4]-[8], and if the AC losses will be reduced enough to the practical level, the ac application will have large markets. However, the DC superconducting system has lots of benefits for power applications. Because of many efforts to develop the superconducting technology in the past 20 years, the engineering problems of the power cable are understood clearly, and the HTS tape conductors can be practical for the DC applications in the present technology. And we are free from the many engineering problems originated from the AC losses. But if we are going to develop the DC power transmission line, we must consider the cost of the inverter because the cost of inverter is the major part of the DC power transmission line [9], and this is a real reason why the R&D of the power cable was started for the AC applications at first 15 years ago. However, the DC power transmission line has been used even for the copper cable system from the last 50 years in all over the world [10]-[12]. Actually the efficiency of the DC transmission line is higher for a case of the long distance than that of the AC power transmission line, and effective even for short distance of 50 km if the cable is installed into the water. Moreover, the DC system is lower investment cost and easy asynchronous interconnections, has a high controllability, limits the short circuit current, and is good for environment for the ultra-high voltage (UHV, 250kV to 800kV) copper-cable system [10]-[12] in the present time. These merits will be enhanced by the superconducting system. Even for the short-distance, relative low voltage (2 kV to 4 kV) for the copper cable system, the DC power transmission line is thought to be effective by the recent development of the inverter [13]. Therefore, we propose to develop the DC power transmission line by using HTS power cable. We discuss both the engineering and cost aspects of the DC power transmission line in this paper, and describe the present design of the DC power cable system that is under the construction in Chubu University, Japan.

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II. Principle of the DC Superconducting Power Transmission Line

In order to realize and enhance the full merits of the DC superconducting power transmission line (DCSC-PT), we discuss and consider almost all engineering aspects of the DCSC-PT, and the principle of the system for each part individually as below.

A. Inverter

As we wrote in the previous section, the cost of the inverter is expensive for the DC power transmission line of the copper cable system in the present time [9], [10]. The estimated cost of the inverter system was 430 US$/kW in Japan. This cost is almost the same as the instrumental cost of the power station if the Back-to-Back inverter system is applied. The reason of the high cost depends on its engineering specifications and the market size. Since the voltage of the DC power transmission line is 250 kV to 800 kV because of the copper, there is almost no market without the power transmission line. In the Other hand, an actual cost of the inverter is about 180 US$/kW for the factory use in Japan, and the rated voltage of the inverter is around 400 V to 1.8 kV, this kind of inverter has wider market. The hybrid vehicle (HV) was developed by TOYOTA [14]-[16], and recently HV is familiar all over the world. The HV uses the inverter to drive the motor and regenerate the braking system. The cost of the HV's inverter is estimated to be 30 US$/kW, and the working voltage is 600 V and its power range is 50 kW to 120 kW/unit in the present time. Variable Voltage and Variable Frequency (VVVF) control is applied for the HV's inverter in contrast with the frequency control only for the inverter of the power transmission line. The switching frequency of the HV's inverter is almost ten times higher than that of the DC power transmission line. Higher switching frequency can reduce the interference of the higher harmonics in the power grid. Moreover, the transmission efficiency of the HV's inverter is higher than that of the power transmission line's. Technological specifications of the inverters are summarized in Table 1. These progress of the inverter technology is realized by the progress of the electric power device and the assemble technology. Therefore, it is natural to apply the HV's inverter technology to the DCSC-PT. Of course, the low voltage inverter can be applied only for DCSC-PT, and not to apply the copper cable system because of the resistance. Therefore, we will use the relatively low voltage (several kilovolt to 30 kV) inverter for the DCSC-PT to reduce the cost of the inverter. This is the fundamental reason to start the project of the DCSC-PT.

TABLE I
COMPARISON PF THE INTVERTERS OF HYBRID VEHICLE AND POWER TRANSMISSION LINE

	Hybrid Vehicle	Honshu-Hokkaido (Japan)	Honshu-Shikoku (Japan)
device	IGBT	SCR	SCR
Switching Freq.	> 10kHz	< 1 kHz	< 1 kHz
Device Voltage	~ 1 kV	4 kV	8 kV
Device Current	~ 200A	1.5 kA	3.5 kA
Circuit Voltage	500 – 650 V	±250 KV	±500 KV
Circuit Current	~ 200A	1.2KA	2.8 kA
Power/unit	50 – 120 kW	0.6 GW	2.8 GW

The connection of the HV inverter is 1S1P for switching unit, but it is many series and one parallel connection in the connection of the power transmission line.

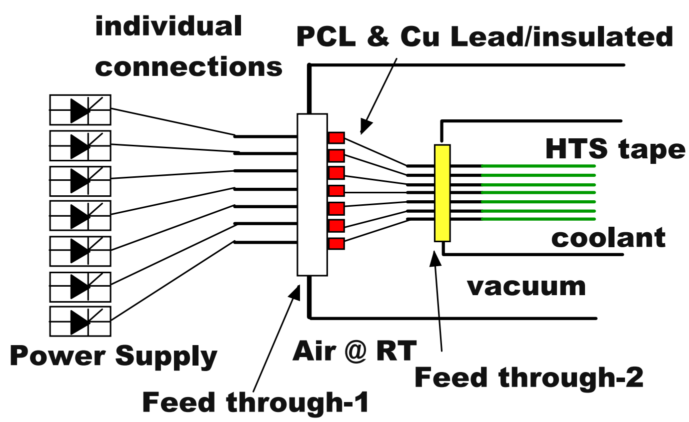

Fig. 1. Configuration of the SC cable, current lead and the power supply connection

B. Cable, Current Lead and Power Supply system

As mentioned above, instead of not using the UHV system, we must increase the magnitude of circuit current in order to transmit the higher electric power. It is suitable in the urban areas because the voltage range of the final consumer is around 400 V to 1.8 kV. Therefore, the inverter should be connected in parallel. Fortunately, it is not difficult to operate the parallel connection of the inverter because of the low voltage. Instead of using UHV, the circuit current is large, and therefore we can expect the effect of the SMES [17]. The power grid has the inductance, and since its value is around several μH/m, the electric energy storage is around 50 MJ for the length of 20 km and the current of 30 kA. This magnitude of the value excesses the present largest SMES [18], [19]. It is well matched with the sustainable energy sources like the solar battery system and wind firms to connect to the power grid because of avoiding the ripple of the outputs of these sources.

The superconducting cable is not necessary to increase the diameter even for the large current because the part of the superconducting (SC) tape is small in the cable. Some studies show that the electric power can be transmitted five times higher in DC than in AC [20],[21] for the same size of the SC cable. The reasons depend on the AC losses of the HTS tape and the electric insulation, and it will mean the cost of DC cable will be one fifth of the AC cable. Since the electric insulation material usually has low thermal conductivity, it is not easy to remove the heat from the AC losses of the HTS tape through the thick electric insulation layer to the cryogen, and therefore the temperature of the tape itself will be lightly high for the temperature of the cryogen. These are the reasons that the cost of the superconducting DC cable is cheaper than that of the AC cable. Of course, we should consider the ripple of the current even for the DC applications. Depending on the discussions with the cable maker, it is better to choose the insulation voltage of around 30 kV for the SC cable in order to minimize the cost of the cable. If the operation voltage is lower than 30 kV, this voltage is 10 times lower than that of the present UHV power transmission line at least. The system is Corona-free totally, and this will realize the lower cost of the whole system.

Because of these situations, we propose the configuration of the SC cable, the current lead and the power supply connection as indicated in Fig. 1. Figure 1 also shows the structure of the terminal, too. Each inverter is connected to each strand of the current lead and to the tape conductor individually, and they are insulated each other. Therefore, we are free from the current imbalance of the cable conductor. And even if the large current inverter will be connected several HTS tape conductors, the current imbalance will not be appeared because each circuit of the HTS tape includes the resistance of the current lead strand [22],[23]. We believe that this configuration is effective for the present quality of the HTS tape conductors because we can always monitor the voltages and currents of all HTS tapes individually.

We also use the Pelteir current lead (PCL) [24] in order to reduce the heat leakage at the terminal as shown in Fig. 1. Table II shows the calculation results of the heat leakages for each the terminal of liquid nitrogen system. When we make the optimized current lead to minimize the heat leakage to the cryogenic system, the heat leakage is proportional to the magnitude of current. There are two ways to reduce the heat leakage, one is called gas-cooled lead, and the cold evaporated gas from the cryogen must pass through the current lead and exchange the heat of the thermal conduction and the Joule heat generation of the lead. If the gas carries out the heat of its heat capacity completely, this correspond to “f = 1” in the Table II, and when the gas does not carry out the heat completely, it corresponds to “f = 0”. The other way is called PCL, and the heat flux can be carried from low temperature side to high temperature side by Peltier effect. When we install the PCL, the heat leakage is 27.8 mW/A for “f = 0”, and this is not so higher than 23.3 mW/A of “f = 1” in the conventional current lead. If we adopt the PCL and “f = 0”, the system does not need to use the liquid nitrogen at the terminals, and we are not afraid of the dewdrops of the terminals and the degradation of the insulation voltage.

C. *Cryogenic system*

The total losses of the copper cable transmission lines are about 110 MW for AC 400kV system and 80 MW for DC ± 400 kV system both for the distance of 1000 km [10]. If the heat leakage of the thermally insulated double layer pipe is 1W/m, the total heal leakage is 1 MW for the distance of 1000 km. Since the efficiency of the refrigerator for liquid nitrogen is about 10 %, the total loss will be 10 MW. This value is almost one-tenth of the copper cable system, and the major loss of the DCSC-PT will be the heat leakage from the thermally insulated pipe. However, we should also consider the pressure drop of the circulation of the cryogen and its power consumption of the cryogen pump [25], [26], and it sometimes is not small and the same level of the heat leakage of the pipe [27]. In order to save the power consumption of the pump, we propose to use the principle of siphon. Figure 2 shows the configuration of the cooling stations and the transmission line. The cooling stations must be located at higher places, and push the cold cryogen into the pipe and receive the warm cryogen from the pipe. Since the low temperature cryogen is higher density, it would be falling down to lower part of the pipe by the gravity. After the temperature of the cryogen will be increased by the heat leakage through the pipe, it is lighter and moves toward upward. Thus, we can save the power of the circulation pump. Of course, we should reduce the pressure drop of the cryogen

TABLE II
HEAT LEAKAGES PER UNIT CURRENT AT THE TERMINAL FOR DIFFERENT FOUR CURRENT LEAD

	f = 0 (no gas-cooled)	f = 1 (gas-cooled lead)
Conventional Copper Lead (CCL)	42.5 mW/A	23.3mW/A
Peltier Current Lead (PCL)	27.8 mW/A	18.6

The temperature of the hot side is 300 K, and the temperature of the cold side is 77 K.

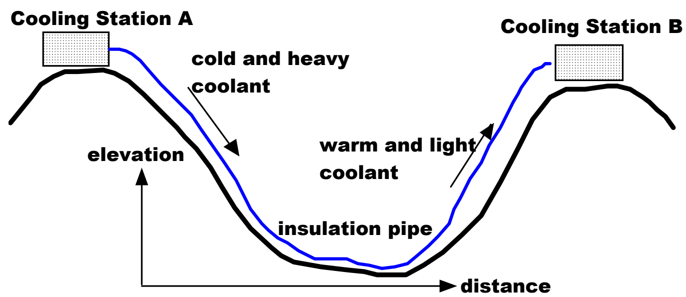

Fig. 2. Configuration of the SC cable, current lead and the power supply connection

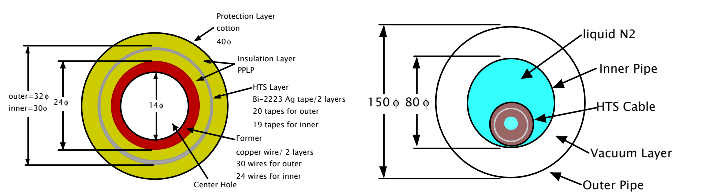

Fig. 3. Cross-section of the SC cable and the thermally insulated double layer pipe.

circulation as possible as we can. One of the solutions is that one SC cable is put into the wider pipe if the installation cost is acceptable. And this structure is matched well with the natural siphon circulation because the pressure of siphon is not high.

The multilayer thermal insulation (MLI) is used to shield the radiation from the outer side of the pipe [28]. The major issues of the cryogenic system are related to use the MLI. The MLI is the high outgas rate, wider surface, and burnable. These aspects increase the cost of the installation. Therefore, we should find the practical solutions to keep the high vacuum and installation of the pipe system in the field [29].

III. DESIGN AND CONSTRUCTION OF DCSC-PT IN CHUBU UNIVERSITY

After the above studies, we started to construct the experimental device of DCSC-PT in Chubu University, Japan. The total length of the SC cable is 20 m, and the cross sections of the SC cable and the insulated pipe are shown in Fig. 3. The Bi-2223 HTS tape is used, and its critical current is slightly larger than 100 A, and the number of the tape is 39. Therefore, we can expect that the magnitude of the current excess 2.0 kA at least. These tapes are connected to the strands of the current lead individually and we installed the PCL like Fig. 1. We also adopt the straight inner pipe and a larger pipe diameter as compared with the diameter of the SC cable to minimize the pressure drop of the cryogen circulation. The aspect ratio of the inner and outer pipe radius is almost two, and higher than that of the previous researches of the AC power cable in order to reduce the pressure drop, but the MLI is used. The study of the inverter is separated for the experiment of the SC power cable initially, and we will test the performance of the several HV's inverter independently.

IV. Discussion and Conclusion

There are many merits to use the UHV DC power transmission line even for the copper-cable system, and actually the DC power transmissions are applied even for the short distance line [10]-[13]. Therefore, if we can reduce the cost and the loss of the inverter, we can realize these merits both for the copper cable system and the DCSC-PT. The DCSC-PT is effective from the short distance transmission in the metropolitan area to the intercontinental power transmission. As compared with the other long power transmission lines like the oil and natural gas pipe lines in all over the world, the efficiency of the DCSC-PT will be high clearly because of no mass transfer basically. The authors believe that the DCSC-PT will be one of the key technologies in this century.

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