

Technical Challenges and Potential Solutions for Cross-Country Multi-Terminal Superconducting DC Power Cables

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Abstract. Opportunities for applications of high temperature superconducting (HTS) DC power cables for long distance power transmission in increasing the reliability of the electric power grid and to enable easier integration of distributed renewable sources into the grid are discussed. The gaps in the technology developments both in the superconducting cable designs and cryogenic systems as well as power electronic devices are identified. Various technology components in multi-terminal high voltage DC power transmission networks and the available options are discussed. The potential of ongoing efforts in the development of superconducting DC transmission systems is discussed.

1. Introduction

There is a renewed interest in DC systems in power transmission and distribution. By the start of the last century, an efficient electrical power transmission system was needed to transfer the power over long distances and to start the expansion of the power grid. Changing the voltage levels by the AC power transformers was the settling point for the War of the Currents and the start of utilizing the AC power system by the end of the nineteenth century [1]. Even though AC power became the norm since then, DC power transmission was not totally ignored. This is due to the fact that the DC power technology provides an efficient and effective interconnection between any two independent AC grids to transfer power [2], in addition to adding rigidity to both of them. The conventional solution for this is known as the rotary converter. It is essentially a motor-generator coupled machine. The unit connected to the grid that supplies the power to be transferred operates as a motor, and the other unit operates as a generator and is connected to the grid receiving the power. This method is used in several locations around the world. For instance, in Japan, it is used to connect power networks of adjacent areas with different frequencies, 50 and 60 Hz. Hundreds of MVAs can be transferred using this method [3]. Basically, the motor-generator coupled machine need to be built to the maximum rating of the power transferred, so the coupled machine must be built to GW scale if it is intended to transfer power in that range. However, there is a growing trend towards using of solid-state solutions based back-to-back (B2B) high voltage direct current (HVDC) grids tying systems [4].

Having mostly relied on the AC power transmission and distribution (T & D) systems for the last century, the utilization of the DC systems is being considered and the interest is growing [2]. The new trend of increasing reliance on renewable energy sources, which provide ample amounts of energy usually at remote locations, requires a very efficient method to transmit these large amounts of energy to the urban demand centers. The rapid development in power electronics has contributed in utilizing



HVDC power transmission and making it feasible and controllable. Currently, and after decades of notable success in the HVDC transmission field, DC transmission is preferred over the AC when the power transmission distance exceeds the break-even point. It presents the meeting point for the AC and DC systems' capital and operational cost curves. The break-even point is in the range of 500 to 800 km for overhead lines, but much shorter for underground cables, which is between 20 and 50 km for submarine cables and twice as long for underground cables [5]. The reason behind the lower values for the break-even length in cables is due to the cable's capacitive charging length when transmitting power in AC form [6]. However, this limitation does not exist when transmitting DC power. Additional benefits for the HVDC transmission system over the HVAC are discussed elaborately in the literature [1, 7]. In conclusion, HVDC transmission is an efficient and economical choice for transmitting large amounts of power over long distances.

The next step will be to expand HVDC point-to-point links to a true multi-terminal HVDC (MT-HVDC) system, which has the ability to provide all the above mentioned benefits while adding more flexibility with respect to system control. Recently, enhancing the transmission system capacity and improving the system control are the two major challenges that are facing the power sector in North America [2]. Therefore, considering the MT-HVDC power transmission systems is a prospective innovative solution that can help with addressing these two challenges. MT-HVDC systems support the grid in many aspects, like serving as asynchronous ties between multiple grids/networks and providing a system that can transfer power in a more efficient way over long distances, besides the ability to receive or deliver the power at multiple points necessary for integrating distributed renewable energy sources into the grid.

The realization of the need for the MT-HVDC systems is increasing every day because they offer a full seizing of the technical and economic benefits of the HVDC transmission system [8]. Figure 1 below shows the potential of MT-HVDC systems in decreasing the total capital cost by reducing the converter stations needed. However, switchgears are needed to control the power flow.

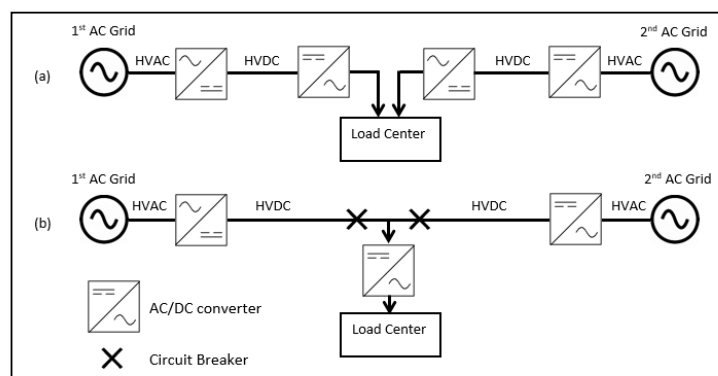


Figure 1. (a) Two point-to-point HVDC links with 4 converters. (b) The same Two DC links connected in a MT-HVDC configuration with 3 converters.

2. Need of Superconducting Cable Technology for the MT-HVDC Systems

The MT-HVDC system involves handling large amounts of power, on GW scale. This will lead to some challenges such as:

- i. If the suspended overhead cables and transmission lines were used, they would be vulnerable to weather conditions.
- ii. If the underground conventional cables were used, the complexity and size of the project would be substantially high since these cables need to be separated by several meters to avoid the overheating [9]. Besides, due to their size, it is more difficult to obtain right of ways for larger areas for the station footprints, especially when it is within urban areas [2].

All these problems could potentially be addressed by replacing the conventional cables technology with state of art high temperature superconducting (HTS) cables. Underground HTS cables will address the weather conditions concerns. Besides, the Superconducting DC power cables have the attractive “zero

loss” state. Although the Superconducting cables are much higher in efficiency when transmitting AC power, compared to the conventional cable technology, they are even better when transmitting DC power due to the absence of the significant negative impact of the AC losses, which will be discussed in the next section. Thus, each Superconducting HVDC cable has the ability of carrying currents up to 100 kA whereas the conventional HVDC line can carry a few kA at most [2], and so, less right-of-way and foot print are needed. In addition, if more cables are needed for the sake of expansion, the Superconducting DC cables can be buried closer to each other unlike the conventional cables due the fact that magnetic field can be completely eliminated outside the superconducting cable with a proper cable design [9]. In summary, the HVDC based HTS cable technology offers the optimum solution to achieve higher performance and power density for the MT-HVDC systems.

In Europe, the vision of using superconducting HVDC for long distance transmission is being explored under a large project aimed at moving towards low-carbon economy called the “Best Paths” program. The program intends to develop technology to increase the capacity of the European interconnected transmission networks [10]. The main goal is to integrate the abundant renewable energies, from the wind farms, smoothly and efficiently into the pan-European power transmission network. Thus, the program intends to achieve the European MT-HVDC based HTS cable power transmission network. The HTS cable for the program intends to use the magnesium diboride (MgB_2) superconductor and cooled with gaseous helium (GHe), and they are investigated to carry currents up to 5 – 10 kA under 200 – 320 kV of high voltage levels to transfer up to 3.2 GW of power [11].

3. AC Losses in Superconducting Cables Due to The Ripple and Harmonics from Converters

AC Superconducting power cables suffer from AC losses. DC superconducting cables do not produce any losses as long as the DC current is clean and free from AC ripple and harmonics that originate from the power converters [12]. The extent of losses due to ripple is small, but it is necessary to eliminate it for long distance superconducting DC cable systems to make them more efficient and to minimize the expensive cryogenic cooling capacity required [13]. The harmonics could also come from reversing the power flows in HVDC based HTS systems. There are a few different converter topologies that can be used in HVDC systems [13-17]. The selection of converter topologies for HTS HVDC systems has to be based on their suitability for high current operation and the need for clean DC power. It has been reported that the parallel hybrid modular multilevel HVDC converter design offers significant reduction in the extent of ripple in HVDC systems. [17]. Long distance cables tend to dampen the ripple in general, but it is important to consider this issue in the design of superconducting cable for HVDC applications for negligible steady state losses [12-16].

4. Technical Challenges and Solutions for the MT-HVDC HTS Cables Technology

4.1. The Superconducting Technology Challenges

HTS technology has the potential for providing an efficient MT-HVDC systems, but has its own technical challenges, cost issues, and lack of standards and industry accepted test protocols.

Regarding to cost, there have been several early and recent research studies for utilizing superconductors to transport large amounts of power over long distances [18, 19]. The electric power research institute (EPRI) conducted research on the economic feasibility of utilizing superconducting cables for transmitting large amounts of power over long distances. The analysis concluded that a superconducting cable system would cost approximately the same as a conventional transmission line if the line is transmitting power in excess of 5 GW, over a long distance of about 1,600 km. Part of that result due to the fact that the cost of the cryogenic system, which is needed to maintain the superconducting properties, will be a small share of the total cost [2]. In addition, while the efficiency of the conventional power transmission lines drops substantially when carrying bulk power over long distances, the high efficiency of superconducting cable systems will not be affected. Furthermore, the power losses in the terminations are constant and not affected by the cable length. These terminations losses are a large fraction of the total losses of the system because they handle the connection between the ambient temperature of the current leads and the cryogenic temperature of the superconducting cable. However, these losses decrease relative to the whole system losses with the increase in cable length to negligible values with respect to the total cost. Furthermore, a drop in the cost of the superconductor

and power electronic converter technology is expected in the near future. The increase in manufacturing capacity of volume of HTS materials and cables will bring about a substantial decrease in the cost due to economies of scale. On the power electronics side, the device prices are dropping rapidly, which will reflect on the capital cost drop for the converter substations. However, the new technology devices, like silicon carbide (SiC) devices, are still not in the mass production level to allow a practical cost estimation. In addition, the prospective development in the HTS materials and the efficiency of the cryogenic cooling system is expected to further reduce the capital and operational costs. Thus, at this point the technology is not mature enough to conduct a meaningful economic analysis for such systems.

One obstacle for HTS technology is the lack of standardized test methods. It is still an issue for the utility companies to perform testing for the HTS DC cables because there is no standard test for it, in contrast to the HTS AC cables as was achieved discussed [20]. This presents one of the major challenges for utilizing HTS DC cables widely in power grids. HTS DC cable has its unique challenge in performing a load cycle, contrary to the HTS AC cable or the conventional HVDC cable. Applying both voltage and current simultaneously through the use of a current transformer is impossible due to its AC loss characteristics [21, 22]. Thus, some appropriate new methods for performing reliable and acceptable qualification tests on HTS DC cable are needed. On the other hand, thermal cycling studies of HTS cables is very important for utilities to demonstrate and verify the cable's lifetime since the cables will be subjected to several contractions and expansions during cool-down and warm-up cycles during installation and operation. The thermal cycles are similar to HTS AC cables that are in operation and hence some data exists. The thermochemical issues are design dependent and further work is needed to qualify the designs for 30-40 years of service as required by electric power companies [23, 24]. However, for the planned and installed HVDC based HTS cable projects, the utilities companies have started constructing test centers and establishing specialized tests for the new technology. One of the latest projects that was implemented in South Korea, which has combined two standardized tests, besides the HTS experience. South Korea is one of the earliest countries that adopted the smart and clean energy applications and has been considerably progressing in developing the HTS power cables integration to the real Grid. A project by the Korea electric power corporation (KEPCO) and LS Cable Limited has done the designing and manufacturing part, and started researching the HVDC based HTS cable integration into the Gumak grid in 2011 [25]. The big picture of the project is to connect two conversion stations, from Halim Conversion Station to Gumak Conversion Station, by a 5.3 km long DC line. A 0.5 km long underground HTS DC cable project was meant to connect an existing 4.8 km long DC overhead transmission line to Gumak Conversion Station. Therefore, a ± 80 kV, 3.25 kA, 500 MW DC HTS cable was constructed and installed in the Gumak converting station. After passing successfully all the tests by the 101 m cable prototype, the actual cable was installed and started the demonstration in the real grid since October 2014 [26]. For testing, the recommendations were based on Electra 496 and Cigre TB 538, and the HTS experience. In addition, an additional measurement for the DC HTS cable lifetime was performed. That was done through the investigation of the cable response to the mechanical stress due to cool-down and warm-up cycles. The testing period was from 20 Dec. 2012 to 31 Oct. 2013, and the results showed that a combination of HV tests with the HTS experience, which was called the qualification test, is required for the HTS DC cable project. Finally, a test for the cryogenic system is always required to verify the ability of the cooling system to handle the cable performance as designed.

4.2. Cryogenic Systems Challenge to Support Long Distance Superconducting HVDC Systems

One of the major challenges in bringing HVDC based HTS cable systems to the power grid until recently has been the lack of reliable and economic cryogenic refrigerator systems. This challenge has recently been addressed by the industry through the development of large cryo-refrigerators based on Turbo-Brayton cycles with >150 kW cooling power at 70 K [27, 28]. These large cryogenic systems are significantly more efficient and require little maintenance compared to Stirling refrigerators and Gifford-McMahon cryocoolers [29]. Turbo-Brayton cryocoolers have been used successfully for the HTS cable projects in Korea [30, 31]. Further new approaches are being investigated to reduce the complexity and costs of the cryogenic systems for large HTS systems [32, 33]. Further technical advancements are needed to improve the reliability and reduction of capital and operational costs of cryogenic systems and the interfaces between the room temperature components and cryogenic components at the terminals of MT-HVDC systems.

4.3. *The MT-HVDC Systems Technology Challenges*

The MT-HVDC based HTS cable systems will face the same challenges of the conventional MT-HVDC systems, such as the DC fault protection and the control of the power flow for the meshed DC system with different kinds of converter types.

One major difference between HVDC and HVAC is in the management of faults. While HVAC systems rely on its natural current zero crossings to clear the fault, HVDC requires more complicated circuits to create artificial current zero crossings. It has been reported that the fault current magnitude in HVDC transmission systems will be lower than in HVAC systems for the same amount of the power transmitted [34]. The real problem with the DC systems is the faster rate of the rising fault current than in AC systems [35]. This is due the faster DC system dynamics and transients, which means a very sensitive DC fault relay is needed to detect and remove faults quickly. Unfortunately, these kinds of DC circuit breakers are still not commercially available, but there have been some developments of building and testing of a few prototypes [36]. However, this issue can be dealt with by using the HTS cables, if these cables were designed to operate as fault current limiting (FCL) cables [6]. The Superconducting material loses its superconducting property when the current exceeds its critical value (I_c) and transitions to the normal state of being a high resistance material. However, the HTS cables should be designed in a specific way for that particular purpose, or else they could be damaged by the massive fault currents. Thus, this is a great feature for the HTS power transmission cable systems that give them a distinguished advantage making them more attractive over the conventional systems. To conclude, use of FCL HTS cables can a contributing factor to solve the protection problem for the MT-HVDC systems, which is a big draw back for the conventional cable/line based MT-HVDC systems.

4.4. *The Challenge of Establishing Research and Development Centers*

The laboratory establishment for research and development of large superconducting systems is still a challenge for the MT-HVDC based HTS cable systems. Unlike the advantages of changing the magnitudes of voltage and current by the transformers in the case of AC system experiments, establishing the required large DC power sources for testing MT-HVDC based HTS cable systems is a major challenge, especially coupled with the need for collocating the large cryogenic systems in the laboratories and research facilities. The conventional cables' laboratories and testing facilities lack for the existence of cryogenic cooling systems. As a result, the experimental research work on MT-HVDC based HTS cables is still an issue that needs to be addressed by making the necessary investments, which will accelerate the development and implementation of this game changing technology. Therefore, for modelling and analysis of the MT-HVDC based HTS cable systems, simulations are needed. The real-time simulation for these system is very important as for any new piece of power equipment that needs to be integrated into the grid. The simulations are also important due to the fact that the DC system stability and dynamics are much faster compared to the corresponding AC systems [35].

5. **The System Components**

5.1. *The Converters*

Many types of converters have been utilized in the HVDC systems all over the past years. The load commutated converter (LCC), based on thyristors, was introduced first during the 70s of the past century [37]. It is suitable for bulk power transmission, with low losses (approximately 0.7% of losses per converter), but it lacks for the turn off feature. Thus, it has a drawback regarding to controllability. Besides that, it has disadvantages of needing variable reactive power from the Grid, AC source on both ends for successful commutation, and transformers on AC sides to have a 30-degree phase shift. Then the voltage source converter (VSC), which utilizes insulated gate bipolar transistors (IGBTs) was introduced by ABB and marketed as "HVDC Light" in 1997 [37]. It uses the pulse width modulation (PWM) technique for better voltage waveform and less harmonics. It has higher losses compared to LCC (typically 1.7% of losses per converter). However, it has many other advantages over the LLC, besides the source controllability: First, the conversion station is more compact, less foot print, due to the less of the harmonic filters needed. Second, it can be utilized anywhere in the grid, whether it is a weak or strong network, with no consideration for phase shift. The capability of offering the blackstart and the many other technical features made the VSC to be more preferable over the LLC. In 2010, a

new multilevel VSC technology called modular multilevel converter (MMC) was introduced simultaneously by two companies (Siemens and ABB) in two projects [37]. Siemens's HVDC PLUS technology project, the Trans Bay project, was an 88 km subsea cable installed to transfer 400 MW of power from Pittsburg to the city of San Francisco in California [38]. This converter was introduced by Marquardt and Lesnicar in 2002 [39]. It has a better efficiency than the VSC (almost 1% of losses per converter) due to the less needed switching frequency, with better control. Thus, it really represents the state of art for the HVDC converters' technology.

5.2. The HVDC HTS Cables

The HTS HVDC cables connect the converter station in one grid to the other, or extend between any two converter stations as in a MT-HVDC radial link. These cables, which are actually pipelines, handle and carry a large DC current between the conversion stations. Since the application in which the HTS cable is going to be used is directly impacted by the design configuration decision, a single pole per envelope design configurations is used for the HV applications [6]. Different cable layouts have been proposed, the Warm, the Cold and the Two Stage Dielectric HTS cable layout. Each one of them has its own advantages and disadvantages. The different aspects of these designs have been investigated and the results showed that the Warm Dielectric Cable design is the right fit for the HVDC HTS cables due to the absence of the induced currents on the cryogenic piping [40]. Besides, it is expected to be less costly, because there is no need for a special cryogenic dielectric medium. Additionally, it requires smaller diameter of cryogenic piping. However, it occupies more volume because each DC pole requires an individual separate cryostat [6]. Thus, the total cross section of the Warm Dielectric HTS cable is significantly larger than the Cold Dielectric for a given power rating, which reflects in lower effective power density of the cable. Therefore, the Cold Dielectric cable design is preferable over the Warm dielectric where compact HTS cables are preferred.

Regarding insulation, so far no successful extruded insulation has been reported in the technical literature, except extruding thin layers on the HTS tapes directly [6]. Although the extruded insulation possibilities exist for the Warm Dielectric cable design, but not for the Cold Dielectric designs, where the lapped tape insulation has been used. Here, the insulation tapes wrapped onto the HTS layer and surrounded by the cryogenic coolant, which penetrates the butt gaps in the insulation layers to serve also as dielectric medium, inside the cryostat. However, the dielectric properties vary for the different kinds of the cryogenic coolants. For example, with one sheet of polypropylene laminated paper (PPLP), at 77 K of temperature and within a uniform electric field, liquid nitrogen (LN₂) has higher dielectric breakdown strength of values around 270 kV/mm of DC voltage and 115 kV/mm of AC voltage than GHe, at 1.0 MPa, which is around 180 kV/mm and 60 kV/mm of DC and AC voltages, respectively [41]. Nevertheless, it would be more economic and easier in cable manufacturing if the researchers or the manufacturers succeed in developing an extruded cryogenic insulation which can form a thin layer over the HTS layer instead of the lapped tape insulation.

Since the cryogenic coolant submerge the insulation tapes, it is critical to keep the coolant operating temperature under the boiling temperature to avoid having any bubbles which can deteriorate the insulation integrity, and consequently, the performance of the HTS cable. For that purpose, pressurizing and subcooling are used to increase the margin between the operating and the boiling temperatures. For instance, the permissible temperature raise of LN₂ over the operating temperature, which is 75 K, increases from 2 K at 100 kPa pressure to 20 K at 500 kPa of pressure [42]. Increasing the temperature margin will also increase the HVDC cable length limit, with the absence of the charging length limit in HVAC cables, so that the cooling stations can spaced apart farther. Moreover, for long distance HTS cables, the corrugated cryostat pipes, which helps with making the pipes flexible for bending, can be replaced by flat smooth pipes to reduce the pressurized coolant friction and the cost.

5.3. The HTS Cables Terminations

The cable terminations are interface for the room temperature components and the cryogenic components of the system and are the locations of current injection and the cryogenic inlet and outlets. A schematic of a cable termination is shown in Figure 2. The thermal, the mechanical and the electrical stresses are all mostly concentrated in the terminations and hence the MT-HVDC based HTS cables system requires efficient and effective termination designs.

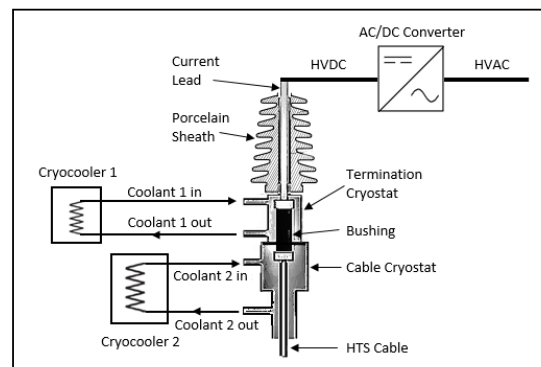


Figure 2. Proposed Two-Stage Cooling HTS Cable's Termination

6. The System Configuration

Several possible configurations exist for MT-HVDC based HTS cables systems. According to the particular application served by the MT-HVDC system, an appropriate configuration has to be designed. If the application is to have a MT-HVDC system that spans long distances, Cross-Country MT-HVDC system, the radial configuration as shown in Figure 3 is more suitable. This Cross-Country radial MT-HVDC scheme is appropriate for transferring the power from a renewable energy source, Terminal 1, all the way to the far away AC grid of the load center, Terminal 4. It also has other taps at certain locations in between to deliver or withdraw power from the cable system, terminals 2 and 3. In addition to the bidirectional power injection that these two terminals offer at their locations close to other generation/load centers, it can serve the purpose as cooling stations for the HTS cable system to maintain the operating temperature and pressure for the cryogenic coolants.

To calculate the distance between any two cooling stations, the following equation is used:

$$Q = \dot{m} C_p \Delta T$$

For instance, if LN_2 is used with the operating temperature range (ΔT) of 68 to 78 K, a mass flow rate ($\dot{m}$) of 200 (g/s), and specific heat capacity (C_p) of 2 (kJ/kg/K), then the maximum heat load of the cable (Q) between the cooling stations can be up to 4 kW. Considering 1 W/m of the heat flux for the HTS cable will give us 4 km, which is the maximum length that the HTS cable can go between the cooling stations. However, calculating the distance between the cooling stations involves other factors such as the pressure drop which should be taken into consideration too. An alternating rigid and flexible sections of the cryostat, which was developed by Chevchenko [43], is a potential solution to decrease the friction of the inner surface of the cryostat. Furthermore, smooth cryopipes can be proposed to replace all the corrugated sections since the pipes are going to be buried underground and no flexibility is needed for bending them. This will significantly reduce the total friction of the inner surface of the cryostat. On the other hand, the topography can also add complications to the pressure drop consideration when the cable route involves inclined areas. Moreover, since the heat load of the DC cable is solely from the heat leak into the cryostat, the cryostat design is the key factor to increase the distance that HTS cable can go between refrigeration stations. A team of researchers from EPRI led by Hassenzähl have come with a very interesting result of 20 km distance separating the cooling stations which can be achieved with a cryostat design that uses counter-flow, using go and return streams for the LN_2 [44]. A 3 kg/s of mass flow rate and 3.1 MPa as maximum pressure, with allowable 1.0 MPa of flow pressure drop, were developed for the EPRI study to enable the 20 km distance. Finally, it is possible to add cryogenic cooling stations in the middle of cable sections which adds additional flexibility to the system [2].

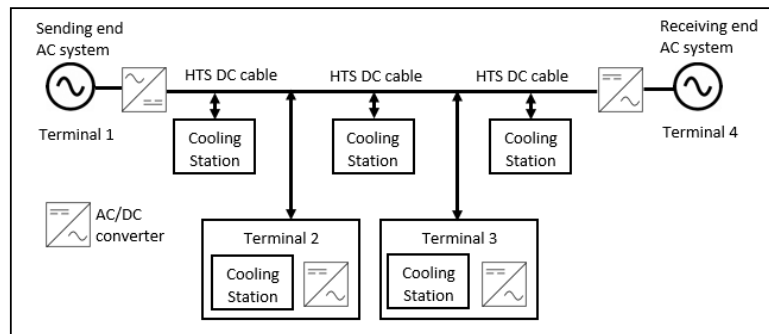


Figure 3. Simplified Four-Terminal Radial MT-HVDC based HTS DC cables with cooling stations scheme.

7. Conclusion

The paper outlined the opportunities for increasing the efficiency of long distance electric power transmission systems by using HTS DC power cables. The multi terminal superconducting HVDC transmission systems allow easier integration of diverse power grids and the insertion of distributed renewable sources into the power network. The integration of the grids and renewable energy sources eliminate the use of fossil fuels for meeting the transient power demands and improve the resiliency of the whole electric power network. There are, however, several technology advancements needed in areas of HTS, cryogenics, and power electronic systems to make the long distance superconducting multi terminal HVDC transmission systems a reality. The technology gaps and possible options for various components of HVDC systems are discussed.

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