A High-Power Superconducting DC Cable

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***Abstract*—The long-range future of large electric power systems depends on achieving secure and reliable transmission of electric power at the gigawatt level. Also, changes in the production and use of electricity *vis-à-vis* the drive to "green" power sources have heightened the importance of improving the efficiency of electric power transmission. With these thoughts in mind, a small group supported by EPRI began assessing the possible function and form of a high-temperature superconductor-based dc cable of the future. The goal of the effort is to produce a conceptual design with sufficient engineering content that it could be built with present-day engineering capabilities. The only recognition of potential advancements in the concept is the anticipated performance of superconductors some 15 to 20 years hence. This presentation discusses results of the effort to date and describes much of the cable and infrastructure design necessary to install and operate a multi-gigawatt superconducting dc cable.**

***Index Terms*—DC power transmission, power cables, power systems, superconductivity.**

I. INTRODUCTION

THE future electric power system will be very different from what we see today. Advanced technologies such as hydrogen production, use, and transport; power flow control; fuel cells; superconductivity; and cryogenics will all impact the design and effectiveness of the future power grid. Three issues will be paramount in the selection of the new technologies to be widely implemented: efficiency, reliability, and security. Superconducting power system technologies are attractive in general because they are inherently more efficient than equivalent resistive technologies. Superconducting power cables will be easier to site because they require less land (a smaller corridor) than do overhead power lines, which face considerable resistance from environmental advocates. The concept proposed will be highly reliable because it uses two full-capacity cables that can share the load or can operate independently at full power. Because the superconducting dc cables will be underground, they will be more secure and more reliable than conventional transmission lines.

Thomas Edison proposed the use of direct current for power transmission. That approach was successful during the early period of electrification when power levels and the maximum current were low. As electric power demand increased, the resistive losses associated with increased current in the dc system led to the development of ac systems in which transformers are used to maintain modest currents by increasing the voltage for transmission and distribution while maintaining a safe voltage for residential and commercial use. Today, ac systems are still the preferred mode of power generation, transmission, and use. Details of the design and the procedure for choosing various parameters for the cable system will be included in a complete report of the study, which is now in process.

II. BACKGROUND

In the mid 1960s, when the first glimmer of practical superconductors for electric power applications appeared, Garwin and Matisoo [1] carried out an analysis of a multigigawatt, superconducting dc power cable. This effort was followed by a proposal by Bartlit, Edeskuty, and Hammel of the Los Alamos Scientific Laboratory [2] to integrate the transmission of electric power, hydrogen, and liquefied natural gas in a single pipe. This concept took advantage of the fact that each of these modalities of energy transmission requires cryogenic technology to be effective. The Los Alamos Scientific Laboratory was an early proponent of dc power transmission and developed a cable using low-temperature superconductors [3], [4]. When it became apparent that high-temperature superconductors (HTS) could eventually be effective for power transmission, the Electric Power Research Institute (EPRI) supported a study by Schoenung and Hassenzahl [5] of an HTS dc power transmission system. More recently, Starr [6] and Grant [7] of EPRI proposed a SuperGrid that would combine a liquid hydrogen distribution network and a superconducting power transmission system.

In 2005, EPRI initiated a study to develop a dc power cable using HTS materials. This study evaluated a variety of scenarios in which dc power cables might be of interest. The team selected two power ranges and cable lengths for further work. One is an intraregional cable rated in the 2 GW range and having a length of about 200 km. The other is an interregional cable rated at 10 GW and having an installed length of 1000 km or more. This report addresses the interregional cable, which will normally operate at 100 kV and have a maximum current of 100 kA. The intent of the program is to address technical and engineering issues associated with the fabrication, installation, and operation of these cables. One of the strengths of a dc system is the inherent ability to operate asynchronously *vis-à-vis* the ac power grid. That is, it can accept and deliver power at any number of nodes or interconnects to generators and loads. Stability of the

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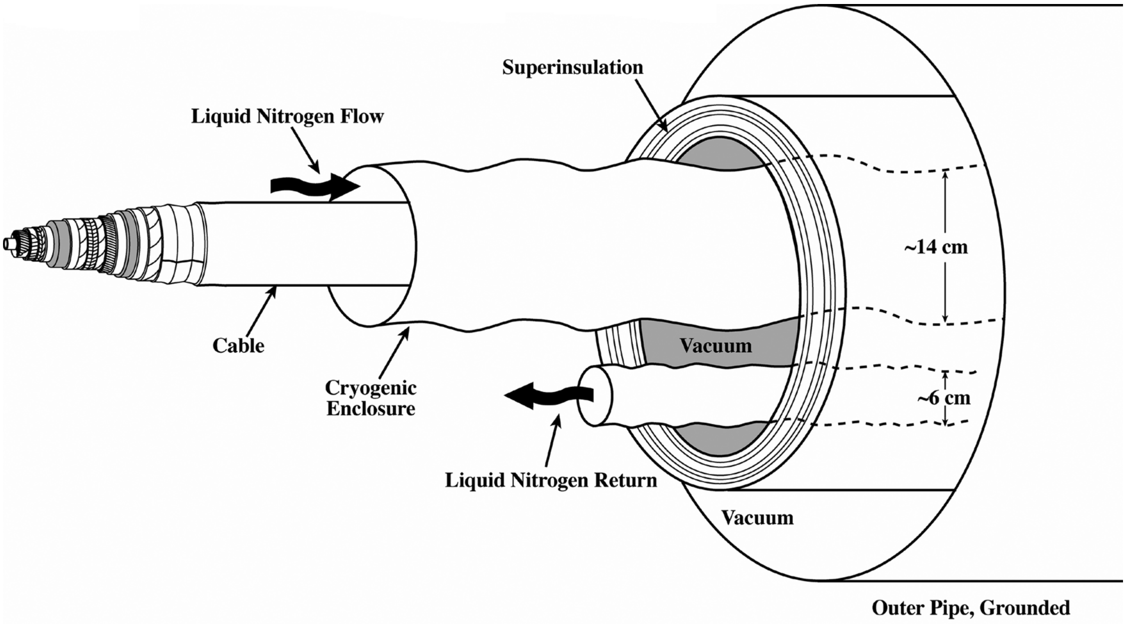

Fig. 1. The overall design of the superconducting dc cable is based on the use of an external steel pipe that contains the working components of the cable, which are thermally isolated from the ambient environment by a vacuum and multilayer thermal insulation. The dimensions are approximate.

ac grid is improved by this asynchronous linkage. Experience in the western US has shown that stability and power flow is enhanced by a 3.1 GW dc intertie [8], [9].

III. CABLE DESIGN

During the initial assessment of various technical issues associated with the superconducting dc power cable, it became apparent that system reliability would be a primary design driver. In particular, the need to ensure the high efficiency offered by superconductivity required low heat flow into the cryogenic portions of the system. Only vacuums with multilayer insulation (superinsulation) afforded adequate thermal insulation. This conclusion has been reached in the selection of thermal insulation for existing superconducting ac power cables. Those ac cables are a few kilometers long and make use of several segments of permanently sealed vacuum tubes, each of which is about 100 m long. These vacuum enclosures are known to be very effective, but they have a failure rate (i.e., they occasionally experience leaks [10]), that would affect the availability and reliability of a system composed of thousands of units in series, the failure of any one of which would require system shutdown and repair. The superconducting dc cable design incorporates a large, annular vacuum space with multilayer thermal insulation as in Fig. 1. The area of the vacuum region in the dc cable is sufficiently large for the vacuum pumps to be spaced at distances of approximately 1 km.

A. Cable Core

The superconducting dc cable core design, Fig. 2, is based on experience gained from the manufacture of conventional power cables. The superconducting portion of the cable consists of two multilayer sections of tape that are separated by electrical insulation designed to meet all requirements for the 100 kV operating voltage. The rated cable current of 100 kA requires 500 tapes, each carrying 200 A. The challenge is to design a winding system that can apply multiple layers of superconductors. Winding heads that can apply 50 strands of tape are available today, and sequential heads are common. However, there is no experience with winding 500 tapes on a single mandrel. Achieving large numbers of conventional wires in a single conductor is generally accomplished by forming a rope of conductors, which are wrapped around a mandrel. This process requires a material that is very pliable, while today's superconductors are rather brittle and would be sensitive to the stresses introduced during the initial rope formation.

Conventional copper conductors are in close contact with each of the superconductor sections. These normal materials can carry the full current for short periods; for example, during a fault when the critical current of the superconductor is exceeded. To limit eddy currents in the normal conductors, they are placed in regions of low magnetic field, i.e., inside the inner or positive superconductor layer and outside the outer or neutral superconductor. The neutral layer of the cable is nominally at ground potential; however, a variety of conditions occur that cause the neutral conductor to reach voltages that are more than half the operating voltage. To accommodate these upset conditions, a ground or shield layer is included. It is not designed to carry significant current, and it is separated from the neutral conductor by a layer of electrical insulation.

The fabrication of conventional power cables can be readily adapted to the superconducting dc cable. Perhaps the biggest change in procedure will be the number of passes that the cable must make through the forming equipment during the application of conductors, insulation, and various layers added for mechanical protection. This part of the procedure will require the extension of various technologies to larger capacities and greater cable weights. During the final step of cable fabrication, these cables are wound onto spools that are used to transport

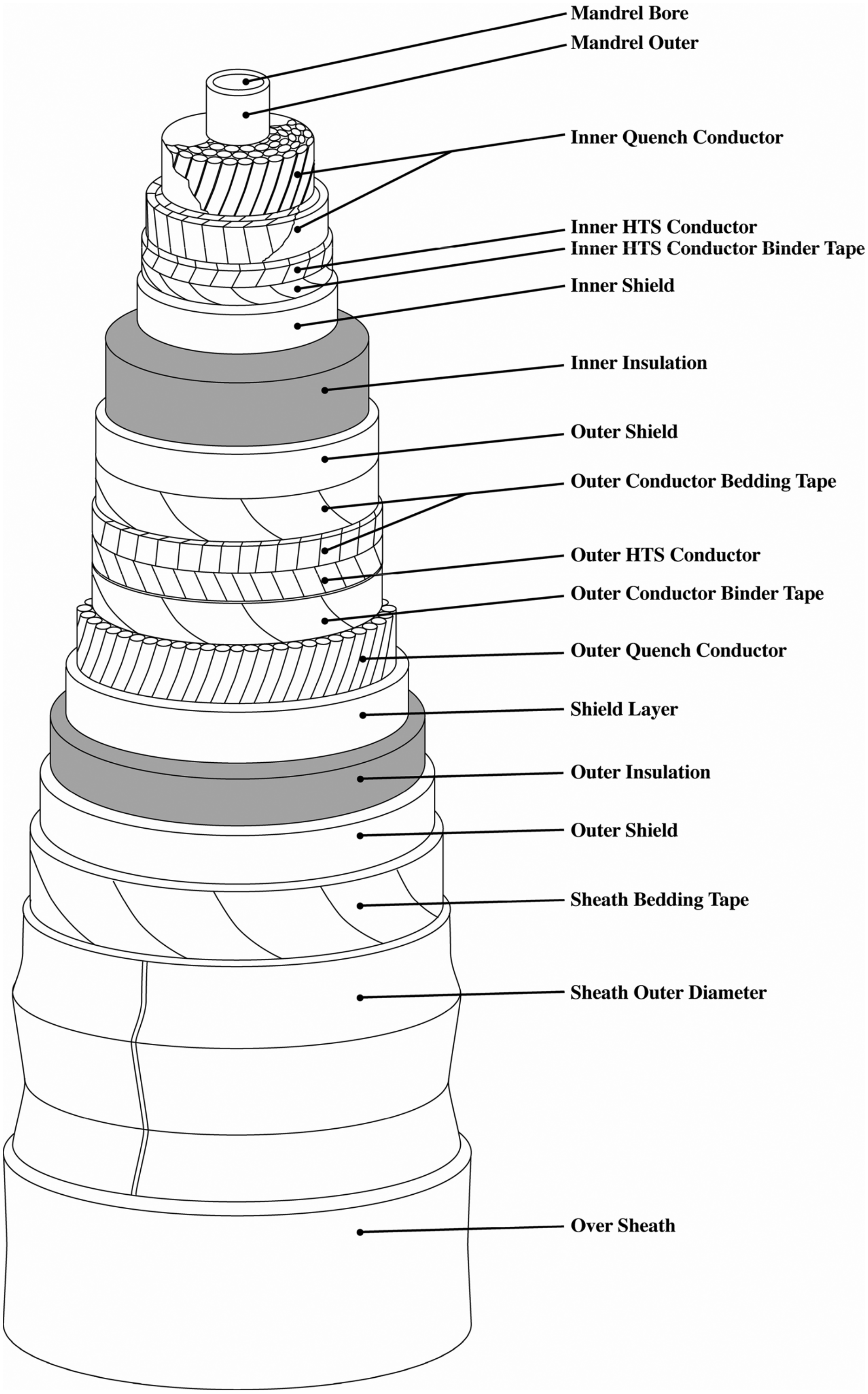

Fig. 2. Artist's concept of the dc superconducting cable. The innermost part is a tube, which may contain flowing liquid nitrogen. The two layers of superconductor can carry currents of 100 kA, and the insulation is designed to meet all requirements for a 100 kV dc system.

them from the factory to the installation site. Based on the outer diameter of the cable core (see Fig. 2) and the weight of the cable per meter of length, one can estimate the longest transportable cable section. It appears that this length is about 1100 m for the design in Fig. 2. Further design studies on the cable will be needed to select the exact cable section length and the dimension of the outer steel pipe.

B. Heat Flow Into and AC Losses Within the Cable

There are three sources of heat flow from ambient temperature to the cryogenic portion of the cable: conduction, convection, and radiation. Conduction heat leaks are associated with the cable supports, which must support the weight of the cable and resist the forces associated with installation and cooldown.

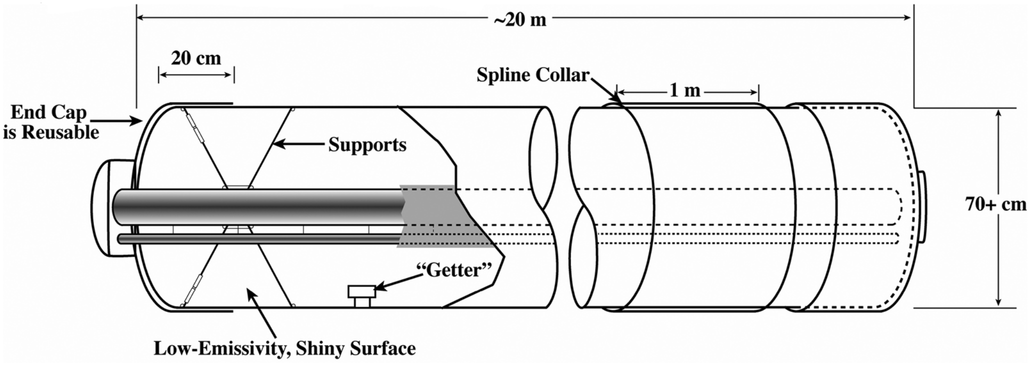

Fig. 3. A dc cable pipe section prepared for transport to the installation site.

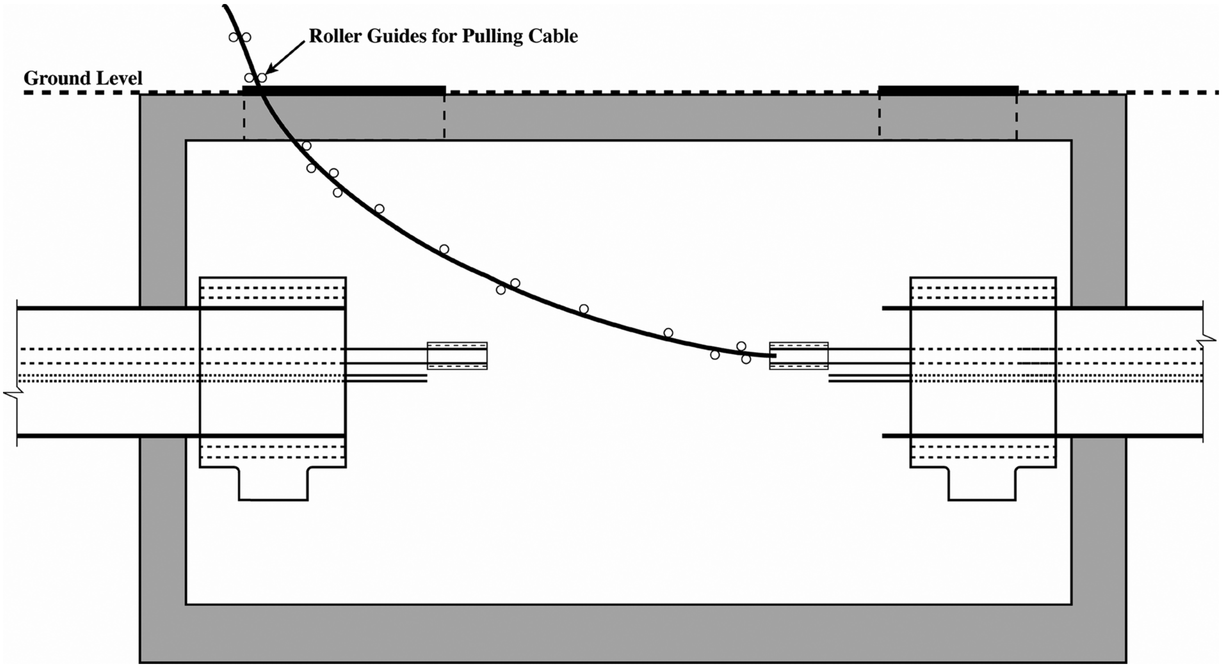

Fig. 4. The cable splice and vacuum vaults will have pipe sections entering from each side. After splicing is completed, the collars will move to seal the vacuum and to accommodate connections to vacuum pumps.

These supports will be at discrete locations along the cryogenic enclosure and will have heat flow of less than 0.1 W/m of cable length.

Radiation and convective heat flow is from the ambient temperature walls of the outer tube to the two cryogenic pipes. If a gas were used in the space between the outer pipe and the cryogenic tubes, the heat flow would be about 400 W/m of cable length. This flow can be decreased to about 50 W/m by using foam insulation, and it can be decreased considerably further by evacuating the space. The magnitude of the heat flow in a vacuum depends on the areas and emissitivities of the radiating and absorbing surfaces, the quality of the vacuum, and the number of layers of superinsulation. As the number of layers increases, the reduction in loss per layer decreases, so that most systems use between 20 and 50 layers, which are installed in bats. The radiation losses associated with 30 layers will be about 0.1 W/m. The convection losses in an evacuated section depend on the gas pressure. Lower pressures lead to lower losses. However, in the range of 0.0133 Pa $(10^{-4}\ \mathrm{torr})$, the reduction in losses saturates, and there is little improvement beyond about 0.0013 Pa $(10^{-5}\ \mathrm{torr})$. Here we selected a nominal vacuum of 0.0266 Pa $(2 \times 10^{-4}\ \mathrm{torr})$. This value is readily attainable with conventional vacuum pumps.

To the extent that the current is purely dc, there will be no resistive loss in the cable. However, because the voltage is fixed, changes in power level lead to equivalent changes in current. In addition, the systems used to convert ac to dc produce some current variations. These currents are usually at frequencies that are multiples of 60 Hz; modern power converters often introduce currents at other frequencies. Filters can be used to reduce the magnitude of these currents.

Superconductors that are subjected to varying currents exhibit hysteresis and therefore have losses. Rather than address filter design and the detailed loss, it was decided to set a limit of heat generation within the cable from this source at 0.5 W/m and to design the end stations to produce an integrated, allowable level of ac currents. Equation (1) shows the relation between harmonic currents I_n at frequency ω_n and the allowable power

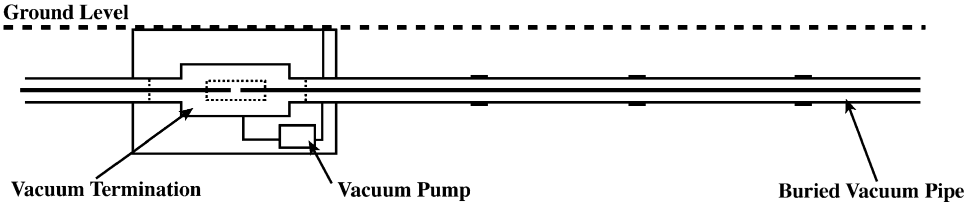

Fig. 5. View of several installed pipe sections, showing the spline collars attaching adjacent sections. The vacuum pump is installed in the splice and vacuum vault.

loss. This limit is conservative; high-frequency currents and the induced losses will be much smaller at large distances from the end stations.

$$\mathrm{P(W/m)} \cong 4 \cdot 10^{-7} \sum_{\mathrm{all\_n}} \omega_{\mathrm{n}} \cdot \mathrm{I}_{\mathrm{n}}^{2} \leq 0.5\ \mathrm{W/m} \qquad (1)$$

The total heat input into the system along the cable is expected to be less than 1 W/m. However, power leads discretely introduce heat into the cryogenic environment. Their nominal heat flow from ambient to 77 K is about 45 W/kA. Thus, two 100 kA leads at a single point of power entry will introduce 9000 W into the 77 K environment. This is equivalent to the heat leak along a 9 km length of cable. Because of this large contribution to the heat flow into the system, each set of power leads will be chosen based on the needs of the connection to the local power grid.

IV. VACUUM SYSTEM

Just as with the vacuum systems in use for ac cables, leaks in the outer pipe and the cryogenic pipes are unavoidable. It is not possible to anticipate the number of leaks in any section or the magnitude of gas that will be introduced into the vacuum by any one of the leaks. It is possible, however, to assess the frequency of leaks and the leak rates that have been observed in systems fabricated by state-of-the-art welding techniques. Vacuum system design is based on the assumption that a vacuum pump will be installed at every electrical cable joint, i.e., every km, and that some of these 1 km sections will have leaks of 0.001 $\mathrm{cm^3/s}$ of air or gaseous nitrogen. Vacuum pumps having a capacity of 50 L/s at 0.0133 Pa $(10^{-4}\ \mathrm{torr})$ have been chosen for installation at each cable splice location. The large vacuum cross section is required by the low allowable pressure drop along 500 meters of c. Redundancy has been built into the system; pumps of this capacity have sufficient capacity to maintain the annular region of the cable at a sufficient vacuum level even if each section had a leak of 0.001 $\mathrm{cm^3/s}$ and if only every other pump was operational.

It is the expectation of the design group that there will be only a few leaks and that, after a vacuum has been established, only a few pumps will be needed for normal operation. Getters will be installed approximately every 20 m along the pipe to assist in maintaining a good vacuum by removing gases desorbed from the various materials in the vacuum space.

V. CRYOGENICS

Because the maximum current will produce a peak magnetic field of about 0.7 T, the cable is expected to operate below 77 K. The operating temperature has not been selected, but use of pressurized nitrogen at 67 K will minimize the formation of bubbles and avoid two-phase flow in the cryogenic pipes, and the lower temperature will reduce superconductor requirements by a factor of 2.

The assumption is that heat inflow into the cryogenic system amounts to about 1 W/m. If the liquid nitrogen is allowed to warm up 1 K between refrigeration stations, there is a tradeoff between nitrogen flow and refrigerator separation. The specific heat of liquid nitrogen is 1.7 kJ/liter/K. Thus, a 10 km length of cable with 1 W/m heat input must have a flow of at least 7 L/s. Because there are friction losses associated with moving the cryogenic fluid through the pipes, the total refrigeration requirements must be about 30% larger. The pressure drop in liquid nitrogen in a 10 km section of cable will be about 300 kPa (3 atm), and the velocity of the flowing liquid in a 7 cm diameter pipe will be about 3 m/s. The initial pressures of the liquid when it leaves a refrigeration station has not been determined. Nominally this pressure will be about 1 MPa (10 atm) but will likely depend on the terrain because a 11 m change in altitude will result in a pressure change of 10 kPa (1 atm).

VI. END STATIONS, CONVERTERS, AND GRID INTERACTIONS

EPRI is supporting a separate study to explore in detail the relationship between the superconducting dc cable and the ac power grid. This effort will be presented in separate papers at the appropriate conferences. Briefly, however, voltage source converters are the only practical choice for a dc cable system with a large number of feeds and taps. The latter and the relatively low voltage, 100 kV, of the dc cable permits connections to 100 to 200 kV voltage ac systems. As a result, converters rated at 200–300 MW can be placed at substations near load centers rather in remote areas where 2000+ MW converters would be installed and connected to 500+ kV ac.

VII. FABRICATION AND INSTALLATION

Fabrication of the superconducting dc cable is based on the maximum use of existing materials. The outer steel pipe shown in Fig. 1 is typical of a pressurized natural gas pipe. Long lengths of steel plate (or sheet) will be brought into a factory and formed into pipe sections that are approximately 20 m long, as shown in Fig. 3. Each section will receive a set of fixtures for the attachment of supports for the getters, for struts that maintain the cryogenic pipes in place, and for the superinsulation. The pipe will be moved into a clean room, and the inner surface of the pipe and all fixtures will be thoroughly cleaned to remove any materials that might evaporate and contaminate the vacuum. A short spline collar that has received the same cleaning treatment will be placed on the outside of the pipe and lightly attached for shipment. A sheet of low-emissivity material will be applied to the inner surface of the pipe. The getters and struts will be installed and the cryogenic pipes, which are slightly longer than the steel pipe, will be surrounded by bats of superinsulation and will be moved into the pipe section. The supports will be attached to each end of the cryogenic pipes and the outer pipe. These struts will maintain the angular orientation and the axial position of the cryogenic pipes. Reusable plastic end caps will placed over each end of the pipe to protect the components and to maintain cleanliness during transportation to the site.

After the pipes have been delivered to the site, they will be placed end to end, and the cryogenic components will be welded together. Some bellows sections will be added to each cryogenic section to accommodate contraction during cooldown. After the cryogenic sections have been welded and leak tested, the spline collar will be drawn into place and welded onto the outside of the two steel pipes. A splice and vacuum vault will be constructed every kilometer or so (50 pipe sections), as shown in Figs. 4 and 5. These vaults will allow cable splicing and provide for installation of vacuum pumps.

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