• BNL 16747

CONF-720513--1

MASTER

To be presented at the 1972 Applied Superconductivity Meeting, Annapolis, Maryland, May 1-3, 1972.

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FACTORS INFLUENCING THE CHOICE OF SUPERCONDUCTOR IN AC POWER TRANSMISSION APPLICATIONS*

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1. Introduction

The last decade has seen both paper studies and model experiments in the laboratory on power transmission cables. Although a majority of workers studied niobium supported on rigid pipes,^{1,2} flexible cables of niobium, niobium-zirconium, and lead have been examined³ and recently conductors of niobium-tin have been proposed.⁴⁻⁶ In most of these studies the choice of conductor has been made on the basis of the hysteretic losses to be expected at the operating current. Some attention has been given to physical properties necessary for fabrication and subsequent satisfactory operation and to the cost of the materials. A recent study of superconducting power transmission cables carried out at Brookhaven National Laboratory for the National Science Foundation has shown that the choice of superconductor is profoundly influenced by overall system design decisions and the hysteretic losses are not an overriding factor.⁶ A more comprehensive list of influencing factors is shown below; the order does not indicate priority or relative importance.

5. Economics:

The overall system must be examined for capital costs and running costs.

Not all these factors have been examined in detail during the study; however, the work done clearly indicates that an optimum cable system will probably use a type II superconductor with as high a transition temperature as possible.

2. Cryogenic Design

The influence of the superconducting material on the design of the refrigerator and circulating system has been determined by investigating several cable designs using niobium or niobium-tin. Of particular interest are:

- Heat transfer and fluid flow in the transmission line.
- Optimum operating temperature range as a function of the input power to produce the refrigeration.

The steady state heat transfer and fluid flow calculations were made utilizing a computer program based on the one described in Report 10703 of the National Bureau of Standards.⁷

The conceptual lines used for this comparison are fully described in the report to the National Science Foundation.^{6,8} Two geometries most extensively studied are an interleaved ribbon configuration and a flexible coaxial cable. Magnetic losses were based on measurements at the appropriate field levels at 60 Hz. Dielectric losses were based on reported values of ϵ_r and $\tan \delta$ at cryogenic temperatures.⁹ The external heat influx was based on a Dewar design using 5 cm of multilayer super-insulation in vacuum with one helium gas-cooled (80° to 100°K) intermediate shield. The cable nominal rating was always assumed to be 3,000 MVA. The cooling system was designed to maintain the helium in the single phase, supercritical region. The effect of inlet temperature variation was studied using an interleaved ribbon design made of niobium-tin. For a two degree rise down the line, inlet temperatures of 4.2°, 6.2°, 8.2°, and 10.2°K were tried. For the coaxial cable design calculations were made using both niobium and niobium-tin superconductor. The temperature range for the niobium version was restricted to 4.4°K inlet temperature with 0.6°K rise. The niobium-tin design was evaluated for the operating regimes 6.2° to 8.2°K and 6.2° to 7.2°K.

- Cryogenics: As the only practical coolant is helium, a compromise must be made between the properties of the coolant and the superconductor in the temperature and pressure regions of interest.
- Cable design: Many geometries are possible. It may have one or many conductors per phase. These may be interleaved or shielded. The insulating dielectric may be helium, vacuum, or plastic.
- Electrical system: Network matching determines some necessary material properties of the conductor. During fault conditions when heavy overload currents are drawn satisfactory performance will be achieved by carefully balancing the design of the cryogenic system and cable geometry with the material properties.
- Material properties: This includes loss as a function of temperature and current, physical properties and transition parameters.

* Work supported by National Science Foundation.

† Operated by Associated Universities, Inc. under contract to U.S. Atomic Energy Commission.

Figure 1 Cooling Systems for Superconducting Cables (a). Below $\sim 6^\circ\text{K}$. (b) Above $\sim 6^\circ\text{K}$.

lines, above 6.2°K , were based on the simpler system, shown in Fig. 1(b). Both systems have been extensively analyzed at BNL and by other workers.¹⁰ System (a) adds a penalty to the system because the pumping losses are removed at the low temperature and the present pumps are $<50\%$ efficient. This factor has been taken into account and the pump losses added to the total refrigeration required for the 4.2° to 6.2°K systems. A summary of the calculations is given in Table I. A detailed discussion of these calculations is given in Reference 6. Two coefficients enable quick comparisons to be made. The first coefficient is the Cryogenic Performance Coefficient or CPC, defined as:

$$\text{CPC} = \frac{\text{watts of power to refrigerator}}{\text{watts of cable losses plus heat leak}} \quad (1)$$

This depends on the Carnot efficiency, performance coefficient of the refrigerator and the inefficiency introduced by the circulation system within the Dewar. This last factor is influenced by the need for circulating pumps, Joule-Thomson coefficient and specific heat of the helium at the various temperatures and pressures present in the transmission line.

TABLE I
Performance Coefficients of Conceptual
3,000 MVA Lines

Cable design	Temperature range, $^\circ\text{K}$	Conductor material	CPC W/W	TPC* W/MW-km
Interleaved ribbon	4.2- 6.2	Nb ₃ Sn	226.7	69.6
	6.2- 8.2	"	162.6	58.0
	8.2-10.2	"	126.4	55.2
	10.2-12.2	"	103.1	60.4
Flexible coaxial	4.4- 5.0	Nb	251.4	132.8
	6.2- 8.2	Nb ₃ Sn	161.2	70.2
	6.2- 7.7	"	176.8	77.0

* End effects not included. Unity power factor and 100% load factor assumed.

The second coefficient of interest is the Transmission Performance Coefficient, TPC, defined as:

$$\text{TPC} = \frac{\text{watts of input power to refrigerator/km}}{\text{MVA transmitted}} \quad (2)$$

This coefficient is a measure of the line efficiency. Fixed heat loads at either end caused by potheads can be included by using a mean power per kilometer based on total refrigerator input.

For the designs considered the improvements in extending the temperature differential to 2°K and raising the inlet temperature above 6.2°K are obvious. The best TPC is obtained for the 8.2° to 10.2°K interval and is about a factor of two better than the niobium-based cable design.

To date not all combinations of inlet and outlet temperatures and pressures have been explored. The possibilities are shown in Fig. 2, which is a pressure-temperature plot for helium showing the contours of constant Joule-Thomson (J-T) coefficient and the transposed critical line. The possible operating ranges for Nb and Nb₃Sn analyzed to date are superimposed. The temperature limits placed on a cooling system by Nb are quite restrictive. The low pressure in the line should not be allowed to drop below the critical pressure such that two phases are formed, yet if the total system pressure is raised, the J-T coefficient becomes more negative. A negative J-T coefficient increases the pumping losses of the system, thus increasing the ambient power requirements. The operating region for Nb₃Sn is not as restrictive but still has some possible problems. Operation at higher temperatures and pressures is possible without going into a region of large negative J-T

Figure 2 Locus of the Transposed Critical Line, and Contours of Constant Joule-Thomson Coefficient as a Function of Pressure and Temperature.

coefficients; however, the fault handling characteristics of the line may be jeopardized. It should be noted that the range shown on Fig. 2 crosses the transposed critical line. There is reason for concern on this point because it is possible that critical point phenomena, such as oscillations, may appear in this region. This particular area will be thoroughly investigated in future work; however, there is every reason to believe that this problem is soluble.

3. Influence of the Electrical Network

In contrast to many applications of superconductivity, the design of a power transmission cable must match the requirements of the electrical system into which it is incorporated. That is to say, the system can not necessarily be modified to match any proposed superconductor. Thus by relating properties of the superconductor to system characteristics, quantitative values can be found for these properties which must, of necessity, be possessed by the superconductor. During steady state conditions it is possible to relate the linear current density and the peak electric field intensity. During transient or fault conditions which produce abnormally high currents the heat pulse will change some of the properties of the superconductor. In some proposed designs the rise in temperature may even cause a reversion to the

normal state. As soon as the heat pulse is over it is most desirable, from the system point of view, to be capable of resuming power transmission at the rated current; this requirement defines lower limits for the transition parameters of the material.

3.1 Steady State

At any point in an electric network it is possible to define the rated, or base, values of voltage, current, impedance, and power. These quantities will be subscripted by "b." In a three-phase system the base quantities are related as follows (where applicable rms values are used):

$$P_b = \sqrt{3} E_b \cdot I_b^* \quad (3)$$

where

$$\begin{aligned} P &= \text{power in VA,} \\ E &= \text{line-to-line voltage, V,} \\ I^* &= \text{complex conjugate of line current I, A,} \\ Z_b &= \frac{E_b^2}{P_b} \end{aligned} \quad (4)$$

where

Z = impedance, ohms. A system frequency of 60 Hz will be assumed.

The voltage, current, or other parameter at any point in the system may be normalized to the base value to produce the "per unit" value. The per unit method is of great value in analyzing power systems; per unit quantities obey the normal laws of circuit analysis. For example, a current I may be normalized to I_b as follows

$$\bar{I} = \frac{I}{I_b} \quad (5)$$

The equivalent circuit of a section of circular cable is shown in Fig. 3.

Using the symbols shown it can be proved:⁶

$$\bar{Z}_L = 1.08 \frac{\sigma}{S} \text{ mile}^{-1} \quad (6)$$

$$\bar{Z}_C = \frac{2.64 \times 10^5}{\epsilon_r} \frac{\sigma}{S} \text{ mile} \quad (7)$$

$$\bar{Z}_O = \frac{534}{\sqrt{\epsilon_r}} \frac{\sigma}{S} \quad (8)$$

where

Z_O = characteristic or surge impedance of the cable,

σ = linear current, A/cm, and

values of S between 100 and 200 kV/cm are typical of those to be expected in a superconducting cable.

Figure 3 Cable Symbols and Equivalent Circuit.

S = peak electric field intensity, V/cm.

For a concentric geometry S is defined by:

$$S = \frac{\sqrt{2} E}{\sqrt{3} r_1 \log_e (r_2/r_1)} \quad (9)$$

The per unit surge impedance, $\bar{Z}_0$, is most useful in defining desirable steady state properties of the conductor. The demands of the electrical system can usually be met by a range of Z_0 lying between 0.5 and 2.0. It should be noted that conventional underground cables are usually unable to meet this requirement and generate a substantial amount of reactive power that must be absorbed elsewhere in the system.

The value of ϵ_r depends on the insulator chosen for a superconducting cable. A common choice is helium which is present as the coolant. The dielectric constant is close to unity and from this standpoint the choice is a good one, however it remains to be seen if helium will successfully withstand the voltage stress imposed in normal and abnormal service. The choice of a laminar plastic insulator may improve the breakdown performance at the expense of ϵ_r , which would then be about 2.0. Using these values, Eq. (8) is plotted in Fig. 4(a) and (b) for $\bar{Z}_0$ and σ with S as a parameter. The

Figure 4 (a) and (b). Linear Current Density vs. per Unit Surge Impedance with Dielectric Constant and Stress as Parameters.

For unity surge impedance loading, i.e., $Z_0 = 1$, we note $\sigma = 281$ A/cm and 397 A/cm for $c_r = 1.0$ and 2.0 respectively, using the median stress of 150 kV/cm. These values of σ are within the acceptable range for many materials considered for power transmission application. The power density or power per unit area of pipe is proportional to the product of σ and S , thus it is desirable to maximize the product consistent with maintaining the correct ratio, as discussed.

3.2 Fault Conditions

The type of fault which has been given the most consideration is the symmetrical short circuit, during which the current in each phase is assumed to rise immediately to ten times its initial value. Depending on the precise timing, a transient dc offset will occur in two or all phases which may double the peak current. The typical surface flux density during this condition will be of the order of 10 kG, thus if niobium is used to carry rated current it will revert to the normal condition. To minimize dissipation an alternative current path must be provided and it has been suggested that a backing layer of pure metal or high field type II superconductor may be used.¹¹ If the conductor consists solely of a high-current type II material it may be of sufficient thickness to carry faults as supercurrents. The dc component of the fault waveform would not contribute significantly to dissipation if the material is superconducting, however the dissipation in a normal conductor would increase by a factor of three in the phase with the largest offset.

On first examination a normal metal backing seems the clear economic choice, especially since a certain amount of normal conductor would be necessary for flux jump damping during steady state operation. However, an analysis of temperature and pressure rise within the cable during the fault period suggests that they will be too high to permit rated transmission to be resumed as soon as the fault is cleared. A fault period of 67 ms (4 cycles) has been used for these calculations. The conditions at the end of the fault period for a coaxial cable using niobium with aluminum backing or niobium-tin are summarized in Table II.

The temperature rise has been calculated for two assumptions as there are insufficient data available at present on heat transfer under transient conditions. The best case assumes the steady state heat transfer coefficient of 0.335 W/cm²K applies. In the worst case heat transfer to a thin shell of helium occurs by conduction only. The temperature dependent loss of the niobium-tin is as described by:

$$W = W_0 (H/H_0)^3 (1-T_0/T_c) / (1-T/T_c) \quad (10)$$

where W_0 is the loss at T_0 and H is the change of surface field. H_0 is the field which produces W_0 at T_0 and T_c is the transition temperature.

It can be seen from Table II that a dc component of the fault waveform produces large temperature rises in cables stabilized for faults by aluminum. This is true even under the best case assumption using steady state heat transfer. With no dc offset and best case heat transfer the niobium-tin line stabilized with aluminum may be marginally acceptable. However, even in this cable

TABLE II

Conditions in Cable Following a Fault

	Nb-Al backing		Nb ₃ Sn-Al backing		Thick Nb ₃ Sn	
Rated current density, σ , A/cm (rms)	320		320		320	
Duration of fault, ms	67		67		67	
Aluminum thickness, mm	2		2		0.2	
Superconductor thickness, mm	0.06		0.005		0.09	
Cable o.d., cm	5.1		5.1		5.1	
Inner cooling channel diam, cm	2.34		2.34		2.34	
Initial temperature (outlet end), °K	5.0		8.2		8.2	
Initial pressure (outlet end), atm	2.3		5.1		5.1	
Fault waveform component, $\times 10$ ac plus:						
	dc offset	no dc offset	dc offset	no dc offset	dc offset	no dc offset
Peak field during fault, kOe	11.4	5.7	11.4	5.7	11.4	5.7
Peak fault dissipation, W/cm ²	2.35	0.78	2.35	0.78	0.05	0.05
ΔT at 67 ms (best case), °K	7.0	2.3	7.0	2.3	0.16	0.16
ΔT at 67 ms (worst case), °K	62.3	20.8	62.3	20.8	1.43	1.43
ΔT at 30 s, °K	2.4	0.81	2.4	0.81	0.59	0.59
ΔP at 30 s, atm	2.5	0.84	3.0	1.0	0.07	0.07

a high pressure would remain after 30 s. This period is assumed to be long enough for equilibrium to be achieved in the inner cooling duct down the center of the cable. It is based on a calculated helium mixing time of 8.6 s. Other time constants of interest are shown in Table III. It can be seen that heat is transferred relatively slowly to the outer reservoir (main body of the Dewar), the equilibrium time for heat flow from region 1 to 7 being about half an hour. The high pressure following a fault in aluminum-backed cables will almost certainly stall the coolant flow in the inner channel, leading to loss of turbulent conditions. If rated current is applied immediately after the fault thermal run-away is very likely.

TABLE III

Thermal Characteristics of Niobium-Tin Coaxial Cable System

Region	Description	Time constant
1	Inner helium channel, 2.34 cm diameter.	Helium mixing time, 8.6 s
2	2 mm composite Al segment (includes 10 mils high-purity Al backing).	$\approx 8 \mu\text{s}$
3	Superconductor of sufficient thickness to carry times 20 fault current (about 0.009 cm thick on inner conductor).	$\approx 77 \mu\text{s}$
4	Insulation, 0.85 cm thick. Probably impregnated tape.	$\approx 31 \text{ s}$
5	Superconductor on outer conductor about 0.006 cm thick.	$\approx 28 \mu\text{s}$
6	2 mm Al composite (similar to Region 2).	$\approx 8 \mu\text{s}$
7	Outer helium reservoir shared by 15 cables	$\approx 60 \text{ s}$
1 and 7	Thermal equilibrium time constant between inner and outer helium reservoirs.	$\approx 32 \text{ min}$
8	Pumping time for full circuit.	8 to 24 h

4. Hysteretic Loss

This has been the most important property influencing the choice of material in many studies of superconducting power transmission. Its importance has been considerably over-emphasized,

leading to the choice by many workers of niobium which has very low losses when operated in the Meissner region. There is some justification for making the losses comparable to the intrinsic heat leak into the Dewar, although in most proposed designs using niobium the magnetic losses are a small fraction of the refrigerator load caused by heat influx. With the low losses to be expected from niobium, Dewar designs have evolved with very low leak rates using elaborate multishields.¹ This optimization is probably not economically justified. Conceptual designs studied at Brookhaven used a Dewar with one shield at $\approx 100^\circ\text{K}$. Even so the designs using niobium-tin material had losses which increased the refrigeration load by about five times over that due to the heat influx and other fixed losses. These losses are based on measurements on commercial niobium-tin ribbon; typical dissipation as a function of the linear current density is shown in Fig. 5. Care should be taken when comparing this curve to similar curves for niobium as the geometrical configuration of the sample and the surface treatment make comparison difficult. Despite the much higher losses of niobium-tin the overall transmission efficiency is better than for an identical cable using niobium. This is shown in Table I and is mainly due to the reduced refrigeration power necessary to maintain a line at the higher operating temperature.

Figure 5 Magnetic Loss as a Function of Current for $\frac{1}{2}$ -in.-wide Nb₃Sn Ribbons in the Form of Bifilar Coils. Measured at 60 Hz and 4.2°K.

The choice of operating loss also fixes the choice of maximum linear current density. This is because the factors are related by an equation of the form:

$$\lambda = \text{Const } (o)^n \quad (11)$$

where λ = loss per unit area and n lies between 2 and 3. For niobium-tin with losses similar to those shown in Fig. 5 operation much above 500 A/cm would require refrigerators which are too large. For niobium cables this current density is also close to the optimum as a significant increase would bring the superconductor uncomfortably close to the transition boundary.

The losses may be reduced by choosing cable geometries in which the surface field is reduced by interleaving of conductors. In addition, the construction of the conductor itself offers the possibility of lower losses. It has recently been shown that losses in niobium-tin are reduced by a concentric layer construction,¹² which may however be expensive to fabricate.

It is often suggested that use of multifilamentary composite wire of the type used for constructing pulsed magnet coils¹³ may lead to low loss cable conductors. In ac cables the benefits of these materials may be small or non-existent, however. A. R. Eastham and R. G. Rhodes¹⁴ found that the ac losses in NbZrTi composite wires were almost independent of filament size, twisting, and resistivity of the matrix. They found that transposition of the wires in small bundles (up to 19 wires) led to small decreases (up to 40%) in the losses. Their suggestion that a fully transposed cable of 6,000 wires might have a factor 100 lower losses than the equivalent solid conductor is based upon a very doubtful extrapolation to larger numbers of wires. Measurements at Brookhaven on braided (i.e. transposed wire) ribbons of composite NbTi wire yielded higher losses than Nb₃Sn ribbons in low 60 Hz fields at 4.2°K.⁴

5. Economic Factors

Several technologies are being investigated as the best way of transmitting underground power two decades from now. These are: Forced cooled, copper with paper substitute; High voltage, copper with polyethylene; High voltage, aluminum with SF₆ (spacer gas); Cryoresistive, pure metallic elements with LN₂ cooling; and Superconducting, rigid or flexible cables. Clearly the cost will be an important factor when the choice is finally made. An estimate of specific costs is shown in Fig. 6. This indicates that not all the technologies under consideration cover the same power range and that superconducting systems become competitive above 2,000 to 3,000 MVA. Naturally there are uncertainties in these estimates as new industries will have to be created to build superconducting cables and cryogenic enclosures in the quantities needed to build underground transmission systems. This uncertainty is reflected in the spread in the costs of superconducting cables. However, within this spread, cost estimates by various groups show

Figure 6 Estimated Specific Costs of Underground Cable Schemes.

remarkable agreement, regardless of the superconducting material proposed. The lower limit is taken from the Linde study in which rigid niobium pipes are proposed.^{1,16} Other comparisons with conventional and cryoresistive cables have been made: Graneau¹⁸ made an economic comparison of LN₂ aluminum (vacuum insulated) conductors with rigid niobium cables (Linde design). He concluded that superconducting cables would be less expensive above 69 kV. This conclusion has been generally endorsed at Brookhaven. Although it is possible to achieve very high currents in superconducting cables by using flux-canceling geometries the hard fact remains that superconductor costs a great deal more than insulation. Thus the highest voltage and highest stress possible must be used, consistent with practical designs of the insulation and cryogenic potheads. The optimum voltage for the first superconducting cables is probably in the range of 70 to 150 kV.

The effect of the choice of superconductor can be evaluated by considering a typical design, for example a niobium-tin 3,000 MVA cable system. The cost breakdown is shown in Table IV. A fabricated niobium-tin cost of \$160/kg has been assumed. This should be compared with the price of niobium quoted by Meyerhoff¹⁵ of \$60/kg. However, as discussed in Sections 2 and 4, this choice increases the complexity and cost of the Dewar. Thus the percentage assigned to this item is less in the Brookhaven design. The cost breakdown of a Linde cable is also shown in Table IV. This comparison is made to illustrate the economic effect of technical design decisions, note the power ratings are dissimilar. As shown in Section 3.2, the fault capacity of a niobium-copper backed cable is probably inadequate. In addition the thermal penalty of the circulating pump, reflected

in Table I, is not included in the refrigeration system for the niobium line. The reduced installation percentage of the niobium-tin line is due to the somewhat simpler Dewar and the flexible cable concept, which minimizes the number of splices. The large amount of superconductor necessary to handle faults as supercurrents increases the relative cost of this component for the niobium-tin line.

TABLE IV

Cost Breakdown of Conceptual Niobium-Tin and Niobium Lines

	Niobium system ¹⁾	Niobium-tin system ⁶⁾
Voltage, kV	138	132
Power, MVA	1690	3160
Refrig. spacing	5 miles	10 km
Envelope o.d., cm	34	42
Specific cost, \$/MVA-mi	601	600

	\$/mi	%	\$/mi	%
Cable system	147,000	14.6	500,000	26.7
Cryogen enclosure, terminals, etc.	300,000	29.5	300,000	16.0
Refrigerator	149,000	14.7	500,000	26.7
Helium	42,500	4.2	75,000	4.0
Installation	265,000	26.1	300,000	16.0
Capitalized operating expenses	111,200	10.9	200,000*	10.6

*100% load factor.

6. Conclusions

It has been shown that the choice of superconducting material must be made to optimize the performance and cost of the complete system. Probably the most important properties required are as high an operating temperature as possible and temperature differential along the line of at least two degrees. By operating above 6°K, the refrigeration costs are minimized and the cooling system becomes much more efficient. This requirement stems from the surprising result of computer runs to determine refrigeration characteristics for identical cables operating above and below 6°K. Niobium lines required about twice as much input power to the refrigerators as niobium-tin lines despite the inherently lower loss factor of niobium. Electrical network requirements can be satisfied with a maximum linear current density of about 500 A/cm. It is fortuitous that this value is precisely in the range at which acceptable losses are obtained and also provides transmission power densities competitive with other transmission technologies. The requirement that an underground cable shall be capable of immediately resuming transmission after a fault dictates the use of a type II material of sufficient thickness to prevent reversion to the normal state under any

foreseeable conditions. The losses of presently available niobium-tin are marginally acceptable and some reduction is desirable. If this can be achieved by means of layered conductor construction, metallurgical treatment or other means then niobium-tin will be superior to any other material for construction of 60 Hz power transmission cables.

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