A Techno-Economic Design Study of High-Temperature Superconducting Power Transmission Cables

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Abstract

The results of a comprehensive techno-economic design study of power transmission cables utilising High-Temperature Superconductors are presented. A cable design is described, based upon superconductors operating at liquid nitrogen temperatures. The dimensions and operating parameters of an optimized underground cable are calculated. Based on this design the manufacture, installation, losses and operating costs of an AC High-Temperature Superconducting (HTSC) Cable are estimated and compared with conventional underground cables for a new power link. Significant conclusions of the study are: for transmitted powers greater than 1 GVA the HTSC cable transmission costs become the same as for conventional cables when the superconductor critical current density exceeds 200 kA/cm^2 at liquid nitrogen temperature; the HTSC-based cable is capable of transmitting up to seven times as much power (to 700 MVA at 66 kV) as a conventional cable in a 150 mm fixed diameter duct at the same transmission cost.

1 Introduction

This paper is based on the results of a 21 month study into the techno-economic aspects of the application of High-Temperature Superconductivity (HTSC) to electrical engineering. The project was financed by the European Commission under the Joule initiative and by the major European cable makers on their own initiative. This was in response to the rapid developments in HTSC worldwide and, in particular, the significant funds now being allocated to this topic in the United States and Japan. The objective was a co-operative study between the major European cable makers in order to prevent overlap and duplication in pre-competitive research into the economic and environmental issues underlying the commercialisation of high-temperature superconductivity. Similar motives and concerns were behind the formation of a Brite-Euram project in which the same partners undertook materials investigations, process development and measurement of HTSC artifacts of relevance to cables.

The emphasis in the study was toward the high-temperature superconducting cable (some 80 % of the overall effort). The technical and economic aspects of the HTSC cable were examined in detail, resulting in the production of eleven substantial reports over the period covering various aspects of the technology or economics.

The majority of the work described above must remain confidential to the Consortium, but in order to provide a wider audience with some idea of the scope and results of the studies this paper has been prepared for general publication. In Section 1 the motivation for the development of a high-temperature superconducting cable and the superconducting materials likely to be available in the future are discussed. Section 2 outlines the proposed design of the phase conductors, the cable construction and cooling system. The scheme for calculating the various dimensions of the conductors and cable is then outlined, as are the important design assumptions. The results of the calculations are presented in Section 3 in terms of predicted cable losses, and most importantly for the development of such a cable, the first estimates of the economics of the proposed superconducting cable. These are compared with the costs of the best conventional, copper based, cables.

The final section deals with another possible application of a HTSC cable which has received some attention in the past, this is the replacement of fixed diameter-ducted low-power (to 100 MVA) links in metropolitan areas.

1.1 Background

The idea of transmitting electrical power without loss using superconducting cables dates back almost to the time of *Kamerlingh Onnes* and his discovery of zero resistance in superconductors in 1911. Until the mid-1960's the technical problems seemed insurmountable, superconducting materials were not available and cryogenic technology was not sufficiently developed. From the mid-1960's onwards serious effort was directed toward the development of the helium-cooled superconducting transmission cable [1], culminating in the construction of two prototype cable sections in the 1980's [2, 3]. Both these cables utilised superconductor based on niobium cooled with liquid helium, the operating temperature being up to 5 K.

These low-temperature superconducting cables can be considered to be a technical success, in that they demonstrated that a superconducting cable could be designed, constructed and would carry the design load. They also furnished much data, whose value may not yet be fully realised. Unfortunately these prototypes also demonstrated that, except at very high power ratings, a helium-cooled superconducting cable was not an economically viable alternative to the conventional power transmission cable. Consequently, by the mid-1980's very little experimental work was still being carried out on the application of superconductivity to power transmission [4].

The same is broadly true of superconductivity in power engineering in general, although there are some notable exceptions. Techno-economic studies on energy storage using low-temperature superconductors continued around the world throughout the 1980's, the major engineering studies though centred in Japan where work on a high-speed levitated train and Magneto-Hydro-Dynamic (MHD) drive ship both resulted in the construction of substantial prototype machines.

The discovery in 1986 of superconductors exhibiting zero resistance above 77 K changed the perception of many power engineers toward superconductivity. The dramatically simplified cryogenic requirements, increased heat capacity of materials and the reduced cost of cooling to 77 K, using liquid nitrogen, rather than 5 K, using liquid helium, made superconducting power machinery seem attractive again. A number of papers have appeared since 1988 on the conceptual design of superconducting cables (for example [5]).

The present paper extends some of those works by considering not only the technical aspects of the HTSC cable but also the requirements for the cable to be economically viable. Studies on low-temperature superconducting cable identified a "break-even" rating, above which the economic choice would be a helium-cooled cable as opposed to the conventional cable solution. This rating was estimated to be of order 5 GVA, considerably higher than any foreseen requirement. The much simplified HTSC cable should reduce this break-even rating, and values below 3 GVA would bring the cable into contention. The length of the link studied is also important, the longer links favour the superconducting cable (due to the reduced losses per km) a value of 10 km was chosen as representative for this study.

Both AC and DC transmission have been considered in this study as superconducting cables are particularly suited to DC transmission (the majority of the direct power losses are proportional to frequency). Unfortunately, unless a DC link is required for system purposes the cost of AC to DC conversion (and vice versa) makes DC transmission more expensive than AC. It is estimated that the capitalized cost of a 10 km DC cable system rated at 1 GVA is five times higher than that of a similar AC system, but over 90 % of the DC system cost arises from the capital costs and losses of the AC-DC conversion equipment. If, on the other hand, DC transmission is required (for example, to isolate two linked systems as in the UK/France DC link) the superconducting cable may become even more attractive. The cost of AC-DC conversion has decreased in recent years with the development of better high-power solid-state devices, so the DC cable may become important.

1.2 Motivation

Before contemplating the design of a HTSC cable, the possible advantages of such a cable must be examined. There are three possible advantages of a HTSC cable over a conventional power transmission cable:

- reduced energy loss,
- compact cable designs, and
- possible lower cost of power transmission.

In some cases these advantages are mutually exclusive, for example a very compact cable will always have higher energy losses than a larger diameter cable.

The vast majority of power transmission links are overhead lines, this is due to the much lower cost of the overhead line as compared to buried cables. For this reason, high-power underground cables have traditionally only been considered in built-up areas or in places where the visual impact of overhead lines is not considered acceptable. All underground cables have minimal visual impact, and in addition, the design adopted in this study results in both the electric and magnetic fields being almost wholly confined within the cable. A superconducting cable must offer either a less expensive power transmission solution or some capability that a conventional cable cannot provide.

One of the major problems to be addressed in the design of a conventional high-power underground cable is the need to remove the heat generated in the cable. This is done either by active cooling (forced flow of oil through the cable) or by conductive cooling to the surrounding soil. In the latter case, the cable phases must be separated by a sufficient distance so as to keep the overall cable temperature within acceptable limits. The natural cooling solution would be the economic choice for ratings ≤ 1 GVA; the minimum trench size for the cable (which strongly influences the cost of a conventional cable installation) is determined by the required separation between phases for cooling purposes. The force-cooled cable is more economical in trench space for a given rating, but the cable and cable accessories tend to be more expensive. The HTSC cable can be viewed as an extension of the force-cooled cable. There is essentially no thermal interaction between phases and they can be packaged as close together as their diameters will allow.

Most conventional high-power cables are rated at very high voltages (up to 450 kV) to minimize the current and consequently the resistive heating in the conductor. The superconducting phase conductor can be designed for higher currents than the conventional copper conductor, thus the working voltage can be much lower for a given power. This reduces the dielectric diameter required, significantly reducing the overall cable diameter. There is an inevitable compromise though between acceptable losses and overall cable diameter.

The diameter reduction is offset to some extent by the need for a thermal insulation barrier around the cable, but the possibility still exists to produce a very compact cable. This could be increasingly important in the future when the provision of power to metropolitan areas becomes increasingly difficult due to the high density of underground services. The possibility of re-equipping existing ducts to allow higher transmitted powers is also very attractive and is discussed in Section 4.

The energy losses of HTSC cable need also to be examined as a possible motivation for construction. These are more fully described later (Section 2.3) but in general the losses of the cable itself are very low (around 5 % of the losses of a conventional cable). Unfortunately, these are losses at liquid nitrogen temperatures and must be removed by refrigeration. The efficiency of refrigeration at this temperature is of order 10 %, so the advantage of the superconducting cable is not as straightforward as it may at first seem.

1.3 HTSC Materials

In the five years since the discovery of high-temperature superconductors a range of materials have been developed which become superconducting when cooled to 77 K in liquid nitrogen. Unfortunately, as yet the highest critical temperatures are no more than 130 K. This immediately implies that any superconducting cable one can realistically foresee at the present time will have to be cooled by liquid nitrogen. The most promising HTSC conductor at the moment contains 2223-BSCCO, $T_c = 110$ K, formed into silver sheathed tapes by a powder in tube technique.

In the "powder in tube" manufacture method, the 2223-BSCCO powder is packed into silver tubes, the composite is then drawn down to < 1 mm diameter wire. The wire is then rolled to a tape typically 2 mm wide and ≈ 100 µm thick. A lengthy process of cold working and heat treatment is then required to produce the highest current density samples. A considerable world-wide research effort is under way at present to increase the current density and simplify the production process.

The maximum current density J_c in wires containing this material has been increasing steadily over the past two years, with changes in processing techniques [6]. Critical current densities of nearly 10000 kA/cm^2 (10^8 kA/m^2) have been achieved in samples of thin film 2223-BSCCO at 77 K and very low magnetic fields ($\ll 0.2$ T). These values of J_c are all at low magnetic fields and the value of J_c falls with increasing magnetic field. The cable application is unusual in that the magnetic field will be moderate i. e. < 0.2 T. Wires carrying over 60 kA/cm^2 at 77 K are now possible in short lengths (< 10 cm) and there is no reason to believe that a limit has been reached. Researchers involved in this work are confident that $J_c > 100$ kA/cm^2 will be achieved for wires in the near future. It is also reasonable to expect that with increased experience of processing the lengths of 2223-BSCCO superconducting wire will be increased to the km scale. 2223-BSCCO tape is now being produced in lengths to 100 m with a critical current density of 10 kA/cm^2 at 77 K.

It was felt important that the assumptions made in this paper should be as justifiable as possible. For this reason it has been assumed that the HTSC material used in the cable will be 2223-BSCCO with a transition temperature of 110 K (i. e. no new higher T_c materials will become available), the proposed design of the cable assumes a $J_{c,rms}$ in the region of 100 kA/cm^2 (10^6 kA/m^2) is attained. This represents a conservative view of the potential results of the world-wide research effort into BSCCO (and other) wires. If significantly higher critical current densities are attained in long lengths a more appropriate cable design may be required.

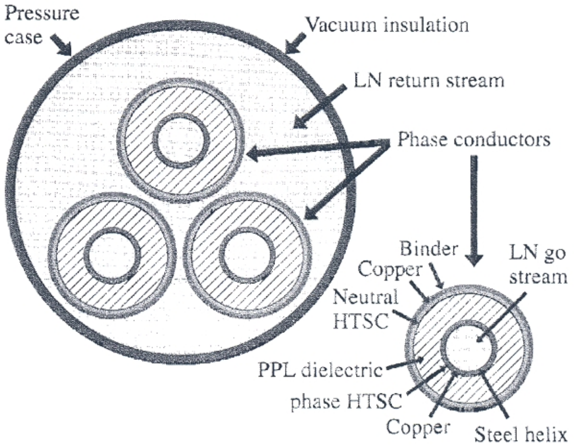
2 Cable Design

2.1 Phase Conductor Outline

The proposed cable design is similar to that discussed by a number of authors for both low- and high-temperature superconducting cables [7] and is shown in **Fig. 1.**

A steel support helix defines an internal duct carrying the liquid nitrogen coolant. Copper tapes are then wound on the helix, these perform the vital task of cryogenic stabilisation of the conductor. The superconductor tapes are then wound over the copper. The conductor screening and dielectric layers are as for conventional cables. There are then superconductor and copper return conductors, with the whole phase conductor being enclosed by a binder tape.

The cable is assembled from three such phase conductors, each phase having liquid nitrogen flowing along its inner duct. The whole cable is enclosed by a double walled steel vessel, in the space between the walls is a vacuum and a number of layers of superinsulation (an aluminium-coated plastic which greatly reduces heat transfer in cryogenic thermal insulation). The liquid nitrogen is returned in the interstitial space between the cores of the cable. Cooling is by forced convection to the liquid nitrogen. Although boiling heat transfer is more efficient than convective, the problems associated with multi-phase flow along the cable are considerable. Accordingly the liquid nitrogen pressure is always such that the liquid is sub-cooled and no boiling takes place, with the temperature and pressure varying between 70 K and 20 bar (at the entry) and 85 K, 10 bar (exit).



ET161.1A **Cable trefoil** **Cable cores**

Fig. 1. Cable construction (LN: Liquid Nitrogen; HTSC: High-Temperature Superconducter; PPL: Polypropylene/Paper Laminate)

2.2 Phase Conductor Dimensions

The scheme for calculating the various dimensions of the phase conductor is outlined in **Fig. 2**.

The duct diameter and dielectric diameter are obtained by balancing the superconductor dissipation against the cooling capability of the flowing liquid nitrogen. Although superconductors have zero DC resistance they do not have zero AC dissipation. The movement of the magnetic self field due to the AC current generates a voltage in the superconductor, which leads to a dissipation. This can be estimated using the Critical State model [8].

The copper tape layers are present to by-pass current around any low J_c areas of the superconductor (caused either by local mechanical damage or heating) and to provide a larger thermal mass to reduce temperature rise during a current overload. The current overload considered is double the design working current for a period of 1 s; the cable is designed to be capable of carrying full load immediately after the overload. This assumed overload current may require the development of a superconducting fault-current limiter.

Following Fig. 2, the working current can be calculated from the power and voltage. The voltage determines the thickness of dielectric required. In this study, Polypropylene/Paper Laminate (PPL) tape dielectric was assumed. The properties at reduced temperature are well known and the windings can more easily accommodate differential contraction during the cool down of the cable.

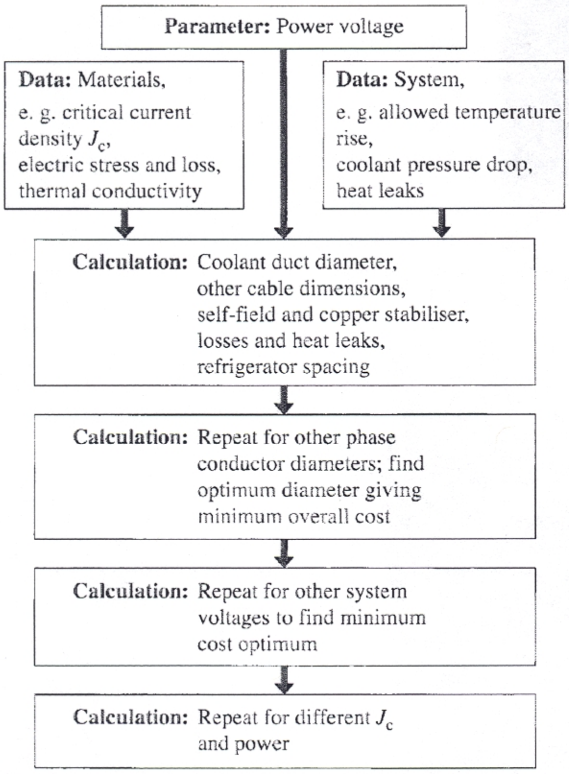


Fig. 2. Schematic diagram of calculation for minimum cost cable

Cable component	Outside diameter in mm	Thickness in mm
Duct	24.8	–
Steel Support	28.8	2.0
Copper	30.8	1.0
HTSC phase conductor	30.9	0.1
Screen 1	31.9	0.5
Dielectric	57.3	12.7
Screen 2	58.3	0.5
HTSC neutral conductor	58.4	0.05
Copper	59.4	0.5
Cable core:	**60.0**	–
Three core assembly	128	–
Metallic tube	154	3
Thermal insulation	182	14
Outer Tube	192	5
Cable Diameter:	**192**	–

Tab. 1. 1 GVA optimum cable dimensions (voltage: 220 kV; current (rms value): 2.625 kA)

An example of the installed cable dimensions are shown in **Tab. 1** for the minimum cost 1 GVA, 220 kV cable. This calculation assumes a critical current density at nitrogen temperature of $2 \cdot 10^6$ kA/m^2. Note that the actual thickness of the HTSC layer is only 0.1 mm to carry the rated current (rms value) of 2 625 A, and as such contributes very little to the overall dimensions of the cable cores. The HTSC material does contribute significantly to the cost of the cable though.

2.3 HTSC Cable: Sources of Loss

The losses of the HTSC power cable arise from:

- *Superconductor Losses* (sometimes referred to as 'hysteresis losses'). They are generated in both superconductor layers, although the losses in the neutral conductor are much lower. For the optimum cable design these losses become very small at the higher values of J_c ($> 3 \cdot 10^6$ kA/m^2).
- *Dielectric Losses* – these are calculated from the standard equation [9].
- *Thermal Losses* – due to heat leak from ambient temperature through the thermal insulation barrier of the cable. Vacuum insulated pipeline is already manufactured by a number of companies as cryogen transfer pipeline. The heat-leak values in this study were obtained from extrapolation of manufacturers data.
- *Pumping Losses* – calculated from the pressure drop and velocity of the liquid.
- *Joint Losses* – at the junction between cable sections, it will probably prove difficult to produce superconducting joints *in situ*, consequently there will be local generation of heat.

All the above losses generate heat in the liquid nitrogen, which must be removed by the refrigeration system at 10 % efficiency as discussed earlier. There will also be a number of losses at ambient temperature, for optimum cable designs these tend to be less than the "cold" losses but, for example, losses in the reactive compensation

Source	in W/m
HTSC phase conductor *	0.68
Dielectric losses *	1.13
HTSC neutral conductor *	0.19
Thermal in-leak (+)	1.68
Hydraulic losses (coolant pumping) (*)	0.32
Terminations – resistive losses *	0.15
Terminations – thermal leak (+)	0.26
Various – power losses *	0.05
Various – thermal leak (+)	0.50
Total Cold	
Losses (sum of *)	2.52
Heat flow (sum of + and *)	4.96
Total room temperature losses	**55.6 W/m**

This calculation assumes a 10 km long cable with two pumping and cooling stations and does not include reactor losses which will be approximately 1 % of the transmitted power. It is further assumed that 1 W of heat flow at liquid nitrogen temperature requires 10.7 W of power to refrigeration at ambient temperature.

Tab. 2. 1 GVA / 220 kV cable losses

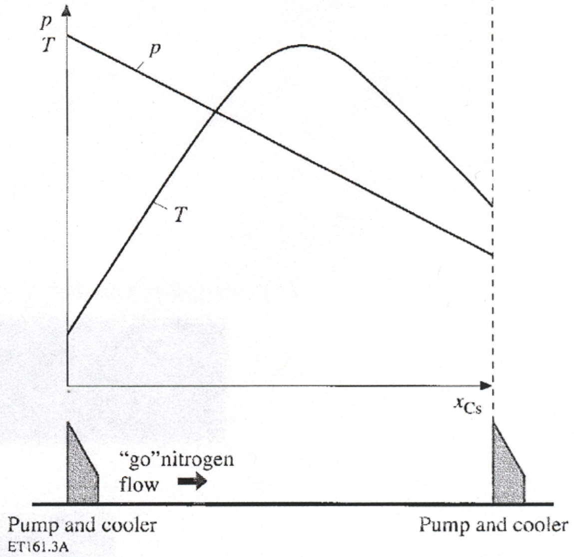


Fig. 3. Cooling system and variation along cable (p Pressure; T Temperature; x_{Cs} Cooling section)

equipment can be significant. **Tab. 2** contains the calculated losses for the 1 GVA, 220 kV example of Tab. 1.

2.4 Important Design Assumptions

In calculating the dimensions given in Tab. 1 the following important assumptions have been made:

- The cable has been designed for minimum overall cost. These costs include elements for cable materials, construction, installation, refrigeration, accessories (terminations, joints, pumps, coolers) and for capitalized losses (phase conductor losses, dielectric losses, pumping losses, thermal heat-leak losses and losses due to resistive cable joints). If, alternatively great emphasis was to be placed on energy conservation the cable losses could be significantly reduced by increasing the cable diameter and accepting greater overall costs. The design could also be optimized for minimum diameter but this would tend to increase the transmission costs.
- The working voltage has been adjusted from the optimum voltage for minimum cost to the nearest common system voltage (220 kV in the examples).
- The superconductor critical current density has been assumed to be in the range 10^5 kA/m^2 … 10^7 kA/m^2.
- The temperature rise in the liquid nitrogen coolant along a section of cable is assumed to be no greater then 15 K.

2.5 Cooling System

The cooling system for the cable is assumed to consist of a bulk liquid-nitrogen storage (or production storage) facility at one end of the cable with pumps and Stirling refrigerators spaced as required along the length of the cable. The proposed coolant circuit is shown schematically in **Fig. 3**; also shown in Fig. 3 is the variation in coolant temperature and pressure along one section of the cable. The liquid nitrogen requirements of the cable are considerable, 30 t/d … 100 t/d of liquid will need to be pumped each way along the cable. Calculations indicate that the liquid nitrogen will require recooling every 1 km … 10 km, depending on J_c, load and cable design. As indicated above the maximum temperature rise at any point in the cable is limited to 15 K. Due to the complex interaction between the two liquid nitrogen flows, the temperature does not linearly increase along the cable, but has a maximum at some point between the refrigerator stations. The efficiency of the cooling system is calculated for the working temperature and load, but is approximately 10 % (i. e. for every 1 W of dissipation in the cable, 10 W of power are required to remove the heat generated), this can be compared to cooling at liquid helium temperatures where the efficiency is below 1 %.

3 Results for Optimized Design

3.1 Cable Losses

In **Fig. 4** the calculated values for the overall energy losses of a HTSC cable are shown as a function of J_c and cable transmission rating. For comparison the losses of the best copper-cable solution at 1 GVA and 3 GVA are also shown. At 1 GVA the conventional solution is a three-core system, each core 2 100 mm^2 conductor cross section with natural cooling. The 3 GVA case requires a more sophisticated solution, utilising three oil-filled force-cooled cables with 2 500 mm^2 cores. Even at the lowest J_c considered the HTSC cable losses are significantly lower than those of the conventional cable.

When the superconductor J_c is greater than 10^6 kA/m^2 the losses in general cease to be a strong function of J_c and reach approximately 25 % of the copper cable losses for the 3 GVA cable (50 % for the 1 GVA). For the lower J_c the losses are dominated by superconductor hysteresis losses. These become negligible at the higher J_c though, when the thermal in-leak

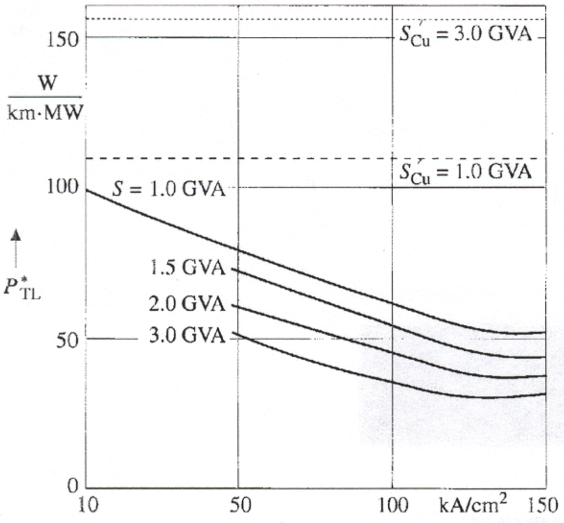


Fig. 4. Variation of transmission losses P^*_{TL} with critical current density J_c for some power-transmission ratings S

losses dominate. It is interesting to note that the superconductor losses can be reduced to any desired value simply by increasing the diameter of the conductor, this reduces the magnetic field strength H, producing a dramatic reduction in losses. Doubling the diameter of the conductor has the same effect on hysteresis losses as using a superconductor with a J_c increased by a factor of eight. This will of course increase the overall diameter of the cable. The effect on losses of increasing the phase conductor diameter is illustrated in **Fig. 5** for a number of cable ratings; there is a strong reduction initially when the superconductor losses dominate. As the diameter is further increased, other losses become more important until finally heat in-leak becomes the dominant loss and increases with cable diameter.

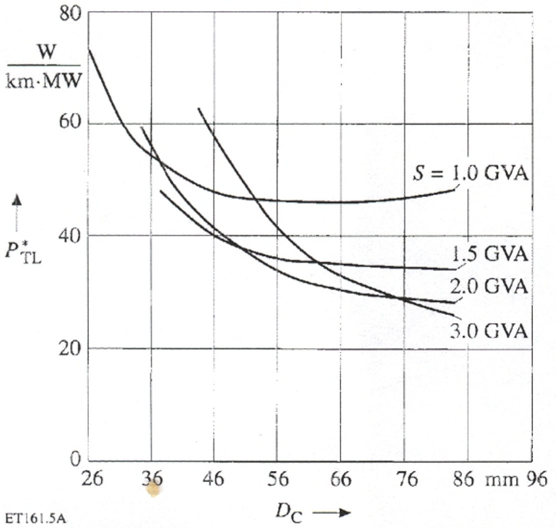


Fig. 5. Variation in transmission losses P^*_{TL} with phase conductor diameter D_C (J_c = 200 kA/cm²) for some power-transmission ratings S

3.2 Economics

The calculation of the costs of a superconducting cable are of necessity very imprecise at this stage in the development. This problem is approached by estimating the cost of the various elements that make up an installed cable i. e.:

- the cable itself,
- the cable accessories,
- the cooling system,
- cable installation,
- capitalized cable losses.

The most basic unknown at present is the cost of the superconductor itself. The cost used in these calculations has been based on an estimate of material, processing and testing costs. The cable accessories have been assumed to be of equivalent complexity to 400 kV oil-filled conventional cables, which represent the most costly cable accessories presently in general use. The thermal insulation costs have been estimated from manufacturers data.

Fig. 6 shows the overall transmission cost of a HTSC cable as a function of J_c. The data for conventional cables is also shown. It is interesting to note that the 1 GVA and 3 GVA superconducting cables both become the economic choice when the superconductor critical current density exceeds $2 \cdot 10^6$ kA/m² (rms value). Furthermore, there is a diminishing return (in economic terms) for increased J_c in the 1 GVA cable over $4 \cdot 10^6$ kA/m², the cable lifetime costs are then dominated by factors other than the losses and the superconductor specific costs.

The effect of increasing the phase conductor (and hence the overall cable) diameter in reducing the losses of the system were discussed above. **Fig. 7** illustrates that an optimum conductor diameter can be found, which represents the most economic cable design.

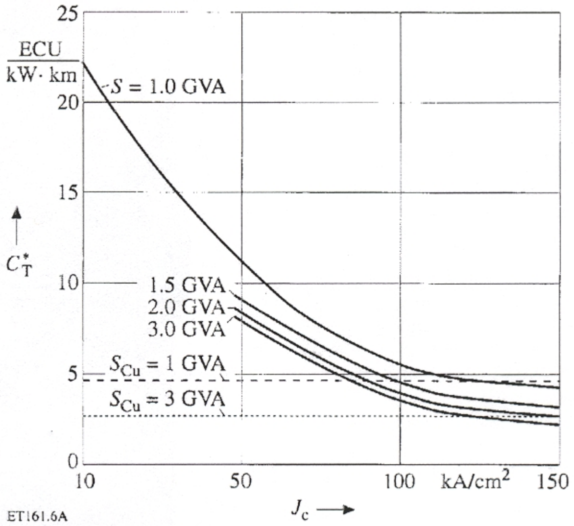


Fig. 6. Variation of transmission costs C^*_T with critical current density J_c for some power-transmission ratings S

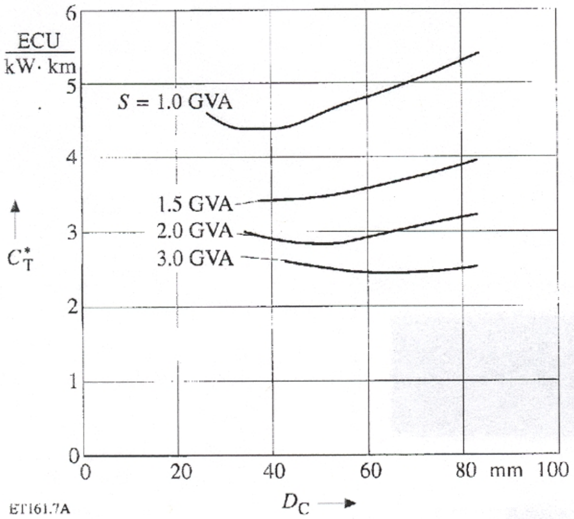


Fig. 7. Variation in transmission costs C_T with conductor diameter D_C ($J_c = 200$ kA/cm^2) for some cable ratings S

4 Results for Re-Equipping Existing Ducts

The stimulus for this cable design is the knowledge that power requirements in urban areas are increasing, whilst at the same time the space available for underground services is becoming increasingly restricted. It is likely that in the future a number of utilities will require to increase the capacity of underground circuits in urban areas, and this can be achieved in a number of ways:

- provide new circuits in new ducts,
- uprate the circuits in existing ducts using conventional "copper" cables, or
- uprate the circuits in existing ducts using high-temperature superconducting cables.

In this section of the paper the economics of these three possibilities are examined. The aim is to maximize the transmitted power and minimize costs and losses at 38 kV/66 kV within the constraints of existing 150 mm cable ducts. The same design and calculation procedure was followed as for the high power HTSC cables.

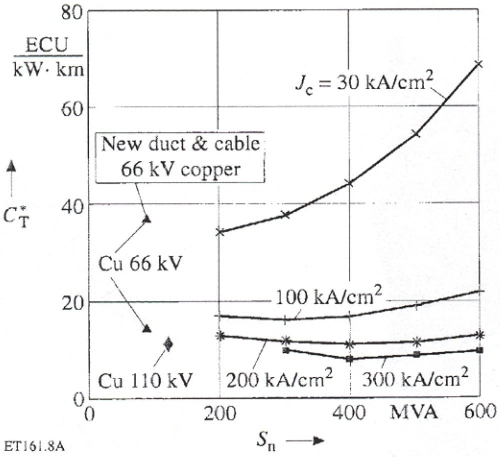


Fig. 8. Variation in transmission costs C_T^* with nominal power S_n for cable; HTSC cable replaced in 150 mm duct at various J_c

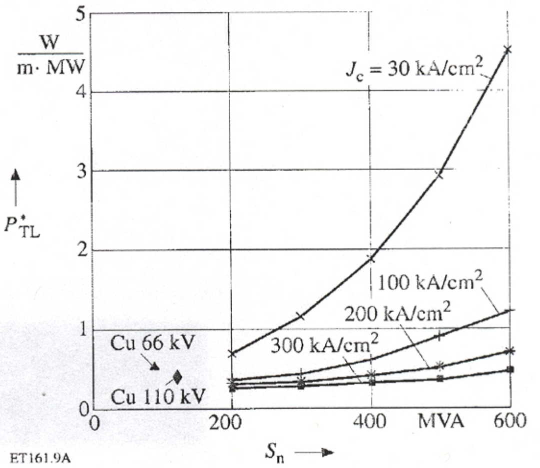


Fig. 9. Variation in transmission losses P_{TL}^* with nominal power S_n for HTSC cable replaced in 150 mm duct at various J_c

The results of these calculations, for transmission costs and losses, are shown in **Fig. 8** and **9**. From Fig. 8 it is apparent that three-core cable with diameters up to 130 mm may be designed for an operating voltage of 66 kV with transmissible powers up to 500 MVA for $J_c > 10^6$ kA/m^2. The costs of this cable show a minimum around a nominal power of 400 MVA with losses comparable to the conventional cable rated at 100 MVA (Fig. 8 and 9). This implies that a system could be uprated to 400 MVA, using HTSC, and occupy the same ducts as would be required by a 100 MVA conventional system with comparable transmission costs and losses. Also shown in Fig. 8 are the transmission costs for the maximum rated conventional cable in a 150 mm duct for three cases:

- re-equipped duct with the latest technology 66 kV cable,
- re-equipped duct with the latest technology 110 kV cable (this will incur other system costs e. g. transformers), and
- completely new installation of a 66 kV cable (assuming it is possible to install a new 150 mm duct).

A comparison of HTSC and conventional cables of the same rating shows that the specific cable losses of a HTSC-based cable (W per MVA per km) are a factor of three to five lower for J_c in the range (rms values) $1 \cdot 10^6$ kA/m$^2 \ldots 2.5 \cdot 10^6$ kA/m^2 with substantial cost savings.

On comparing different types of cable to transmit the same power in a 150 mm duct, the HTSC solution appears to be not only capable of a substantially higher range of power (up to 700 MVA) but also to be competitive in terms of costs and losses.

5 Conclusions

The most important conclusions from this period of work relate to the economics of the high-power cable.

The cost of the HTSC cable has been calculated including:

- capital cost of cable,
- capital cost of cooling system,
- cost of installation, and
- capitalized cost of transmission losses.

Based on these calculations it is concluded that:

- The critical current density for the HTSC high power link (greater than 1 GVA) to become economic ("break-even J_c") is $\approx 2 \cdot 10^6$ kA/m^2 (rms value) at liquid nitrogen temperatures.
- With $J_c > 2 \cdot 10^6$ kA/m^2, the total energy losses of the most economic HTSC cable are significantly lower than those of the conventional cable.
- Energy losses can be reduced still further by optimizing the cable design, although transmission costs then increase.
- The break-even J_c of the high-power link is sensitive to superconductor costs and installation costs.
- Increasing the link length or power makes the HTSC solution increasingly attractive.
- The HTSC solution allows a four fold increase in power transmission in an existing (150 mm) diameter over the conventional 100 MVA solution, at the same transmission costs (assuming $J_c \geq 200$ kA/cm^2).

The most important conclusion must be that it is possible for a HTSC power transmission cable to be economic at useful levels of transmitted power e. g 1 GVA with moderate J_c. As described in Section 1.1, previous work with low-temperature superconductors proved the technical feasibility of the superconducting cable given the availability of conductor. Effort must now be directed toward developing the HTSC wire to the required level; this effort is now underpinned by the knowledge that the HTSC, unlike the low T_c cable, has the prospect of becoming a useful and saleable product.

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