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SUPERCONDUCTING POWER TRANSMISSION BY LOW VOLTAGE CABLE

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ABSTRACT

The concept of multiple paralld circuits carrying power at low voltage (below 20 kv) is considered. An illustrative design is worked out for a 5000 MW line at ± 13 kv and for a 500 MW line at ± 1300 volts. It is shown that superconducting transmission is most efficient (in the sense of making the best use of conductor material) at low voltages, which is just opposite to the situation for non-superconductors. The 5000 MW line consists of over 1000 conductors in parallel. Each conductor carries 360 amps at ± 13 kv, dc, and consists of a superconducting (Nb_3Sn) core of diameter 0.096 mm, surrounded by normal metal (Al) cladding to a diameter of 0.70 mm, with insulation to an outside diameter of 7.0 mm. Alternatively, with the same number of conductors one can have a 500 MW line at ± 1300 volts dc, and a conductor outside diameter of only 1.4 mm. The superconductor design current density is $5 \times 10^6 \text{ A/cm}^2$ at 15 koe. The design voltage stress on the insulation is 16 kv/mm for the 5000 MW line and 8 kv/mm for the 500 MW line. Only 69 kg of Nb_3Sn is required per km of cable in either case. The examples are dc, but the general concept applies to ac superconducting transmission also. It is argued that a low voltage superconducting cable could be economically interesting, even for dc.

The transmission of electrical energy is a large-scale industry and is growing steadily larger. Some 15 to 25% of the total plant investment of the electric power industry in the United States is in transmission equipment. Thus, an economic justification exists for exploration of new approaches to power transmission.

The great bulk of transmission is via the familiar overhead line, which is efficiently cooled by air convection. A small amount (1% or less) is by underground cable. A cable is typically much more expensive (20 times) than an overhead line of equivalent capacity. Nevertheless, interest in cable transmission and expenditure on large capacity cables is currently very high. In cities cables are becoming more and more essential. Large generating stations must be sited where cooling water is available and (especially for nuclear plants) not in the midst of population centers. Load densities in cities continue to increase, as does popular opposition to overhead lines.

Both ac and dc EHV transmission cables are in use today, ac being the preponderant type.⁽¹⁾ Transmission by ac cable has, of course, the great advantage of compatibility with existing transmission lines and distribution systems. Otherwise, it is not very satisfactory. There are two major problems.

The first of these, which limits the length of ac cables, is that the cable looks like a capacitor to the generator, and the longer the cable, the bigger its capacitance. Each half-cycle, this capacitor must be charged and discharged. A charging current must be provided by the generator, and this charging current cannot be delivered to the load.

For cable lengths greater than 20 to 40 miles, the capacitive charging current exceeds the load current.

The second problem is heating. The heat is generated by ohmic loss in the conductor and by dielectric loss in the insulation and the surrounding earth. There can also be eddy-current heating in nearby metallic objects, such as the pipe containing the cable. Conduction of heat through dielectric and earth does not provide very effective cooling, and capacity is much less than it would be for an overhead line of the same conductor section. Many existing ac cables incorporate oil and water cooling systems to help remove the heat.

Most of the dc cables now in use are underwater intersystem ties.⁽²⁾ Direct current is particularly suitable for intersystem ties because synchronization and stability problems are eliminated. As an extreme example of this, systems of different frequency can be tied together, as with the Honshu intersystem tie (Japan).

High-voltage dc cables for transporting bulk power into centers of dense load are beginning to appear. One such line (± 226 kv, 86 km, 640 MW) for bringing power into London is now being built.⁽³⁾

More dc cable links will probably be built since two of the disadvantages of ac cables, the charging current length limitation and the heating from dielectric loss, are avoided completely with dc. The current limitation is set by Joule heating and the length limitation by voltage drop along the conductor; these limitations are much less stringent. Also, insulation requirements are eased in dc transmission.

Because of these considerations, the installed cost of a particular

cable to handle 500 MW at 250 kv dc is projected to be less than half of the cost of a 275-kv ac cable of the same capacity.⁽⁴⁾ Any cost comparison of dc and ac transmission systems is, of course, dependent on line length, both because of the conversion terminals needed at the ends of a dc line, and also because of the charging current problem in ac cables, which gets worse as the cables get longer. The crossover point is usually quoted as 20 to 30 miles.

The Kingsnorth scheme for bringing dc power into London⁽³⁾ is 81 km long, with a tap at 59 km. An important aspect of the economics here is that the line runs direct from generating station to load center.

The requirement for underground transmission into load centers is for high capacity links, consequently cables now in use operate at high voltages. A number of 275 kv ac cables have been placed in service in England since 1964. All are short, the longest being 20 miles. A number of 400 kv ac cables are to be installed in England, in order to increase capacity even more, and to connect with the national 400 kv grid. A typical installation⁽⁵⁾ is designed for 4400 MVA at 400 kv, using two double circuits each of six 250 mm² copper conductors. About 3.4 MW is dissipated in a two mile length of cable, which in this case is cooled by flowing sea water. A summary⁽⁶⁾ of cables in use in the Western hemisphere at 69 kv and above lists over 2000 circuit miles, but no individual cable over 15 miles. The great majority are under 5 miles. The largest capacity and highest voltage is a 345 kv, 500 MW cable under New York. Higher capacity transmission cables of conventional type will require even higher voltage levels.

Present trends in the growth of power station sizes and load center requirements indicate that it is realistic to plan for cables in the 1000 to 10 000 MW range. Generating plants with capacities over 2000 MW are being built today; future ones will be considerably larger. Average station size in the 1980's has been estimated by one author at 4000 MW.⁽⁷⁾ Load center requirements are already very large in major cities (40,000 MW for London and 10,000 MW for Tokyo in 1969) and seem to be growing at about 10% per year. Intersystem ties also require capacities in the 1000 to 10 000 MW range, according to the criterion that the capacity of the tie should be a substantial fraction of the capacity of the smaller system.

Economics of large schemes are always uncertain until after completion, sometimes even then. High capacity cable transmission is expensive, but there is no alternative. The Kingsnorth scheme ($\pm$ 226 kv, 640 MW, dc) is supposed to cost \$110 million⁽³⁾ (\$1600 per meter!). A paper on the economics of high power cable circuits⁽⁸⁾ gives (depending on copper prices), \$1.2 million per double circuit mile (\$770/meter) for 400 kv, ac, 1100 MVA cable. Barnes et al in the discussion following their paper⁽⁴⁾ quote costs more than double this for 400 kv cable of twice the capacity. Neither of the 400 kv estimates include right-of-way and overhead. The cost of manufacturing and laying the cable comes to about 60-70% of the total, the remainder being civil works, cooling installations, and joints.

It is apparent that the cost of conventional cable transmission is large enough to encourage the examination of alternative concepts, such as superconducting cables.

II. SUPERCONDUCTING POWER TRANSMISSION

A. Background and General Considerations

Superconducting power transmission has been discussed by many authors⁽⁹⁻²¹⁾. Perhaps the earliest proposal is that of Mc Fee⁽⁹⁾. A most ambitious project was outlined by Garwin and Matisoo⁽¹⁰⁾. A summary of superconducting and cryogenic transmission has been given by Minnich and Fox⁽²¹⁾. The most detailed engineering design has been done by the English group⁽¹⁵⁻¹⁸⁾. A very encouraging recent development has been the demonstration of what appears to be a suitable material for an ac cable⁽¹⁹⁾. Although superconducting transmission still is under active discussion⁽²⁰⁾ little or no attention has been given to the fact that the properties of superconductors encourage the use of low voltages in transmission. This is implicit in Klaudy's paper⁽¹²⁾ but has apparently not been considered by subsequent authors.

The characteristic of superconductors that comes immediately to mind in connection with transmission of power is the complete absence of resistance (at least for direct current). Loss-free transmission appeals to the Utopian instinct. Without doubt, zero loss is a substantial advantage, as is also zero voltage drop on a long line. Since, however, capital cost is more important than losses in ordinary transmission systems, the complete elimination of ohmic loss in a superconducting line is not the crucial advantage. The essential property of superconductors for power transmission applications is not zero resistance but high current-carrying capacity.

A conventional copper or aluminum transmission link is usually

designed and operated to transmit as much power as possible. This means that the ohmic and other losses are made very nearly as large as they can be, without damaging the line. The maximum practical current densities for copper conductors are in the range 1.2 to 1.5 A/mm², and for aluminum, 0.6 to 1.0 A/mm². Superconducting Nb₃Sn, by comparison, can carry supercurrent densities in excess of 10 000 A/mm².

For power transmission then, there are two new possibilities. Either 1) transmission cables can be designed with capacities well in excess of any practical conventional cable, or 2) power in moderate or large amounts can be transmitted without the requirement of either large conductor cross sections or high voltages.

The first of these possibilities (a line with very large transmission capacity) is illustrated by the superconducting line proposed by Garwin and Matisoo. They proposed a 1000-km line carrying direct current at 200 kv, and having a power transmission capacity of 100 000 MW. This capacity is much greater (25 times) than any existing transmission lines; it is approximately half the present power generating capacity of the United States. The high capacity is made possible by the high critical current density and the long length by the zero resistance property of the superconducting material.

Although the Garwin-Matisoo proposal appears technically sound, the transmission line they describe will probably not be built in the foreseeable future. An enormous initial investment is required, and the need for a 100 000 MW link is not obvious right now.

This leads to the second possibility--transmission at low or

moderate voltage. Reasonably high capacity is still possible. The outline design in this paper is for a transmission cable of moderate length (10 to 100 km), carrying 5000 MW at ± 13 kv dc. The line is intended for use within or between metropolitan areas.

B. Properties of the Materials

The properties of superconductors lead naturally to low voltage transmission. Consider the dc properties of Nb_3Sn (Fig. 1). The material can carry direct current with zero resistance if temperature, magnetic field, and current are all below their critical values.

Alternating current is not carried without loss. If this were not so, ac power transmission links would probably be under construction already. It is not the loss of power from the line that matters, but the additional load on the refrigeration system. The loss mechanisms are structure sensitive, leading to hope that with better understanding they can be eliminated or inactivated. The work of Meyerhoff and coworkers at Linde⁽¹⁹⁾ in producing electroplated niobium which reportedly carries up to 10^5 amp/cm² with power dissipation of only 1.0×10^{-9} I³ watts/km, at 60 hz, is extremely encouraging. It may thus be possible in the future to use superconductors for ac transmission. For the moment, we will consider only dc transmission where the materials properties are better known. The advantages of low voltage operation apply to ac transmission also.

A good superconducting material with well-known properties is Nb_3Sn . The critical current of Nb_3Sn at zero magnetic field and 4.2°K is in the vicinity of 10^7 A/cm² for the best specimens, and it is dependent

on the method of making the material. Like the strength of steel, the superconducting critical current density is not a fundamental limit, and will likely increase, perhaps by an order of magnitude, as a result of future research. For design purposes, a critical current density lower than the maximum, by several orders of magnitude, must be used when the superconductor is in a high magnetic field environment. Furthermore, it is customary to surround the superconductor with a substantial amount of copper or aluminum for stabilization.

By using a multiple conductor configuration the magnetic field in which the superconductor must operate can, in our conceptual design, be kept to a reasonably low value. The design operating point (Fig. 1 (b)) is $J=5 \times 10^6$ amp/cm²; $H=15$ koe.

C. Conductor Diameter and Low Voltage Operation

When a conventional transmission line is constructed and in place, it is characterized by a certain resistance. A superconducting line, on the other hand is characterized by a certain critical current. An important consequence of this distinction is that the incentive for going to extremely high transmission voltages is much reduced. The superconducting material is more efficiently utilized at low voltage.

In the conventional line, $P_{\max}$, the maximum power that can be generated in the conductor by ohmic heating and safely dissipated without damaging the line, and R , the line resistance (both per unit length), determine $I_{\max}$, the maximum allowable current that can be put through the line:

$$P_{\max} = (I_{\max})^2 R .$$

The value of $I_{\max}$ depends, of course, on the conductor radius r , and $P_{\max}$ depends on the surface area of the conductor. Since $P_{\max}$ is per unit length, it is proportional to r . On the other hand, the resistance r is proportional to $1/r^2$. Thus,

$$I_{\max} \sim r^{3/2}$$

The power transported by the line is the product of $I_{\max}$ and the voltage V impressed on the line. However, V cannot be arbitrarily large. If r is small and V is too large, the electric field at the surface of the conductor will be too high and corona breakdown will result.

The electric field E at the surface of a cylindrical wire at voltage V is given by

$$E = \left[\frac{1}{r} V \right] f ,$$

where f is a slowly varying logarithmic factor containing r and the distances to other conductors in the vicinity. There is a limit to E , call it $E_{\max}$, which is the breakdown field of air, vacuum, plastic, or whatever is surrounding the wire. Thus, there is a maximum permissible voltage

$$V_{\max} \sim r .$$

Consequently, conductors of very small radius are not suitable for high voltage. Since they are not suitable for high currents either, it follows that conventional conductors for transmitting high power must be large.

This is not true, however, for superconductors, where $P_{\max}$ and R

are not applicable. For a superconductor the only material properties that matter are the coordinates - call them J^* , H^* , - of the operating point below the critical current curve of the superconducting material --point x in Fig. 1(b). The coordinates of the operating point determine the conductor radius r . Thus, since H has its highest value at the conductor surface,

$$\int H \cdot ds = I$$

$$2 \pi r H^* = I$$

On the other hand, $I = J^* \pi r^2$, Thus,

$$2 \pi r H^* = J^* \pi r^2, \text{ and}$$

$$r = \frac{2 H^*}{J^*} \quad (\text{mks units}).$$

For $H^* = 15000$ oersted and $J^* = 5 \times 10^6$ amp/cm², r comes out to be 0.048 mm. Thus conductors of small radius are well suited for superconducting lines. In order to use the high critical currents of superconductors at low fields, the conductors must be of small radius. Since corona limitations are the same for superconductors as for normal conductors, small radius implies low voltage operation. Superconducting transmission is thus most efficient at low voltages, just the opposite of the situation for conventional transmission. In fact, since $r_{\text{max}} = 2 H^*/J^*$, and since critical current versus field plots practically always show the highest critical currents at the lowest fields, the superconducting material is used most effectively if the conductors are

made very small--as small as possible. If one thinks of the conductors as wires, then there are certainly going to be practical limits set by fabrication and handling problems. However, there are other limits. The maximum voltage permissible becomes lower and lower as the conductor dimensions drop, because of the corona limitation, and it would probably not be advisable to go below the voltage levels at which the power would ultimately be used, say 440 volts. The minimum conductor radius fixed by this limit depends a little on the insulation thickness used and a great deal on breakdown strength, $E_{\max}$. Taking 16 kv/mm for the latter, and assuming the conductor to be perfectly cylindrical and free from surface irregularities, the conductor radius calculated from $E_{\max} = V/r$ comes out to be about 0.03 mm for 440 volts. The 16 kv/mm is about the highest value for $E_{\max}$ we could reasonably take.

III. ILLUSTRATIVE DESIGN FOR A 5000 MW CABLE (DC)

This is not a summary of a completed engineering design. Rather, what follows is intended as an illustrative design, to illustrate the application of the low voltage concept to a specific transmission situation. This is to be a DC transmission cable.

To begin with, it is necessary to choose some (reasonably low) operating voltage. If the voltage is too high most of the special advantage of the superconductor is lost. If it is too low, the capacity will be small, unless the number of conductors is made unreasonably large. The voltage determines the conductor dimensions. The capacity desired then determines the number of conductors. We choose ± 13 kv as a reasonable operating voltage. The conductor dimensions are more

attractive for voltages lower than this; 26 kv is chosen mostly because it approximately matches generator voltages. If there is a system requirement for some different voltage the conductor design can be adjusted accordingly. However, higher voltages become increasingly awkward. The 5000 MW is chosen rather arbitrarily as a large but reasonable capacity likely to be needed in the next decade. The case of ± 1300 volts and 500 MW is also considered, briefly.

A. Conductors

The discussion of conductor diameter in the preceding section omitted any mention of stabilization. Stabilization, usually with copper, is well established practice in design of superconducting solenoids. In the case of a transmission line with many parallel conductors it would seem that stabilization with normal metal cladding is unnecessary. However, normal metal cladding is needed for other reasons.

The most important of these is that the operating voltage implied by a conductor diameter of 0.096 mm (derived from the operating point J^* , H^* in the preceding section) is much lower than 13 kv. To overcome the corona limitation of the small superconductor diameter, we surround the superconductor with aluminum, in the manner of Fig. 2. Thus, the radius controlling the voltage can be increased to any desired value, while the radius controlling the current remains small, because the current flows only in the superconducting core. The cost of aluminum is much less than the cost of Nb_3Sn .

The geometry of Fig. 2 is not optimal for making best use of the superconducting material. Consider, for example, a superconducting pipe

with the superconducting material on the outside of an aluminum core, rather than vice-versa, as in Fig. 2. If we pass the same current in both cases, the magnetic field present at the outer radius of the superconductor will be lower in the pipe geometry. Thus, the operating point could be shifted to higher J_c and less material used (for the same current). For simplicity, however, and various practical reasons, we proceed with the geometry of Fig. 2. One advantage of having the superconductor on the inside, is that thermal contraction in aluminum is much greater than in Nb_3Sn , so the brittle superconductor will be put in axial and radial compression.

To fix the outer diameter of the aluminum jacket we need to know not only the operating voltage (± 13 kv) but also the properties of the insulation, especially E_{max} , the breakdown field. Conventional insulation materials for power cables are oil-paper-plastic composites. They can be operated (at room temperature) at electric fields as high as 15.7 - 17.7 kv/mm (dc); 13 kv/mm (ac) according to Barnes et al.⁽⁴⁾ Recent experiments indicate that the insulation is not degraded by cryogenic temperature.⁽²²⁾ Ordinary polyethylene can be used at 9.5 kv/mm.⁽²³⁾ Without specifying the exact insulation to be used, we take 16 kv/mm for E_{max} .

Maximum electric field will occur at the inner radius of the insulation. Assuming the inner radius of the insulation (r_2) to be at 13 kv and the outer radius (r_3) to be at ground potential we can compute the insulation dimensions.

$$E = \frac{K}{r}$$

where the constant K contains dimensions. The voltage (13 kv) across the insulation is given by

$$V = \int_{r_2}^{r_3} \frac{K dr}{r} = K \ln \left(\frac{r_3}{r_2} \right); K = \frac{V}{\ln(r_3/r_2)}$$

and the maximum field strength is

$$E_{\max} = \frac{K}{r_2 \ln(r_3/r_2)}$$

We have the freedom to pick the ratio (r_3/r_2) . We choose (arbitrariness)

$(r_3/r_2) = 10$. With $E_{\max} = 16$ kv/mm and $V = 13$ kv, this leads to

$$r_2 = 0.35 \text{ mm.}$$

$$r_3 = 3.5 \text{ mm.}$$

and previously, for the radius of the superconducting core, we obtained

$$r_1 = 0.048 \text{ mm.}$$

The percentage of cross section which is aluminum is thus about 98%. Stabilization is obtained automatically. In a cable with multiple parallel paths, all superconducting, stabilization should not be necessary. It would seem that normal regions should not catastrophically propagate because current would be diverted through the other conductors.

The aluminum has another important role. Suppose a small break or crack develops in the Nb_3Sn core of one of the conductors. That conductor can continue to be used if the resistance introduced by the break is small enough so that negligible additional load is placed upon

the refrigeration system. The aluminum provides an excellent conducting path around the break and makes this possible. Assuming moderately high purity aluminum ($R_{300}/R_{4.2} = 200$) a rough calculation shows that breaks in the superconducting core amounting to as much as several mm/km in the aggregate could be tolerated. For example, we could have several hundred breaks of 10 microns each in every kilometer of conductor. The resistance introduced thereby adds less than 10% to the refrigeration load. Considering the lack of ductility of Nb_3Sn (and similar compounds) this aspect of the aluminum cladding could prove quite important.

B. General Design for the Cable

The current through a single conductor is

$$I = J^* \pi r_1^2 = 360 \text{ amperes} .$$

A cluster of six conductors wrapped about a central support wire (Fig. 3) constitutes three dc circuits of 360 amperes each, and is about 21 mm in diameter. One of the ideas in using a cluster is to place oppositely directed currents next to each other so that magnetic fields cancel. However this is not really very important in our example, because of the thickness of the insulation. At a voltage of ± 13 kv, one cluster can transmit 28 MW. For a capacity of 5000 MW 179 clusters are required, resulting in a total cross section of about 600 cm^2 if the clusters were laid in a close packed array. This cross section can be reduced by half or more, by using more aluminum and less insulation.

There is no reason the clusters have to be assembled in a close packed array. They do not have to be assembled at all, they can just be

laid in randomly. The individual conductors could be manufactured in very long lengths, cabled into clusters, and the clusters laid one atop the other in the refrigerated space. This approach reduces the problem of making reliable superconducting joints in the field, since quite a long length of individual conductor can be carried on one spool. The thermal contraction problem, at least the contraction in length of the individual conductors, is also alleviated, since the clusters can be laid snake-like in the refrigerated space, to straighten out on cooldown.

This concept of multiple conductors laid loosely in a refrigerated space has great potential flexibility. For example, clusters of different voltages can be laid together in the same trench. If the refrigerated space is made large enough to begin with, more conductors can be added from time to time as need arises. A fault in one conducting pair reduces capacity only slightly; repair can be deferred until many faults have accumulated.

C. Refrigeration

Refrigeration needs have been estimated, but the calculations will not be outlined here. They led to a heat removal requirement of 24 watts per km from the 4.2°K space and 2 kw/km from the 77°K space. Removal of heat on this scale is not a problem. Suitable refrigerators exist today. The refrigeration cost is smaller than the capitalized value of the power which would be consumed in a non-superconducting transmission line of equal capacity. The heat leak calculations are not very reliable, but the 24 watts/km is not a critical number either.

D. Fabrication, Installation and Operation

Once mastered, fabrication of the conductors is a continuous mass production operation. Cables of higher capacity will use more conductors - not bigger ones - and so conductors will not have to be custom made for each job.

Getting the trench dug and the prefabricated sections of metal pipe welded or bolted into place, and leak tested, will be an expensive and troublesome business. Once it has been completed the conductors are laid down, the covers bolted on, and cooldown can begin.

Some provision will have to be made for dividing the current equally among all the circuits, since the current flow in the superconductor is voltageless and may, therefore, be controlled by small flaws or by slight differences in contact resistance at junctions. One way to do this is to include in each circuit a small and accurately fixed series resistance of about 10^{-6} ohms. The power dissipated by these terminal resistances is modest and can be removed by air cooling rather than cryogenic fluids.

E. Economic Attractiveness

Economic analyses of novel systems, including superconducting ones, have a tendency to prove the author's point and leave the reader unimpressed. Consequently, we make only a few remarks.

A major expense, and an uncertain one, is the cost of digging the trench and fabricating and installing the pipes and chambers which go into it. However, this is a major expense for a conventional transmission cable also. It may not be too much greater for the superconducting cable

than for the non-superconducting alternative, especially since our cable should have many fewer joints. Estimates made for similar designs^(10,17) lend encouragement.

The cost of conductor material is considerably less than for a copper cable of equivalent capacity. Our design uses 69 kg of Nb_3Sn and 1100 kg of Al per km of line (64.5 and 1020 gm/km for a single conductor). At \$200/kg for the Nb_3Sn and \$5/kg for the Al [basic raw material costs are about \$60 and \$0.6] the cost for the conductors alone is about \$20,000/km. In the 4400 MW conventional cable discussed earlier^(4,5) the copper alone comes to more than ten times this.

The refrigeration cost is, as already mentioned, less than the value of the power dissipated by resistive heating in a non-superconducting cable.

There is no denying that the attractiveness of the line, from the standpoint of compatibility with today's power systems, would be greater if it were not dc. Terminal equipment to convert from dc to ac and vice-versa is not a technical problem, but may be an economic barrier. Present costs of \$20-30/kw per terminal are for high voltage equipment; equipment for 13 kv should be cheaper. Also, the low voltage makes possible the elimination of large transformers at both ends of the line.

Since the capacity can be easily divided, by simply separating conductors, the line is ideally suited for a "tree" system--as opposed to a simple point-to-point link. All circuits could originate at a large generating plant, then branch out to several load centers as the line enters the city. Of course, there are limits to the amount of branching

practical, since each branch must be refrigerated.

F. Variation: 500 MW Cable at Lower Voltage

Recently a large dc superconducting motor has been built,⁽²⁴⁾ and the construction of a superconducting dc homopolar generator has been undertaken.⁽²⁵⁾ Electrochemical industries have been mentioned as one area of application. Transit systems are also possible bulk consumers of dc power. For a homopolar generator, 13 kv may be an unreasonably high voltage, but as we have seen, lower voltages are no disadvantage for superconducting transmission. For 1300 volts dc, reasonable dimensions for the conductor are $r_1 = 0.048$ mm, $r_2 = 0.070$ mm, $r_3 = 0.700$ mm. These are obtained by relaxing the $E_{\max}$ requirement to 8 kv/mm; otherwise no aluminum at all is required to meet the corona limitation. For the same number of conductors the capacity is now 500 MW, the diameter of a cluster (transmitting 2.8 MW) is 4.2 mm and the required cross section of the cold space is reduced by a factor of 20. A 1000 MW fuel cell-coal plant, delivering power at 800 volts, has been discussed.⁽²⁶⁾ The economics of this project would certainly be improved if economical low voltage dc transmission were available.

IV SUMMARY AND CONCLUSIONS

A concept for a superconducting power transmission cable working at low voltage (below 20 kv) has been worked out and illustrated. The principal advantage in using low voltage is that most efficient use of the superconducting material is effected thereby. The concept is applicable to either ac or dc, but the illustrative design has been worked out for dc, since the material properties are better known in this case. The transmission cable consists of a large number of small conductors in parallel; the dimensions of these conductors are given for two cases: 5000 MW, ± 13 kv and 500 MW, ± 1.3 kv.

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FIGURE CAPTIONS

- Fig. 1 Superconducting properties of Nb_3Sn , partially schematized. Both curves, but especially (b), are structure sensitive. The hypothetical operating point shown in (b) is the one used in the design considered in the text ($5 \times 10^6 \text{ A/cm}^2$ at 15 k_{Oe}). The curve in (b) is taken from unpublished data (D.P. Snowden, Gulf General Atomic).
- Fig. 2 Individual conductor (not to scale). This conductor is designed for 360 amps at 13 kV; dc.
- Fig. 3 Conductor cluster (not to scale). This cluster is designed to transmit 28 MW at $\pm 13 \text{ kV}$.

XBL 703-602

Fig. 1

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Fig. 2

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Fig. 3

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