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(54) IMPROVEMENTS IN OR RELATING TO SUPERCONDUCTING CABLES

(71) We, CENTRAL ELECTRICITY GENERATING BOARD, a British Body Corporate, of Sudbury House, 15 Newgate Street, London, E.C.1, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to superconducting power cables and has for its principal object to provide an improved construction of cable for carrying large alternating current.

Present designs for superconducting cables rely on niobium layers for carrying the normal operating current. Each conductor is a tube of a highly conducting metal (copper or aluminium) coated on its inside or outside surfaces with a thin layer of niobium. These niobium layers carry the normal operating current and so screen the copper or aluminium tubes (referred to hereinafter as the normal metal tubes) from the alternating field. The criterion for the minimum diameter of any conductor of the cable is that, under normal current operation, the surface field should not exceed the lower critical field H_{c1} of the niobium. Since H_{c1} is a function of temperature, reducing to zero at 9.2°K, the operating temperature is restricted to be below about 7°K. Under fault current conditions (typically seven times the normal operating current), the niobium is driven to a normal (i.e. non-superconducting) state and, if the copper or aluminium tube itself is used to carry the fault current, the ohmic losses place an embarrassingly heavy load on the refrigeration system.

Thus the use of niobium places restrictions on the size and operating temperature of the cable. Furthermore, the niobium is of no use for carrying the fault current. An alternative approach would be to use a hard type II superconductor for carrying the normal operating current and which would also serve for carrying the fault current. The usefulness of this approach is limited by the alternating current losses in hard type II superconductors. These losses are inversely proportional to the superconductor's critical current density Jc and this prevents the use of conventional bulk type II superconductors for carrying the normal operating current.

Type II superconductors are superconductors in which the coherence length of the superconducting wave function is less than the London penetration depth. Such superconductors in bulk form allow the flux to penetrate them in the form of quantised vortices so reducing the free energy and allowing the superconducting state to persist to very high values of applied magnetic field. However, in the ideal condition, such materials are not capable of carrying any useful impressed current. The present invention is directed more particularly to a form of type II superconducting material which will permit of considerably higher current densities than is possible in present day commercially available hard type II superconductors. Such current densities reduce the heat produced during normal operation and fault conditions of a superconducting a.c. power transmission cable.

According to this invention, in a cable for carrying alternating current, superconducting material is employed formed of thin continuous layers of type II superconductor separated by layers of dielectric material or material which, at the operating temperature, is highly resistive compared with the superconducting material, each superconductor layer having a thickness between 0.01 and 0.5 microns.

As will be more fully explained later, the laminated structure would usually be put on one surface of a copper or aluminium tube to form a cable conductor. The complete cable for a single phase system may comprise two concentric tubes with the laminated structure on the outer surface of the inner tube and the inner surface of the outer tube. For a multi-phase system, several pairs of concentric tubes may be provided in one cryogenic envelope or a multiple coaxial assembly of tubes may be used.

The layers of dielectric or highly resistive material separating the superconducting layers are of a material which is not superconducting itself at the operating temperature and the layers of superconducting material are made sufficiently thin to discourage the formation of current vortices inside the layer, so long as the magnetic field is parallel to the layer. The expression "highly resistive material" is used to mean material which is highly resistive compared with the superconductor. The highly resistive material may conveniently be a metal such as for example certain forms of steel or copper-nickel alloys or brasses which have a relatively high resistance compared with, for example, high purity copper. Many other materials can be used. These materials are characterized by a short electron mean free path in order to prevent the effective thickness of the superconducting layer from increasing. With the construction described above, the thickness of each superconductor layer is less than the London penetration depth. This penetration depth is a function of temperature. The layers of superconducting material have a thickness between 0.01 and 0.5 microns and typically would have a thickness of less than 0.1 microns. Use of material thicker than 0.5 microns would not generally be practicable except where operation is strictly confined to temperatures very close to the critical temperature. The thickness of a dielectric layer may be 0.01 to 0.1 microns whilst a resistive layer may be 0.01 to 0.5 microns.

The use of a laminated superconducting material as described above increases the critical current density and it is possible, with a laminated superconducting material, to have a critical current density closely approaching the theoretical limit provided current vortices do not exist in the superconducting layer. The critical field for current vortex entry will be higher than that for the bulk material, that is H_{c1}. In forming a cable, preferably the superconducting layers are made cylindrical so that any magnetic flux in the intermediate layers of dielectric or more highly resistive material must have entered by passing through a superconducting layer.

The superconducting layers may be formed, in principle, from any type II superconductor. Conveniently niobium or niobium-based alloys or compounds with a high transition temperature are employed. For example a niobium-zirconium alloy with 25% by weight of zirconium might be used having a critical temperature T_c about 10.5°K. As previously explained, within the broadest aspect of the invention, the intermediate layers may be of any dielectric or highly resistive material and they may conveniently be formed of stainless steel. In this case the composite material may be made by suitable deformation processes such as rolling, drawing or extruding. If however the intermediate layers are formed of a dielectric material, conveniently silicon monoxide or oxide of niobium is employed. This may be deposited from a vapour phase on a substrate and a laminate can be built up with successive layers of superconductor, each layer having a deposit of silicon monoxide.

The laminated structure described above is intended primarily to carry the normal operating current. Since it has a high critical field, the laminar superconductor would remain superconducting under fault current conditions (assuming that, as in a typical transmission system, the fault current does not exceed seven times the full load operating current for a period of one second). Since the critical current density Jc is extremely high, the alternating current losses under fault conditions would be low and no current would flow in the copper backing.

However, as in a conventional type II superconductor, under fault current conditions the superconductor may be subject to magnetic instabilities which will cause currents in the normal conductor leading to excessive heating. The basic cause of the magnetic instability in present-day commercial superconductors is that the critical current density Jc decreases with increasing temperature T, that is $\frac{\delta Jc}{\delta T}$ is negative. A positive value of $\frac{\delta Jc}{\delta T}$ can be achieved in a laminated system if the layers of the type II superconductor material, which will be referred to as the A material and which has a transition temperature T_{cA}, are separated by layers of a metal B which superconducts at a lower transition temperature T_{cB} compared with the transition temperature T_{cA} of the A material. Provided the layers of the A and B materials are very thin, typically 0.05 to 1.0 microns, pinning of the flux occurs mainly at the boundaries between the layers. The critical current density Jc would then increase as the temperature is increased through T_{cB} and boundary pinning becomes more effective. The transition temperature T_{cB} is a function of the self-field of the cable current. Thus the transition of the B layers would be aided by the increase of the magnetic field under fault conditions as well as by any increase in temperature. If such composite material is operated at a temperature below T_{cB} but preferably as close as possible to T_{cB} the cable can be operated to give a positive $\frac{\delta Jc}{\delta T}$ and hence magnetic stability can be obtained under the cable operating conditions. Whilst a positive $\frac{\delta Jc}{\delta T}$ is preferred, the stability is in fact improved provided the value of $\frac{\delta Jc}{\delta T}$ for the laminate is, for the same initial current density, considerably less negative than that for the type II superconductor material A.

Thus, for carrying the fault current in an alternating current cable such as has been described above, there may be provided between the copper or aluminium and the laminated superconductor material, a further lamina structure formed of thin continuous layers of a first type II superconductor A having a transition temperature T_{cA} separated by layers of a second material B which is superconducting at a lower transition temperature T_{cB}, the layers being between 0.05 and 1.0 microns thick, and the cable being operated at a temperature just below T_{cB} at the fault current, the laminate of said first and said second material having, at the operating temperature, a rate of change of critical current density with temperature which is positive or is less negative than that of the first material at the operating temperature. Instead of using a single second material, two or more materials may be employed for different layers, these materials having different transition temperatures less than that of the first material, the laminate having, at the operating temperature, rates of change of critical current density with temperature which are positive or which are, for the same critical current density less negative than that of the first material. By optaining a spread of values of T_c for the second layers it is possible to extend the temperature and field range over which $\frac{\delta Jc}{\delta T}$ is positive.

Thus a cable may be formed of concentric tubes having, on the outer surface of a copper or aluminium inner tube and on the inner surface of a copper or aluminium outer tube, a first laminate of alternate layers of different superconducting materials as described above to have a positive $\frac{\delta Jc}{\delta T}$ and having, over each of these laminates, a further laminate of layers of a type II superconductor alternating with layers of a dielectric or highly resistive material having a high critical current density as previously described. The high critcial current density laminates carry the normal operating current and the positive $\frac{\delta Jc}{\delta T}$ laminates carry any fault current.

The laminate having a positive $\frac{\delta Jc}{\delta T}$ may be used not only in cables but more generally as a conductor, e.g. in an electromagnet and is further described and claimed in the Specification of copending Application No. 6539/72 (Serial No. 1,285,442) divided out of the present Application. In that Application, there is claimed a conductor for carrying an electric current wherein a superconducting material of laminar structure is employed formed of thin continuous layers of a first type II superconductor having a transition temperature T_{cA} separated by layers of a second material which is superconductor at a lower transition temperature T_{cB}, the conductor being operated at a temperature just below T_{cB}, said laminar structure having at the operating temperature a rate of change of critical current density with temperature which is positive or which is, for the same critical current density, less negative than that of the first material at the operating temperature, the layers being between 0.05 and 1.0 microns thick. This material wil be referred to hereinafter as the "stable" laminate conductor.

With materials at present available, this "stable" laminate conductor has a smaller critical current density than layers of pure niobium thinner than the London penetration depth and also has a smaller critical current density than the high critical current density laminate previously described and formed of layers of a type II superconductor alternating with layers of a dielectric or resistive material. As described above, therefore in the present invention, the "stable" material may be used to carry only the fault current in a cable, a coating of the high critical current density laminate being provided over the "stable" laminate to carry the normal operating current.

In a cable having the laminated superconducting material described above and formed of two or more concentric tubes, the copper or aluminium constitutes the backing for the separate conductors of the cable. These materials are good normal conductors and serve to carry the current in the event of a failure of the cryogenic envelope and so prevent damage to the cable. The copper or aluminium backing also facilitates manufacturing the cable. Most superconductors can be prepared in thin film form of controlled thickness by vacuum evaporation or sputtering and conveniently such layers are deposited on copper or aluminium tubes of the required final size obviating the necessity of mechanical working after forming a laminated structure.

The following is a description of a number of embodiments of the invention, reference being made to the accompanying drawings in which:—

Figure 1 is a transverse cross-section through a cable;

Figure 2 is a section, to a greatly enlarged scale, of part of the cable of Figure 1; and

Figure 3 is a transverse cross-section through a further construction of cable.

The drawings are not to scale since the thickness of some of the layers of material has to be greatly multiplied to be seen in the drawings.

Referring to Figures 1 and 2, a cable is illustrated formed of two concentric tubes 10, 11. The annular space 12 between the two tubes is for the cable dielectric which may be a vacuum or high pressure helium, suitable supports (not shown) being provided for locating the inner tube with respect to the outer tube. The inner tube 10 comprises a copper or aluminium backing 13 having on its outer surface a laminated material 14 which is illustrated to a greatly enlarged scale in Figure 2. Similarly, the outer tube 11 also comprises a copper or aluminium backing 15 having on its inner face a laminated material 16. The laminated structures 14 and 16 are similar. In each case, the laminated material is formed of layers of a type II superconductor 17 of about 0.1 microns thick alternating with layers 18 of a dielectric less than 0.1 microns thick. The cable is surrounded by a thermal insulation (not shown) and is cooled by a coolant which is circulated to maintain the cable at the required operating temperature.

The backing material 13 (or 15) in this construction serves for support and protective functions. In particular it serves to protect the cable against self-destruction (which would occur due to excessive heating if there were only a laminated structure 14 or 16) in the event of some failure or damage to the thermal insulation or cryogenic system while the cable is in operation. The backing material also provides the structural integrity as the laminated structure 14 or 16 is very thin. The laminated structure 14 or 16 must carry the full load current without undue losses; typically, it may be required that the loss should not exceed 10μ W/cm^2. It must also serve to carry a fault current, the magnitude of which will depend on the transmission system; a typical requirement would be that the laminated structure 14 or 16 should be able to carry a fault current equal to seven times the full load current for one second with a power loss less than 100 mW/cm^2.

The layers of the superconducting material 17 in the laminate 14 or 16 have to be thin so as to ensure a very large critical current density which is necessary to achieve a loss figure of 10μ W/cm^2. Since the laminar superconductor has a high critical field, it would remain superconducting under fault current conditions. As the critical current density Jc is extremely high, the alternating current losses under fault conditions would be low and no current would flow in the copper backing.

The hard type II superconductor in the construction of Figures 1 and 2 would typically be a niobium, a niobium alloy or compound. Preferably a material with a high transition temperature is employed.

The exact fault current specification, in conjunction with the requirement that the backing material should give protection against self-destruction, places a restriction on the minimum possible size of the conductors. This restriction is related to the thermal capacity of the backing material and to the Joule heating produced if all the current is carried by the backing material, as would occur if the cryogenic system of the cable failed in operation.

With the construction of Figures 1 and 2, there may be a limitation arising from the restriction on the possible value of the surface field under fault conditions due to magnetic instabilities (as previously explained). This problem can be overcome in the construction illustrated in Figure 3.

Referring to Figure 3, there is an inner tube 20 comprising a copper or aluminium backing 21 which is a few millimetres thick to provide structural integrity and having on its outer surface a laminated material 22 such as to have $\frac{\delta Jc}{\delta T}$ positive at the temperature of operation and the field appropriate to fault conditions. This laminated structure 22 consists of alternate layers of superconducting materials of different critical temperature and field. Outside the laminated structure 22 is a further laminate 23, similar to the laminates 14 and 16 of Figure 1, consisting of alternate layers of a hard type II superconductor and a dielectric or highly resistive material. This laminate 23 has a high critical current density Jc. The cable has an outer tube 24 formed of a copper or aluminium backing 25 with, on its inner surface, a first laminate 26 (similar to the laminate 22) having a positive $\frac{\delta Jc}{\delta T}$ and, inside the laminate 26, a further laminate 27 similar to the laminate 23 and having a high critical current density. The laminates 22 and 26 serve to carry any fault current whilst the laminates 23 and 27 serve to carry the normal operating current.

The cable of Figure 3 is formed of the inner and outer concentric tubes 20 and 24 with vacuum or helium gas employed as the dielectric. An outer cryogenic envelope (not shown) is provided to maintain the tubes at the required operating temperature.

To obtain a positive $\frac{\delta Jc}{\delta T}$ for the laminates 22 and 26, these are formed of a plurality of layers alternately of different materials, one of which is superconducting at the operating temperature whilst the other has a transition temperature just above the operating temperature. In one particular example the layers which, using the previous terminology will be referred to as the A and B layers, are formed of niobium nitride and niobium respectively, successive layers alternately of these two materials being deposited on the copper backing tube to form each conductor. Niobium nitride is a type II superconductor having a transition temperature of about 14°K and a critical current density of about 10^6 amps per square centimetre. Pure niobium has a transition temperature of 9.2°K. Niobium nitride films can be deposited by sputtering of niobium in an atmosphere of argon containing nitrogen. The B layers are of pure niobium and may be deposited by sputtering of niobium in an inert atmosphere for example argon. Thus transition from a niobium nitride to niobium film deposition can be achieved simply by changing the atmosphere.

The critical curent density for niobium nitride, as has been stated above, is about 10^6 amps per square centimetre and this may not be sufficient for both normal and fault current operation of the cable. For this reason, the further laminates 23 and 27 are provided. These laminates constitute a very high critical current density laminar superconductor making use of continuous type II superconductor film separated by layers of dielectric material may be employed. The superconductor conveniently is niobium nitride, the layers of this being separated by layers of a sputtered dielectric, e.g. silicon monoxide. Such a material forming the laminates 23 and 27 has a higher critical current density than the laminated material of layers 22 and 26 formed of niobium nitride alternating with layers of niobium. These further laminar coatings 23 and 27 can also be deposited by sputtering.

Alternatively the positive $\frac{\delta Jc}{\delta T}$ material of laminaes 22 and 26 may be formed by A layers of niobium and B layers of niobium - tantalum composition chosen to transform to normal (i.e. non-superconducting) state under cable fault conditions.

The examples just described are co-axial systems with two conductors suitable for a single phase supply. However, this technique can be extended to multi-phase systems by placing several co-axial pairs of tube inside the same cryogenic envelope or by using a multiple co-axial tube assembly. In the latter case, some of the tubes must have superconducting layers on both the inside and the outside surfaces of the tubular backing material.

WHAT WE CLAIM IS:—

1. A cable for carrying alternating current wherein superconducting material is employed formed of thin continuous layers of a type II superconductor separated by layers of dielectric material or material which, at the operating temperature, is highly resistive compared with the superconducting material, each superconductor layer having a thickness between 0.01 and 0.5 microns.

2. A cable as claimed in claim 1 wherein each superconductor layer has a thickness less than the London penetration depth at the operating temperature.

3. A cable as claimed in either of claims 1 or 2 wherein the type II superconductor is a niobium alloy and the layers of that alloy are separated by layers of a dielectric material.

4. A cable as claimed in claim 3 wherein the dielectric material is silicon monoxide or oxide of niobium.

5. A cable as claimed in any of claims

1 to 4 and for carrying a single phase alternating current comprising two concentric tubes of copper or aluminium, wherein the superconducting material is arranged on the outer surface of the inner tube and on the inner surface of the outer tube.

6. A cable as claimed in claim 5 and having, between the copper or aluminium and the laminated superconductor material, a further laminar structure formed of thin continuous layers of a first type II superconductor having a transition temperature T_{cA} separated by layers of a second material which is superconducting at a lower transition temperature T_{cB}, the conductor being operated at a temperature just below T_{cB}, said laminar structure having at the operating temperature a rate of change of critical current density with temperature which is positive or which is, for the same critical current density, less negative than that of the first material at the operating temperature, the layers being between 0.05 and 1.0 microns thick.

7. A cable as claimed in claim 6 wherein, in said further laminar structure, instead of using a single second material, two or more materials are employed for different layers, these materials all having different transition temperatures less than that of the first material whereby the range of temperature over which the rate of change of critical current density with temperatures is positive or which is, for the same critical current density, less negative than that of the first material is increased.

8. A cable as claimed in either claim 6 or claim 7 wherein said first material is niobium and wherein said second material is a niobium tantalum alloy having a lower transition temperature than the first material.

9. A cable as claimed in either claim 6 or claim 7 wherein said first material is niobium nitride and said second material is niobium.

10. A cable for carrying alternating current in which the superconductor has laminar construction to have a high critical current density and low a.c. loss substantially as hereinbefore described with reference to Figures 1 and 2 or Figure 3 of the accompanying drawings.

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1285441 COMPLETE SPECIFICATION

2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG.1.

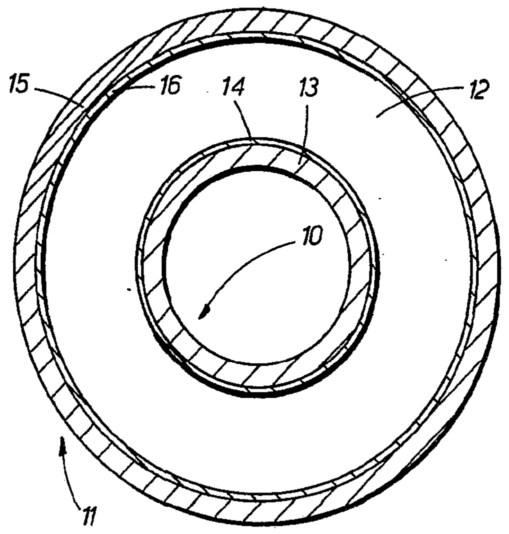

FIG.2.

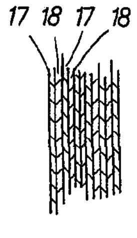

FIG.3.