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DRAWINGS ATTACHED

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(72) Inventors MALCOLM THOMAS TAYLOR and JOHN SUTTON

(54) IMPROVEMENTS IN OR RELATING TO ELECTRICAL CONDUCTORS USING SUPERCONDUCTING MATERIAL

(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 electrical conductors using superconducting material and, in particular although not exclusively to superconducting power cables.

It has for its principal object to provide an improved construction of conductor for carrying a large alternating current.

Present designs for superconducting cables rely on niobium layers for carrying the normal operating current. Each conductor is a tube of 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.

According to the present invention, in a conductor for carrying an electric current 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 superconducting at a lower transition temperature T_cB, the conductor being operated ata 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 will be referred to hereinafter as the "stable" laminate conductor. A cable may comprise two concentric tubes of copper or aluminium with a conductor as described above on the outer surface of the inner tube and on the inner surface of the outer tube.

In a conventional type II superconductor, with a backing of normal conductor material, e.g. a copper or aluminium tube, under fault conditions the superconductor may be subject to magnetic instabilities which will cause currents in the normal conductor leading to excessive heating. The threshold magnetic field for instabilities is controlled by the parameter $\frac{1}{Jc}\,\frac{Jc}{T}$ and the basic cause of the magnetic instability in present-day commercial superconductors is that the critical current density Jc decreases with increasing temperature, that is $\frac{Jc}{T}$ is negative. A positive value of $\frac{Jc}{T}$ can be achieved in a laminated system as described above in which 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 $\frac{Jc}{T}$ and hence magnetic stability can be obtained under the cable operating conditions. Whilst a positive $\frac{Jc}{T}$ is preferred, the stability is in fact improved provided the value of $\frac{1}{Jc}\,\frac{Jc}{T}$ for the laminate is considerably less negative than that for the type II superconducor material A.

Thus, for carrying the fault current in an alternating current cable, a first superconducting material A may be employed formed of thin continuous layers of a type II superconductor 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 which is, for the same critical current density 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 obtaining a spread of values of T_c for the second layers it is possible to extend the temperature and field range over which $\frac{Jc}{T}$ is positive.

The laminate having a positive $\frac{Jc}{T}$ may be used not only for carrying a fault current in cables but more generally as a conductor e.g. in an electro magnet.

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. It also has a smaller critical current density than the high critical current density laminate described and claimed in the specification of copending application No. 22102/68 (Serial No.) (out of which the present application is divided). In that application there is claimed a cable for carrying alternating current wherein superconducting material is employed formed of thin continuous layers of a type II superductor separated by layers of a dielectric 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. The "stable" material therefore may be used in a cable to carry only the fault current, a coating of niobium or of the high critical current density laminate being provided over the "stable" laminate to carry the normal operating current.

The high critical current laminated structure is used as a coating and 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 copper backing. However, as previously explained under fault current conditions, with this high critical current density laminate, as with any conventional Type II superconductor, magnetic instabilities may arise under fault current conditions and these will cause currents in the normal conductor which may lead to excessive heating. The "stable laminate" carries these fault currents and thereby gives magnetic stability.

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 $\frac{Jc}{T}$ 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 critical current density laminates carry the normal operating current and the positive $\frac{Jc}{T}$ laminates carry any fault 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 two embodiments of the invention, reference being made to the accompanying drawings in which:—

Figures 1 and 2 are each a transverse cross-section through a 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 Figure 1 a cable is illustrated formed of two concentric tubes 20, 24. The annular space 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 20 comprises a copper or aluminium backing 21 having on its outer surface a laminated structure 22, 23 to be described later. Similarly, the outer tube 24 also comprises a copper or aluminium backing 25 having on its inner face a laminated structure 26, 27 to be described later. The two laminated structures are similar. 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 21 (or 25) 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 superconduction structure 22, 23 or 26, 27, 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 is very thin. The laminated structure must carry the full load current without undue losses; typically, it may be required that the loss should not exceed $10/\mu W/cm^2$. 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 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.

Referring to Figure 1, 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 $\frac{Jc}{T}$ positive at the temperature of operation and the field appropriately 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, consisting of alternate layers of a hard type II superconductor about 0.1 microns thick and a dielectric or highly resistive material. If dielectric material is employed the layers would be 0.01 to 0.1 microns thick. A resistive layer might be 0.01 to 0.5 microns thick. This laminate 23 as described in the aforementioned application No. 22102/68 (Serial No. 1,285,441) 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 $\frac{Jc}{T}$ 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 1 is formed of the inner and outer concentric tubes 20 and 24 with vacuum or helium gas employed as the dielectric as previously described. An outer cryogenic envelope (not shown) is provided to maintain the tubes at the required operating temperature. To obtain a positive $\frac{Jc}{T}$ 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 current 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 $\frac{Jc}{T}$ material of laminates 22 and 26 may be formed by A layers of niobium and B layers of a niobium-tantalum composition chosen to transform to normal (i.e. non-superconducting) state under cable fault conditions. It is convenient in this case to carry the normay operating current by a surface layer of pure niobium between 0.5 and 30 microns thick put over the laminated structure which then serves to carry the fault current. Such a structure is illustrated in Figure 2 which shows cable with an inner tube 30 formed of a copper backing 31 a few millimetres thick having on its outer surface a laminate 32 of layers of niobium alternating with niobium-tantalum. On the outer surface of the laminate 32 is a layer of pure niobium 33 between 0.5 and 30 microns thick. The outer tube 34 has a copper backing 35 with a layer 36 the laminate on the inside of the copper backing 35 and a layer 37 of niobium between 0.5 and 30 microns thick on the inner surface of the laminate 36. The laminated structure of niobium layers alternating with layers of niobium-tantalum described above may conveniently be made by a metallurgical deformation process. For example foils of the appropriate materials may be wrapped around a copper mandrel and placed in a copper can to form a billet which is warm extruded at 500°C and then cold drawn to the required final size such that the superconducting layers are of the required thickness for example 0.05 to 1.0 microns.

The use of the high critical curent density laminar material, as in Figure 1, is preferred to the use of pure niobium, as in Figure 2, as it leads both to possible higher operating temperatures and to a reduction in cable diameter; the minimum diameter of the cable is at present restricted by the lower critical field of the niobium. However the use of a niobium layer, as in Figure 2, has advantages in other respects, notably the simpler manufacture.

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 tubes 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 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 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.

2. A conductor as claimed in claim 1 wherein, 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 temperature is positive or, for the same critical current density is less negative than that of the first material is increased.

3. A cable comprising two concentric tubes of copper or aluminium with a conductor as claimed in either of the preceding claims on the outer surface of the inner tube and on the inner surface of the outer tube.

4. A cable as claimed in claim 3 wherein the laminate of the first and second materials has an outer coating of niobium.

5. A cable as claimed in claim 3 wherein the laminate of said first and second materials has an outer coating of laminar material formed of thin continuous layers of a type II superconductor separated by layers of dielectric or resistive material.

6. A cable as claimed in any of claims 3 to 5 wherein said first material is niobium and wherein said second material is a niobium-tantalum alloy from that of the first material having a lower transition temperature than the first material.

7. A cable as claimed in any of claims 3 to 5 wherein said first material is niobium nitride and said second material is niobium.

8. 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 Figure 2 of the accompanying drawings.

BOULT, WADE & TENNANT,
Chartered Patent Agents,
112 Hatton Garden, London, EC1N 8NA.

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1 SHEET *This drawing is a reproduction of the Original on a reduced scale*

FIG.1.

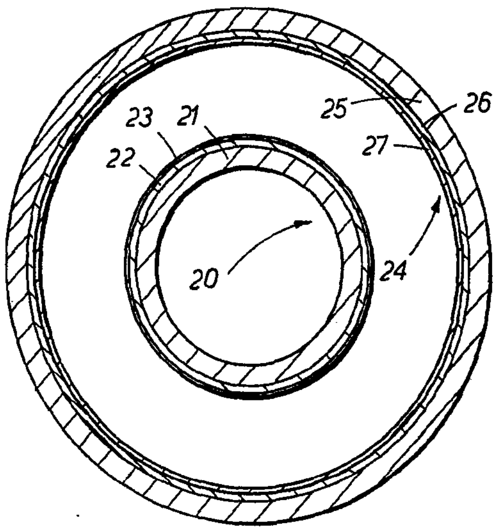

FIG.2.