A high voltage resonator comprising a cable having inner conducting means comprising an inner coil (3) with adjacent turns electrically insulated from each other, cooling means for cooling the inner coil (3), electrically insulating means (4-6) surrounding the inner coil (3), and outer conducting means (7) positioned outwardly of the insulating means, the electrically insulating means comprising an inner layer (4) of semiconducting material in electrical contact with the inner coil (3) only at spaced apart intervals along the length of the inner coil, an outer layer (5) of semiconducting material at a controlled electrical potential along its length and an intermediate layer (6) of electrically insulating material between the inner and outer layers (4 and 5). The cable may have more than on coaxially arranged inner coils.
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An Energy Storage Resonator

Technical Field

This invention relates to a high voltage (HV) resonator having a cooled coil, preferably, but not exclusively, a cooled, superconducting coil. The invention also relates to an energy storage system incorporating such a resonator for storing energy. In this specification the term "high voltage" is intended to mean in excess of 2 kV and preferably in excess of 10 kV.

Background of the Invention

It is known to form the coils of HV induction devices, such as electric machines or HV transformers, from wound electrically insulated cables. However induction devices based on cables are not suited to handling high voltages in combination with low currents. This is because the electrical insulation thickness of a cable is dependent on the cross-sectional area of the conductors. For small conductor cross-sectional areas (i.e. small currents), the electrical insulation is large and the induction device is therefore uneconomic.

Summary of the Invention

The present invention seeks to provide a resonator in the form of a cable having a cooled coil and electrical insulation.

According to one aspect of the present invention there is provided a high voltage resonator comprising a cable having inner conducting means comprising an inner coil with adjacent turns electrically insulated from each other, cooling means for cooling the inner coil, electrically insulating means surrounding the inner coil, and outer
conducting means positioned outwardly of the insulating means, the electrically insulating means comprising an inner layer of semiconducting material in electrical contact with said inner coil only at spaced apart intervals along the length of the inner coil, an outer layer of semiconducting material at a controlled electrical potential along its length and an intermediate layer of electrically insulating material between the said inner and outer layers.

In this specification the term "semiconducting material" means a material which has a considerably lower conductivity than an electric conductor but which does not have such a low conductivity that it is an electrical insulator. Suitably, but not exclusively, the semiconducting material should have a volume resistivity of from 1 to $10^5$ ohm.cm, preferably from 1 to 500 ohm.cm and most preferably from 10 to 100 ohm.cm, typically about 20 ohm.cm.

The present invention makes use of a solid insulation system, preferably based on extruded technology, which provides the capacitance of the resonator. The cable can be from several metres to several kilometres in length.

Conveniently the inner coil has first connection means comprising a first connector at one end of the inner coil and a second connector at the other end of the inner coil and the outer conducting means has second connection means.

Preferably the outer conducting means comprises an outer coil having electrically insulated turns, the outer coil being wound around, and being electrically insulated from, the outer layer of semiconducting material. In this case the second connection means comprises a third connector at one end of the outer coil and a fourth connector at the other end of the outer coil. Suitably the first and third connectors are the input of the resonator and the second and fourth connectors provide the output or termination of the
resonator. If the output connectors are not connected

together (i.e. the output impedance is infinity) then the
resonator is a half-wave resonator for a suitable length
determined by the line frequency. If the output connectors
are connected via a short circuit (i.e. the output impedance
is zero), then the resonator is a quarter-wave resonator.
Alternatively, the output connectors may be connected to
impedance means, for example a variable inductor in parallel
or in series with a variable capacitor. Alternatively,
however, the first and second connectors comprise the input
of the resonator and the third and fourth connectors provide
the output of the resonator.

The electrically insulating means is preferably of
unitary form with the layers either in close mechanical
contact or, more preferably, joined together, e.g. bonded by
extrusion. The layers are preferably formed of plastics
material having resilient or elastic properties at least
during manufacture and assembly at room temperature. This
allows the resonator to be flexed and shaped into any
desired form. By using for the layers only materials which
can be manufactured with few, if any, defects having similar
thermal properties, thermal and electric loads within the
electrically insulating means are reduced. In particular
the insulating intermediate layer and the semiconducting
inner and outer layers should have at least substantially
the same coefficients of thermal expansion (α) so that
defects caused by different thermal expansions when the
layers are subjected to heating or cooling will not arise.
Ideally the layers will be extruded together around the
inner coil.

Conveniently the electrically insulating intermediate
layer comprises solid thermoplastics material, such as low
density polyethylene (LDPE), high density polyethylene
(HDPE), polypropylene (PP), polybutylene (PB),
polymethylpentene (PMP), ethylene (ethyl) acrylate
copolymer, cross-linked materials, such as cross-linked
polyethylene (XLPE), or rubber insulation, such as ethylene
propylene rubber (EPR), ethylene-propylene-diene monomer (EPDM) or silicone rubber or biaxially aligned polymers. The semiconducting inner and outer layers may comprise similar material to the intermediate layer but with conducting particles, such as particles of carbon black or metallic particles, embedded therein. Generally it has been found that a particular insulating material, such as EPR, has similar mechanical properties when containing no, or some, carbon particles. The intermediate layer may be divided into two or more sub-layers by one or more additional intermediate layers of semiconducting material.

In use of the resonator, the electric field generated is confined between the semiconducting inner and outer layers on the inside and outside of the insulating intermediate layer. In the case of concentric semiconducting and insulating layers, the electric field is substantially radial and confined within the intermediate layer. The semiconducting outer layer is designed to act as a screen to prevent losses caused by induced voltages. Induced voltages in the outer layer could be reduced by increasing the resistance of the outer layer. The resistance can be increased by reducing the thickness of the outer layer but the thickness cannot be reduced below a certain minimum thickness. The resistance can also be increased by selecting a material for the layer having a higher resistivity. On the other hand, the resistivity of the semiconducting outer layer must not be too great else the voltage potential midway between adjacent spaced apart points at a controlled potential will become sufficiently high as to risk the occurrence of partial discharge with consequent erosion of the insulating and semiconducting layers. The semiconducting outer layer is therefore a compromise between a conductor having low resistance and high induced voltage losses but which is easily connected to a controlled potential and an insulator which has high resistance with low induced voltage losses but which needs to be connected to the controlled potential along its length. Thus the volume resistivity $\rho_s$ of the semiconducting
outer layer should be within the range $\rho_{\text{min}} < \rho_{\text{s}} < \rho_{\text{max}}$, where $\rho_{\text{min}}$ is determined by permissible power loss caused by eddy current losses and resistive losses caused by voltages induced by magnetic flux and $\rho_{\text{max}}$ is determined by the requirement for no corona or glow discharge. The semiconducting outer layer may have anisotropic resistive properties, i.e. the resistance in the azimuthal direction is very high to prevent short circuits but is considerably lower in the axial direction.

By connecting the semiconducting outer layer to a controlled similar potential along its length, e.g. at spaced apart intervals therealong, the need for an outer metal shield and protective sheath to surround the semiconducting outer layer is eliminated and the diameter of the cable from which the induction device is formed is reduced.

Preferably the inner coil is wound from elongate electrically conducting means having a surrounding electrical insulation, such as varnish. Conveniently the electrical insulation is removed at spaced apart regions along the length of the conducting means so that the latter makes electrical contact with the inner layer of semiconducting material. Typically, the inner layer of semiconducting material makes electrical contact with regions or points at opposite ends of the inner coil. Preferably, the inner layer of semiconducting material also makes electrical contact with the inner coil at one or more points or regions between the opposite end of the inner coil. Suitably the inner layer of semiconducting material makes electrical contact with the inner coil at every n turns of the coil $\pm 0.1n$ turns, where n is typically from 100 to 10,000, typically about 1000.

In most practical applications, the inner coil has superconducting properties. However, the invention is not intended to be limited to the inner coil having superconducting properties and is intended to cover any inner coil whose electrical conducting properties
significantly improve at low temperatures, e.g. at temperatures below 200 K. In the preferred case of the inner coil having superconducting properties, the electrically conducting means of the inner coil may comprise low temperature superconductors, but most preferably comprise high transition temperature superconducting (HTS) materials, for example electrically insulated HTS wires or tape helically wound, for example, on an inner support tube. A convenient HTS tape comprises, but is not limited to, silver-sheathed BSCCO-2212 or BSCCO-2223 (where the numerals indicate the number of atoms of each element in the [Bi, Pb], Sr2 Ca Cu, Ox molecule) and hereinafter such HTS tapes will be referred to as "BSCCO tape(s)". BSCCO tapes are made by encasing fine filaments of the oxide superconductor in a silver or silver oxide matrix by a powder-in-tube (PIT) draw, roll, sinter and roll process. Alternatively the tapes may be formed by a surface coating process. Other HTS tapes, such as TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface coating or surface deposition techniques. Ideally an HTS wire should have a current density beyond \( j_c - 10^5 \text{ A cm}^{-2} \) at operation temperatures from 65 K, but preferably above 77 K. The filling factor of HTS material in the matrix needs to be high so that the engineering current density \( j_e \geq 10^4 \text{ A cm}^{-2} \). \( j_c \) should not drastically decrease with applied field within the Tesla range. The helically wound HTS tape is cooled to below the critical temperature \( T_c \) of the HTS by a cooling fluid, preferably, but not limited to, liquid nitrogen which, for example, may pass through the inner support tube.

It is important that the inner coil has many turns in order to achieve high inductance. The conducting means itself is coated with an electrically insulating material to withstand potential differences of several volts, typically between 0.1 to 100 Volts, maximum 1000 Volts. In normal operation the turn to turn voltage is typically around one Volt caused by the induced flux in a magnetic core of the coil and applying an external AC source to the conducting means. The inner coil may also consist of several conductor
layers electrically insulated against each other, either connected in parallel or in series to each other.

The inner coil may be provided with a magnetic core of magnetisable material, such as particulate material, preferably a compound of iron, wire, e.g. iron based, or tape material, e.g. iron based, amorphous or nanocrystalline. Alternatively, the inner coil may have an air core or a core of other non-magnetisable materials, such as plastics materials or non-magnetisable metals or ceramics. The choice of the magnetic material depends on the application. The core may also be hollow inside to allow a cooling channel of said cooling means to run therethrough. Typically such a cooling channel, especially for cooling superconductors, would carry a cooling medium such as liquid nitrogen to cool the coil down to required superconducting temperatures.

If the core is made of magnetisable material, the core can be formed in two ways along the main axis of the inner coil. With the first possibility, since the magnetic core is at a controlled specific potential, it has to be electrically insulated against the inner coil. The potential of the inner coil at its opposite ends is defined by the voltage applied to the inner coil. The potential along the inner coil itself is given by the induced voltage caused by each turn of the inner coil around the core. Thus the voltage varies along the length of the inner coil. The magnetic core will be at equal constant potential all along the length of the inner coil. The inner coil however has a potential that depends on the induced voltage, as explained above. Thus the potential difference between the core and the inner coil will differ along the length of the inner coil. It is thus necessary to electrically insulate the core sufficiently against the inner coil so that no local discharges occur.

The second possibility for a magnetic core made of magnetisable material is to have no electrical insulation
against the core but to provide an electrically insulated inner coil. This has the advantage of saving insulation material and decreasing the total thickness of the resulting HV induction device. The magnetic core then has to be split up into overlapping "threads" or lengths which are electrically insulated against each other. Since the induced voltage along the inner coil per meter will typically be less than 1000 volts, it is sufficient to utilise standard insulation, such as enamel, for the core. It is also possible to use for the magnetic core thin tape of magnetic material or magnetic powder where the particles are insulated with an electrically insulating coating.

The invention has been described with reference to the cable having a single inner coil. However the invention is intended to embrace the use of two or more coaxially arranged "inner" coils, typically connected in series. In this case, each inner coil is surrounded by a separate "band" of electrically insulating means, each insulation "band" comprising an inner layer of semiconducting material in electrical contact with its associated inner coil only at spaced apart intervals along the length of the inner coil, an outer layer of semiconducting material and an intermediate layer of electrically insulating material between the said inner and outer layers. With such a cable the winding angles of the inner coils may be from just over 0° up to almost 90° to the axial direction for a tightly wound inner coil. The winding angles and/or winding directions of different inner coils of the resonator may be different. Although the winding angle and/or winding direction may be chosen to influence the flexibility of the cable or to reduce mechanical stress for brittle superconducting means, the winding angle and/or winding direction is primarily selected to influence the magnetic field created by a particular inner coil. Thus the winding angles used in the formation of the different inner coils are conveniently selected according to how the magnetic fields from each inner coil are to be arranged with respect to each other. For example, the respective winding angles
and/or winding directions may be chosen so that in certain applications the magnetic fields from adjacent inner coils compliment and strengthen each other whereas in other applications the magnetic fields from adjacent inner coils oppose each other.

In another modification, the winding angles and/or winding directions of the inner coils, and or the inner and outer coils, may be selected as required and may be different or the same.

According to another aspect of the present invention there is provided an energy storage system having a resonator according to said one aspect of the present invention having input means connected to a source of energy input.

Brief Description of the Drawings

Embodiments of the invention will now be described, by way of example only, with particular reference to the accompanying drawings, in which:

Figures 1A and 1B are a schematic, sectional view, on an enlarged scale, and a schematic partly cut-away perspective view, respectively, of one embodiment of a resonator according to the invention having an air core;

Figure 2 is an equivalent circuit for the resonator shown in Figures 1A and 1B;

Figures 3 is a schematic, sectional view, on an enlarged scale of another embodiment of a resonator according to the invention having an air core;

Figure 4 is a partly cut away perspective view of another embodiment of a resonator according to the invention having a magnetic core;
Figure 5 is a schematic, partly cut away perspective view of further embodiment of a resonator according to the invention having a magnetic core;

Figure 6 is a schematic view, on an enlarged scale, of the magnetic core of the resonator shown in Figure 5; and

Figure 7 is a schematic, partly cut away perspective view of a yet further embodiment of a resonator according to the invention having a magnetic core.

Description of Preferred Embodiments

Figures 1A and 1B show one embodiment of a high voltage (HV) resonator according to the invention generally designated 1. The resonator 1 is in the form of a cable comprising an inner coil 2 wound from elongate high-transition temperature ($T_c$) superconducting (HTS) material, for example BSCCO tape or the like, which is electrically insulated, e.g. with varnish or the like, and wound on a support tube 3. The individual turns of the coil 2 are electrically insulated from each other. A solid electrical insulation system surrounds the coil 2 and comprises an inner layer 4 of semiconducting material, an outer layer 5 of semiconducting material and, sandwiched between these semiconducting layers, an insulating layer 6. An outer coil 7 also formed from elongate high-transition temperature ($T_c$) superconducting (HTS) material, for example BSCCO tape or the like, which is electrically insulated, e.g. with varnish or the like, is wound around the solid electrical insulation system 4 - 6. The individual turns of each of the coils 2 and 7 are electrically insulated from each other. The inner coil 2 has connections 2a and 2b at its opposite ends and the outer coil has connections 7a and 7b at its opposite ends.

The HTS material of the inner coil 2 has its electrical insulation, e.g. varnish insulation, removed
therefrom at its opposite ends and preferably also at spaced apart positions along its length so that the inner layer 4 is in electrical contact with the HTS material at opposite ends of the inner coil and also, preferably, at spaced apart positions along its length.

The layers 4-6 preferably comprise thermoplastics materials in close mechanical contact or preferably solidly connected to each other at their interfaces. Conveniently these thermoplastics materials have similar coefficients of thermal expansion and are resilient or elastic at least at room temperature. Preferably the layers 4-6 are extruded together around the inner coil 2 to provide a monolithic structure so as to minimise the risk of cavities and pores within the electrical insulation. The presence of such pores and cavities in the insulation is undesirable since it gives rise to partial discharge in the electrical insulation at high electric field strengths.

By way of example only, the solid insulating layer 6 may comprise cross-linked polyethylene (XLPE). Alternatively, however, the solid insulating layer may comprise other cross-linked materials, low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethylpentene (PMP), ethylene (ethyl) acrylate copolymer, or rubber insulation, such as ethylene propylene rubber (EPR), ethylene-propylene-diene monomer (EPDM) or silicone rubber. The inner and outer layers 4 and 5 of semiconducting material may comprise, for example, a base polymer of the same material as the solid insulating layer 6 and highly electrically conductive particles, e.g. particles of carbon black or metallic particles, embedded in the base polymer. The volume resistivity, typically about 20 ohm.cm, of these semiconductive layers may be adjusted as required by varying the type and proportion of carbon black added to the base polymer. The following gives an example of the way in which resistivity can be varied using different types and quantities of carbon black.
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The outer semiconducting layer 5 is connected at spaced apart regions along its length to a controlled similar potential along its length, e.g. at spaced intervals therealong. Thus the radial E-field is controlled.

The semiconducting layer 5 acts as a static shield which ensures that the electric field of the coil 2 is retained within the solid insulating layer 6 between the semiconducting layers 4 and 5. Losses caused by induced voltages in the layer 5 are reduced by increasing the resistance of the layer 5. However, since the layer 5 must be at least of a certain minimum thickness, e.g. no less than 0.8 mm, the resistance can only be increased by selecting the material of the layer to have a relatively high resistivity. The resistivity cannot be increased too much, however, else the voltage difference mid-way between two adjacent controlled potential points will be too high with the associated risk of partial discharges occurring.

The coil 7 is electrically insulated from the outer layer 5 of semiconducting material.
In the resonator 1, both the superconducting coils 2 and 7 may be cooled by a cooling fluid, such as liquid nitrogen, to the required superconducting temperatures. To cool the coil 2, liquid nitrogen may be passed along a channel (not shown), e.g. an annular channel formed between the support tube 3 and an inner, concentrically arranged tube (not shown) spaced from the support tube 3. Alternatively, the cable-like resonator 1 may be enclosed within a cryostat (not shown) to cool the both the coils 2 and 7 to superconducting temperatures.

Figure 2 is an equivalent circuit of the resonator shown in Figures 1A and 1B. The inductances L21, L22,...,L2N are provided by the coil 2 and the inductances L71, L72,...,L7N are provided by the coil 7. The capacitors C1, C2, CN are provided by the capacitance of the electrical insulation system between the inner and outer coils 2 and 7. A high impedance transformer 8 can be connected to connections 2a, 7a to supply electrical energy. The impedance of the transformer 10 on the side 2a, 7a must be much greater than the impedance of the LC-network of the resonator 1 so that the energy is reflected within the resonator and does not leak out at too high a rate.

The resonator 1 terminates at connections 2b, 7b. The connections 2b, 7b may be connected to a variable impedance 9 comprising a variable inductor in parallel with a variable capacitor. Alternatively the connections 2b, 7b may be connected in a short-circuit so that the impedance is zero and the resonator functions as a quarter-wave resonator. Another alternative is for the impedance between the connections 2b and 7b to be infinity, i.e. an open circuit, in which case the resonator functions as a half-wave resonator.

The resonator 1 can operate in several different modes depending on the application. The distributed resonator circuit stores energy in a form which oscillates between a magnetic field and an electric field. If
oscillations are generated at one end of the resonator, these oscillations travel down the resonator and are reflected back from the other end of the resonator. The reflected wave in turn interferes with the incoming wave and a standing wave pattern is formed along the resonator with antinodes positioned at half the oscillator wavelength from each other. The resonance frequency depends on the length of the resonator and the boundary conditions, i.e. how the output connections are connected. A quarter-wave resonator has one end open and the other end shorted. A half-wave resonator has the two ends either both shorted or both open. Additional half-wavelengths can be added to increase the length of the resonator and the stored energy. The resonator can be from several meters to several kilometres long.

Figure 3 shows a modified cable for replacing a cable of the kind described with reference to Figures 1A and 1B. The cable comprises a first coil 102 wound from elongate high-temperature (T_c) superconducting ("HTS") material, for example BSCCO tape or the like, which is electrically insulated, e.g. with varnish or the like, and helically wound on a tubular support 103. The individual turns of the first coil 102 are electrically insulated from each other. Liquid nitrogen, or other cooling fluid, may be passed along the tubular support 103 to cool the surrounding superconducting first coil to below its critical superconducting temperature T_c.

A band 120 of solid electrical insulation surrounds the first coil 102 and comprises inner and outer layers 120a and 120b, respectively, of semiconducting material and an intermediate layer 120c of insulating material. The HTS material has its electrical insulation, e.g. varnish insulation, removed therefrom at its opposite ends and preferably also at spaced intervals along its length so that the surrounding layer 120a is able to make electrical contact with the coil 102 along its length. The outer layer 120b has elongate axial channels 121 formed in its outer
surface and is surrounded by a metallic tubular support 122 similar to the support 103. The channels and support 122 define axial cooling ducts for cooling fluid if required.

Helically wound electrically insulated elongate HTS material, for example BSCCO tape or the like, is wound on the support 122 to form a second coil 123 around the tubular support 122 having its individual turns electrically insulated from each other. The HTS material forming the second coil 123 has its electrical insulation, e.g. varnish insulation, removed therefrom at its opposite ends and preferably also at spaced intervals along its length so that the surrounding layer 125a is able to make electrical contact with the coil 123 along its length. A further band 125 of insulation is positioned around the second coil 123.

The band 125 comprises inner and outer layers 125a and 125b of semiconducting material and an intermediate layer 125c of insulating material. The outer layer 125b of the outermost electrical insulation band 125 is grounded at spaced intervals along its length as shown schematically at 127. The layers 120a and 125a can be positioned in contact with the underlying coils 102 and 123, respectively, to ensure electrical contact with the insulation removed portions of the coils. Alternatively, however, radial gaps 128 and 126 may be provided, respectively, between the band 120 and the layer 114 and the band 125 and the superconducting layer 123. These radial gaps 128 and 126 provide gaps for expansion and contraction to compensate for the differences in the thermal coefficients of expansion ($\alpha$) between the electrical insulation bands and the superconducting coils.

The gaps 128 and 126 may be void spaces or may incorporate foamed, highly compressible material to absorb any relative movement between the superconducting coils and surrounding electrical insulation. The foamed material, if provided, may be semiconducting to ensure electrical contact between the coil 102 and layer 120a and the coil 123 and layer 125a. Additionally, or alternatively, metal wires may be provided for ensuring the necessary electrical contact. A cryostat 115, arranged outside the semiconducting layer 125b,
comprises two spaced apart flexible corrugated metal tubes 116 and 117. The space between the tubes 116 and 117 is maintained under vacuum and contains thermal superinsulation 118. Instead of the cryostat 115, the resonator may be contained within a thermally insulated, cryogenically cooled container shown schematically at 150.

The coils 102 and 123 may be connected in series. The bands of electrical insulation 120 and 125 are formed in a similar manner to the insulation formed by the corresponding insulation layers described with respect to Figures 1A and 1B. The winding angles and/or winding directions of the coils 102 and 123 may be varied as described above.

An outer coil (not shown) may be provided around the insulated coils 102 and 123.

Figure 4 shows an alternative design of resonator 10 according to the invention and illustrates how an inner magnetic core 11 can be integrated into the design. The resonator 10 is similar to the resonator 1 and, where possible, the same reference numerals have been used to designate the same or similar parts. The magnetic core 11 comprises magnetic material which may be particulate, e.g. in the form of particulate iron or compounds of iron; wire, e.g. iron based; or tape, e.g. Fe based, amorphous or nanocrystalline.

The potential at opposite ends of the inner coil 2 of the resonator 10 is defined by the voltage applied to the elongate superconducting material. The potential along the inner coil 2 is determined by the induced voltage in each turn of the coil around the magnetic core 11. Thus the voltage varies along the length of the coil 2. However, a controlled potential, e.g. ground potential, is applied to the magnetic core 11 which will have this same constant potential along its length. However, since the inner coil 2 has a potential that depends on the induced voltage, as explained above, the potential difference between the
magnetic core 11 and the coil 2 will also differ along the length of the resonator 10. It is therefore necessary to provide a further solid electrically insulating layer 12, similar to that of the insulating layer 6, between the magnetic core 11 and the coil 2. In the embodiment shown in Figure 4, two electrical insulation systems are provided. The first insulation system, comprising the inner and outer layers 4 and 5 of semiconducting material and the intermediate layer 6 of insulating material, is positioned radially outside the coil 2. The second insulation system is positioned radially inside the coil 2 and comprises the insulation layer 12, an outer layer 13 of semiconducting material and an inner layer 14 of semiconducting material. This second insulation system is similar to the first insulation system with the individual layers 12-14 forming a unitary construction. The semiconducting inner layer 4 and semiconducting outer layer 13 should make electrical contact with the coil 2 at opposite ends of the latter and preferably also at spaced apart locations between the coil ends.

An alternative design of resonator 20 is shown in Figures 5 and 6, in which a magnetic core 21 is kept at a "floating" potential along its length which obviates the necessity of having electrical insulation between the magnetic core 21 and the surrounding inner coil 2. In this case, the magnetic core 21 is formed of a plurality of overlapping "threads" or core lengths 22 (see Figure 6) which are electrically insulated from each other. Since the induced voltage along the elongate superconducting material from which the coil 2 is wound will be less than 1000 volts per metre, it is sufficient to use standard electrical insulation, e.g. enamel, to insulate the magnetic core. The core lengths 22 can be made from tape of magnetic material or insulated magnetic particles. In this embodiment, the coil 2 is wound on a support tube which may be made of electrically insulating material or, alternatively, may be made of semiconducting material which is in electrical
contact with the core at least at spaced apart intervals along the length of the magnetic core.

The outer layer 5 of semiconducting material of a resonator 30 (see Figure 7) may be surrounded by an electrically insulated metal sheath 31. It is important that the sheath 31 is not completely closed so as to prevent the creation of an inductive short circuit. The sheath 31 should therefore have at least one interruption, e.g. in the form of a slit 32, along its length. The sheath in this case may replace the outer coil of the resonator with the connections 7a and 7b being at ground potential. The metal sheath also provides mechanical rigidity. Alternatively, rigidity may be provided by a surrounding sheath (not shown) of non-metallic, e.g. plastics, material which may completely enclose the cable.

It is possible to wind the cable from which the resonator is formed about a magnetic core to provide improved induction. For example, the cable may be wound in a helical path around a preferably non-closed magnetic core, such as a toroidal shaped magnetic core having one or more air gaps therein. The current in the cable can be divided into two components, one component flowing in the azimuthal direction with a constant radius and the other component flowing axially along the longitudinal axis of the cable. Since the cable is wrapped around the magnetic core, the effect of the induction is twofold. Firstly as the axial component in the cable, as mentioned above, and secondly as the axial component in the magnetic core. With a superconducting cable, the amount of superconducting means can be optimised. The superconducting coil can be wound as a tight helix or as a loose helix using less superconductor material. Also the "tightness" of the wound cable on the magnetic core can be adjusted as required. The solenoid or "toroidal" shape need not have a circular cross-section but may, for example, be oval-shaped or D-shaped. In the case of a torus having a "D-shaped" cross-section, the "straight" part of the "D" would form an inner cylindrical wall of the
"torus". It is also, of course, not essential for the torus to be perfectly annular or circular in shape. Instead of the cable being wound around a magnetic core, the magnetic core may be arranged around the cable in a shell-type arrangement.

Although it is preferred that the electrical insulation should be extruded in position, it is possible to build up an electrical insulation system from tightly wound, overlapping layers of film or sheet-like material. Both the semiconducting layers and the electrically insulating layer can be formed in this manner. An insulation system can be made of an all-synthetic film with inner and outer semiconducting layers or portions made of polymeric thin film of, for example, PP, PET, LDPE or HDPE with embedded conducting particles, such as carbon black or metallic particles and with an insulating layer or portion between the semiconducting layers or portions.

For the lapped concept a sufficiently thin film will have butt gaps smaller than the so-called Paschen minima, thus rendering liquid impregnation unnecessary. A dry, wound multilayer thin film insulation has also good thermal properties and can be combined with a superconducting pipe as an electric conductor and have coolant, such as liquid nitrogen, pumped through the pipe.

Another example of an electrical insulation system is similar to a conventional cellulose based cable, where a thin cellulose based or synthetic paper or non-woven material is lap wound around a conductor. In this case the semiconducting layers, on either side of an insulating layer, can be made of cellulose paper or non-woven material made from fibres of insulating material and with conducting particles embedded. The insulating layer can be made from the same base material or another material can be used.

Another example of an insulation system is obtained by combining film and fibrous insulating material, either as
a laminate or co-lapped. An example of this insulation system is the commercially available so-called paper polypropylene laminate, PPLP, but several other combinations of film and fibrous parts are possible. In these systems various impregnations such as mineral oil or liquid nitrogen can be used.
1. A high voltage resonator comprising a cable having inner conducting means comprising an inner coil (3) with adjacent turns electrically insulated from each other, cooling means for cooling the inner coil (3), electrically insulating means (4-6) surrounding the inner coil (3), and outer conducting means (7) positioned outwardly of the insulating means, the electrically insulating means comprising an inner layer (4) of semiconducting material in electrical contact with said inner coil (3) only at spaced apart intervals along the length of the inner coil, an outer layer (5) of semiconducting material at a controlled electrical potential along its length and an intermediate layer (6) of electrically insulating material between the said inner and outer layers (4 and 5).

2. A resonator according to claim 1, characterised in that inwardly of said inner coil (123) there is at least one additional inner coil (102) coaxial with said first-mentioned inner coil (123) and at least one additional cooling means for cooling the or each additional inner coil, the or each additional inner coil being surrounded by additional electrically insulating means (120) comprising an inner layer (120a) of semiconducting material in electrical contact with the, or the associated, additional inner coil (102) only at spaced apart intervals along the length of the additional inner coil, an outer layer (120b) of semiconducting material and an intermediate layer (120c) of electrically insulating material between the inner and outer layers (120a and 120b).

3. A resonator according to claim 2, characterised in that the said inner coils (102, 123) are connected in series.

4. A resonator according to claim 2 or 3, characterised in that the winding angle of each of said inner coils (102,
123) is from just over $0^\circ$ up to almost $90^\circ$ to the longitudinal axis of the cable (101).

5. A resonator according to claim 4, characterised in that the winding angles and/or winding directions of different ones of said inner coils (102, 123) are not the same.

6. A resonator according to claim 5, characterised in that the winding angles and/or winding directions are selected so that the magnetic fields from adjacent inner coils (102, 123) compliment and strengthen each other.

7. A resonator according to claim 5, characterised in that the winding angles and/or winding directions are selected so that the magnetic fields from adjacent inner coils (102, 123) oppose each other.

8. A resonator according to any one of the preceding claims, characterised in that the outer conducting means comprises an outer coil wound around the, or the outermost, electrically insulating means.

9. A resonator according to claim 8, characterised in that the outer coil is electrically insulated from the said outer layer of semiconducting material surrounding the first-mentioned inner coil.

10. A resonator according to any one of the preceding claims, characterised in that the or each electrically insulating means is of substantially unitary construction.

11. A resonator according to any one of the preceding claims, characterised in that each semiconducting layer has a resistivity of from 1 to $10^5$ ohm.cm, preferably from 1 to 500 ohm.cm and most preferably from 10 to 100 ohm.cm.

12. A resonator according to any one of the preceding claims, characterised in that the resistance per axial unit
of length of each semiconducting layer is from 5 to 50,000 ohm.m⁻¹, preferably from 500 to 25,000 ohm.m⁻¹ and most preferably from 2,500 to 5,000 ohm.m⁻¹.

13. A resonator according to any one of the preceding claims, characterised in that the semiconducting outer layer of the electrically insulating means surrounding the first-mentioned inner coil is contacted by conductor means at said controlled electrical potential at spaced apart regions along its length, adjacent contact regions being sufficiently close together that the voltages of mid-points between adjacent contact regions are insufficient for corona discharges to occur within the electrically insulating means.

14. A resonator according to any one of the preceding claims, characterised in that said controlled electrical potential is at or close to ground potential.

15. A resonator according to any one of the preceding claims, characterised in that, for the or each electrically insulating means, the intermediate layer is in close mechanical contact with the associated inner and outer layers.

16. A resonator according to any one of claims 1 to 14, characterised in that, for the or each electrically insulating means, the intermediate layer is joined to each of the associated inner and outer layers.

17. A resonator according to claim 16, characterised in that, for the or each electrically insulating means, the strength of the adhesion between the intermediate layer and the semiconducting outer layer is of the same order of magnitude as the intrinsic strength of the material of the intermediate layer.

18. A resonator according to claim 16 or 17, characterised in that the said layers of the or each
electrically insulating means are joined together by extrusion.

19. A resonator according to any one of the preceding claims, characterised in that, for the or each electrically insulating means, said inner layer comprises a first plastics material having first electrically conductive particles dispersed therein, said outer layer comprises a second plastics material having second electrically conductive particles dispersed therein, and said intermediate layer comprises a third plastics material.

20. A resonator according to claim 19, characterised in that each of said first, second and third plastics materials comprises an ethylene butyl acrylate copolymer rubber, an ethylene-propylene-diene monomer rubber (EPDM), an ethylene-propylene copolymer rubber (EPR), LDPE, HDPE, PP, XLPE, EPR or silicone rubber.

21. A resonator according to claim 19 or 20, characterised in that said first, second and third plastics materials have at least substantially the same coefficients of thermal expansion.

22. A resonator according to claim 19, 20 or 21, characterised in that said first, second and third plastics materials are the same material.

23. A resonator according to any one of the preceding claims, characterised in that the at least one inner coil has an air core.

24. A resonator according to any one of claims 1 to 22, characterised in that the at least one inner coil has a magnetic core.

25. A resonator according to claim 24, characterised in that second electrically insulating means is positioned between the magnetic core and the, or the innermost, inner
coil and comprises inner and outer layers of semiconducting material and an intermediate layer of electrically insulating material.

26. A resonator according to claim 25, characterised in that the said electrically insulating material of said second electrically insulating means is the same as the said electrically insulating material of said first mentioned electrically insulating means.

27. A resonator according to any one of claims 24 to 26, characterised in that the magnetic core is at a controlled second electrical potential along its length.

28. A resonator according to claim 27, characterised in that said second electrical potential is at, or close to, ground potential.

29. A resonator according to claim 24, characterised in that the magnetic core has, in use, a non-uniform potential along its length.

30. A resonator according to any one of the preceding claims, characterised in that the or each inner coil is wound from electrically conducting means having a surrounding electrical insulation which is removed at at least two spaced apart regions along the length of the electrically conducting means to enable the latter to make electrical contact with the or each adjacent layer of semiconducting material.

31. A resonator according to claim 30, characterised in that the or each adjacent layer of semiconducting material makes electrical contact with regions or points at opposite ends of the, or the associated, inner coil.

32. A resonator according to claim 31, characterised in that the or each adjacent layer of semiconducting material makes contact with the, or the associated, inner coil at one
or more points or regions between the said opposite ends of the inner coil.

33. A resonator according to claim 31 or 32, characterised in that, for the or each inner coil, the or each adjacent layer of semiconducting material makes electrical contact with the inner coil at every n turns of the inner coil ± 0.1n turns, where n is from 100 to 10,000, typically about 1000.

34. A resonator according to claim 30, characterised in that the electrically conducting means comprises superconducting means, e.g. HTS material.

35. A resonator according to claim 31, characterised in that said cooling means is arranged to cool the electrically conducting means to superconducting temperatures.

36. A resonator according to any one of the preceding claims, characterised in that said cable is wound around a magnetic core.

37. A resonator according to any one of claims 1 to 35, characterised in that a magnetic core is arranged around said cable.

38. A resonator according to any one of the preceding claims, including input connection means and output connection means.

39. A resonator according to claim 38, characterised in that said output connection means comprise two connectors connected to impedance means.

40. A resonator according to claim 38, characterised in that said output connection means comprise two connectors connected together in a short circuit connection.
41. A resonator according to claim 38, characterised in that said output connection means comprise two connectors in open circuit.

42. An energy storage system including a resonator as claimed in any one of the preceding claims.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01F6/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01F H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tr>
<td>A</td>
<td>US 4 431 960 A (ZUCKER OVIDE S F) 14 February 1984 (1984-02-14)</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>GB 2 140 195 A (ELECTRIC POWER RES INST) 21 November 1984 (1984-11-21)</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>US 2 650 350 A (HEATH) 25 August 1953 (1953-08-25)</td>
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</tbody>
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<table>
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<tr>
<th>Patent document cited in search report</th>
<th>Publication date</th>
<th>Patent family member(s)</th>
<th>Publication date</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB 2140195 A</td>
<td>21-11-1984</td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td>US 2650350 A</td>
<td>25-08-1953</td>
<td>FR 1043552 A</td>
<td>10-11-1953</td>
</tr>
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</table>