Title: COIL, COIL ASSEMBLY AND SUPERCONDUCTING FAULT CURRENT LIMITER

Abstract: A coil (12, 112, 212) is described, the coil (12, 112, 212) comprising an electrically conducting element (18, 118, 218) defining a plurality of first turns (20, 120, 220) around a first axis (X1, X101, X201), wherein at least two first turns are adapted to carry a current in opposite senses around the first axis (X1, X101, X201); and a respective plurality of second turns (22, 122, 221, 222) around at least one second axis (X2, X102, X202, X203), wherein at least two second turns are adapted to carry a current in opposite senses around a respective second axis (X2, X102, X202, X203; wherein at least two first turns are connected in series via at least one second turn. A superconducting fault current limiter (400) is described, comprising a coil (12, 112, 212) as described above, the conducting element (18, 118, 218) of which comprises a superconducting material.
This invention relates to a coil, and relates particularly, but not exclusively, to a superconducting coil and a superconducting fault current limiter comprising a superconducting coil or coils.

A superconducting fault current limiter comprises a cryostat containing at least one superconducting component connected at both ends to bushings which pass through the cryostat enclosure. Superconducting fault current limiters have been used in electricity supply networks, which are normally expected to carry currents of a few hundred amperes, but, if a short circuit (fault) occurs, the current can rise to levels which can be several tens of thousands of amperes. When a fault occurs in a network protected by a resistive superconducting fault limiter, the current density in the superconducting material exceeds the critical current density of the material, which ceases to be superconducting and becomes resistive. This process is known as quenching. The presence of this additional resistance in the circuit causes the current to be reduced, or "limited", reducing the potentially damaging effects of excessively high currents in the network.

A particular application of superconducting fault current limiters is for connecting power generators, such as wind turbines, to a grid.

The superconducting component of a superconducting fault current limiter comprises a superconducting wire or tape. The
superconducting component may be tens or hundreds of metres long, depending on the application. To make a superconducting fault current limiter as compact as possible, the superconducting component should occupy as small a volume as possible, so as to accommodate the maximum possible length of wire or tape in the available volume. This is achieved by winding the superconducting component. However, superconducting materials are typically brittle and a superconducting wire or tape consequently has a minimum bend radius. Bending the material more sharply than the minimum bend radius may cause the material to be damaged.

To minimise thermal losses in a superconducting fault current limiter it is necessary to minimise the a.c. losses associated with the superconducting component. This is greatly assisted by minimising the inductance of the winding, which is typically achieved by arranging the winding to be bifilar, such that current flow is in opposing directions in adjacent turns. This can be achieved by arranging the turns in a helical bifilar coil 500, as shown in Figure 1, or in a flat spiral "pancake" bifilar coil 600 as shown in Figure 2.

A significant disadvantage associated with these bifilar coil arrangements is that all of the voltage applied across the coil 500, 600 appears between the two adjacent turns 501, 502, 601, 602 at the end of the coil 500, 600 closest to its terminals. In typical superconducting fault current limiter applications, this voltage may be of the order of tens of thousands of volts under fault conditions, such as, for example, a lightening strike. It is desirable that a superconducting fault current limiter uses as few coils as possible, in order to minimise the thermal losses associated with the connections between superconducting components. Therefore, preferably only one winding per phase is used, which means that all of the voltage applied to the fault
current limiter appears between adjacent turns of a winding.

This has an impact on the size of the coil because the spacing between adjacent turns of the bifilar coil, in particular between the turns of the coil at the end closest to the terminals, must be sufficient to isolate neighbouring turns from each other under these conditions. This increases the overall length of the bifilar coil, thereby increasing the cost of cooling the coil below the superconductor's critical temperature.

A further disadvantage associated with the bifilar coil arrangements is that the superconducting wire or tape must change direction at one end of coil. However, the radius of curvature of the superconducting wire or tape cannot be smaller than the minimum bend radius of the material. In the helical bifilar coil 500 shown in Figure 1, a connecting element 503 is used to join the two counter-wound strands of the bifilar coil 500 together at one end of the coil, so that the overall size of the coil is not increased. However, this connecting element comprises non-superconducting material, the resistivity of which leads to an increase in thermal losses. In the spiral bifilar coil 600 shown in Figure 2, the radius of curvature of the coil is increased to accommodate an S-shaped loop 604 between the two counter-wound parts of the bifilar coil, increasing the overall size of the coil.

Preferred embodiments of the present invention seek to overcome one or more of the above disadvantages of the prior art.

SUMMARY OF THE INVENTION

According to the present invention, there is provided a coil comprising an electrically conducting element defining:
at least one plurality of first turns around a respective first axis,
wherein at least two said first turns are adapted to carry a current in opposite senses around a respective first axis; and
a respective plurality of second turns around at least one second axis,
wherein at least two said second turns are adapted to carry a current in opposite senses around a respective second axis;
wherein at least two said first turns about a respective first axis are connected in series via at least one second turn.

Arranging at least two of the first turns to carry a current in opposite senses around a first axis, and at least two of the second turns to carry a current in opposite senses around a respective said second axis, enables each of the plurality of first turns and the plurality of second turn to have a low inductance.

Advantageously, winding the coil as a plurality of first turns about a first axis, and at least one plurality of second turns about a respective second axis, wherein at least two said first turns are connected in series via at least one second turn, enables the sense of the turns around any one axis to be reversed from one turn to the next adjacent turn.

In this way, a low-inductance coil can be obtained using a monofilar winding. By monofilar, we mean that the conducting element does not double back upon itself as in a bifilar winding. In contrast to a bifilar coil, the maximum voltage drop between neighbouring turns of a monofilar coil is always a fraction of the voltage drop across the entire coil, and may be approximately equal to the total applied voltage.
divided by the number of turns around each axis for example. Adjacent turns can therefore be spaced by a distance which is significantly smaller than the distance permissible between adjacent turns close to the terminals of an equivalent bifilar winding.

A further advantage is that the coil of the present invention can be configured as a relatively compact, low-inductance coil, as the conducting element may have a radius of curvature close to its minimum permissible magnitude along most of its length. In contrast, the turns of the bifilar spiral coil shown in Figure 2 are wound at a radius of curvature greater than the minimum, in order to accommodate the change of direction at the centre of the coil. The bifilar helical coil shown in Figure 1 may be wound close to the minimum possible radius of curvature only if a non-superconducting connection is made between the two strands of the bifilar coil.

Yet another advantage of the present invention is that, by winding the coil around at least two axes, rather than as a single helical coil, the length of the coil is significantly reduced. For example, when two axes are used, the length of the coil may be approximately halved. When the coil is wound around more than two axes, greater reductions in length are achieved. This enables the shape of the coil to be adapted to different applications.

The various embodiments of the present invention provide alternative solutions to the problem of providing a low inductance coil which may be more compact and/or have a lower inductance than known coils.

In preferred embodiments, substantially every, and more preferably each, portion of the conducting element connected
in series between any two turns is arranged to carry current in an opposite direction to an adjacent portion of the conducting element from which it is spaced apart in a direction parallel to said first and/or second axis.

Advantageously, this feature helps to minimise the inductance of the coil, as it ensures that there is magnetic field cancellation at all parts of the coil, not only between the turns of each said plurality of turns, but also between the portions of the conducting element connecting said turns.

Preferably, any two turns of the coil are connected by a portion of the conducting element which is curved along substantially all its length.

Advantageously, this enables the coil to be more compact. By avoiding straight portions, the coil may occupy a smaller volume and can therefore be cooled more economically. A further advantage is that, by curving the path of the conducting element between the first and second turns, it is possible to obtain good cancellation of the magnetic field at locations between the pluralities of first and second turns, in addition to obtaining good cancellation of the magnetic field at each plurality of first and second turns. Yet another advantage of this feature is that curving the conducting element may facilitate thermal contact between the winding and a solid coolant, for example by winding the conducting element around formers comprising a thermally conducting material.

Preferably, the curvature of the conducting element is about axes substantially parallel to said first and second axes.

The path of the conducting element may consist of a
series of circular arcs.

Advantageously, the use of circular arcs simplifies the design of the coil, and any supports around which the coil is wound.

In one embodiment, the conducting element is wound in a figure-of-eight type pattern around one first axis and one second axis; wherein a first turn about said first axis in a first sense is followed by a second turn about said second axis, then a first turn about the first axis in a second sense, opposite to said first sense; wherein the path of the conducting element between the first and second turns always passes substantially through a third axis parallel to said first and second axes.

By ensuring that the path of the conducting element between the first and second turns always passes substantially through a third axis, parallel to said first and second axes, the paths between the first turns and the second turns stack up over each other to provide good cancellation of the magnetic field in the region between the plurality of first turns and the plurality of second turns. Without this feature, portions of the conducting element which cross between the first and second turns (i.e. between two consecutive first and second turns which are in opposite senses) would not overlap at all with portions of the conducting element which do not cross between the first and second turns (i.e. between two consecutive first and second turns which are in the same sense). The above feature ensures that the magnetic field generated by current flowing in the "crossing" paths cancels with the magnetic field generated by current flowing in the "non-crossing" paths.

In this embodiment the first turn about said first axis
in said second sense may be followed by a second turn about said second axis in a sense opposite to that of the previous second turn about the second axis.

In another embodiment, the coil comprises a group of respective pluralities of second turns around multiple respective second axes; the path of the conducting element follows, in a first sense, a loop comprising at least one respective second turn around each said second axis of said group, followed by at least one respective first turn around said or each first axis, followed by another said loop in a second sense opposite to said first sense; and said pluralities of second turns of said group are arranged such that each said loop begins and ends adjacent said plurality of first turns.

This arrangement enables a single conducting element to be wound in multiple layers around multiple axes, thereby reducing the size of the coil, while providing good cancelling of the magnetic field generated at each axis. This is due in part to the location of the ends of the loop adjacent the plurality of first turns. Thus the conducting element may be wound around the loop in opposite directions or senses. Because both ends of the loop are adjacent the plurality of first turns, a change of direction can be achieved after each traversal of the loop, in either sense, by a turn around the (or each) first axis. By providing the same number of turns about the first axis as about each of the second axes, the coil may be particularly compact.

In this embodiment, the loop in said second sense may be followed by a first turn around said at least one first axis, in a sense opposite to that of the previous turn around said first axis.
In this embodiment, each said loop may begin and end at an axis parallel to said first and second axes.

This feature ensures that the paths between the first turns and the loop of second turns stack up over each other to provide good cancellation of the magnetic field in the region between the plurality of first turns and the group of pluralities of second turns.

In another embodiment, the coil comprises a plurality of third turns around a respective third axis; said coil comprises a group of respective pluralities of second turns around multiple respective second axes; and the path of said conducting element follows, in a first direction, a meander comprising at least one respective second turn around each said second axis of said group, followed by a turn around said first axis, followed by another said meander in a second direction opposite to said first direction, followed by a turn around said third first axis.

This arrangement provides further flexibility in arranging the turns of the coil to fit a specified volume.

In this embodiment, the path of said conducting element may next follow said meander in said first direction, followed by a turn around said first axis in a sense opposite to the previous turn around said first axis, followed by another said meander in said second direction, followed by a turn around the third axis in a sense opposite to the previous turn around said third axis.

In this way, there is also cancellation at each of the pluralities of first and third turns of the magnetic field that is generated by a current in the conducting element of the coil.
In another embodiment of the invention, the coil comprises multiple pluralities of second turns around multiple respective second axes; said multiple pluralities of second turns are arranged radially inward of a periphery of a circle, said circle having a radius of curvature larger than a radius of curvature of said multiple pluralities of second turns; and at least two further pluralities of second turns and said plurality of first turns are arranged at separate locations radially outwards of the periphery of said circle.

This provides the advantage of enabling a high packing density of conductive element to be achieved, for example by enabling three pluralities of turns arranged radially outwards of the circle to define a triangle, thereby enabling convenient arrangement of respective coils of three separate phases in a cylindrical tank of coolant liquid or a cylindrical vacuum chamber.

In this embodiment, said at least two further pluralities of second turns and said plurality of first turns may be arranged to define the corners of an equilateral triangle.

In another embodiment of the invention, said coil comprises multiple pluralities of second turns around multiple respective second axes; and said multiple pluralities of second turns and said plurality of first turns are arranged substantially within an area defined by an equilateral triangle.

In another embodiment of the invention, said coil comprises multiple pluralities of second turns around multiple respective second axes; and said multiple pluralities of second turns and said or each plurality of first turns are
arranged substantially within an area defined by a 120 degree sector of a circle.

This also provides the advantage of enabling a high packing density of conductive element to be achieved, for example by arranging three 60 degree sector arrangements (e.g. one per phase) to fit in a cylindrical tank.

Preferably, the ends of the conducting element are located at or extend from locations spaced apart along at least one said first or second axis.

Advantageously, this prevents the full voltage applied across the coil from appearing between two adjacent turns of the coil. This may be achieved by winding the coil of the present invention as a monofilar coil, such that the ends of the conducting element extend from opposite ends of the coil.

Preferably, the conducting element comprises at least one super-conducting material.

Preferably, the superconducting material is continuous along the length of the conducting element.

Advantageously, this avoids joins between separate sections of superconducting material, which would otherwise lead to resistive heating.

Preferably, at least one first turn is connected to at least one second turn by a portion of the conducting element having a radius of curvature substantially equal in magnitude to a radius of curvature of said first and/or second turn.

Advantageously, this feature enables the magnitude of the radius of curvature to be substantially constant along the
entire length of the coiled part of the conducting element, for example at a value close to the minimum radius of curvature of the conducting element. This may be useful in minimising the volume occupied by the conducting element.

Preferably, at least one said plurality of first and/or second turns comprises a plurality of pairs of adjacent said first or second turns adapted to carry said current in opposite senses.

This reduces the electromagnetic forces between adjacent turns, and is particularly advantageous in high-current applications.

Preferably, at least one said plurality of first and/or second turns comprises an equal number of turns in each sense about the respective first and/or second axis.

This helps to minimise the overall inductance of the respective plurality of turns. More preferably, each plurality of turns comprises an equal number of turns in each sense.

Preferably, said first axis and at least one said second axis are substantially parallel.

Preferably, a plurality said first and/or second turns have a substantially constant radius of curvature.

A plurality of said first and said second turns may have a first radius of curvature and a plurality of said first and said second turns may be arranged radially inward of the periphery of a circle having a second radius of curvature, larger than said first radius of curvature, and at least three said turns may be arranged at separate locations radially
outwards of the periphery of said circle.

This provides the advantage of enabling a very high packing density of conductive element to be achieved, for example by enabling three turns arranged radially outwards of the circle to define a triangle, enabling convenient arrangement of turns of three separate phases in a cylindrical tank of coolant liquid.

According to another aspect of the invention, there is provided a coil assembly, comprising: a coil as defined above; and a plurality of formers; wherein each said plurality of first or second turns is wound on a respective former.

In one embodiment, the coil assembly further comprises one or more supports for constraining the path of the conducting element between two or more formers.

Advantageously, the formers and/or supports defined above may be used to help maintain a constant magnitude radius of curvature of the conducting element, or to control the path of the conducting element to minimise the inductance of the coil. A further advantage is that the formers and/or supports may comprise a solid coolant, thereby providing a means for cooling the conducting element by thermally connecting the conducting element to a cooling system.

At least one said support may include a support portion for engaging the conducting element and having a radius of curvature substantially equal to that of at least one said first and/or said second turn.

The conducting element may be in contact with at least one said support and/or former along substantially all the length of the conducting element.
This feature is advantageous when the supports and/or formers are to provide thermal contact between the conducting element and cooling heads of a cryostat, as it ensures that substantially all parts of the conducting element are in thermal contact with the cryostat cooling heads.

At least two said supports and/or formers may be spaced apart by a distance slightly greater than the diameter of the conducting element.

Advantageously, this optimises the length of conducting element which may be in contact with the supports and/or formers.

According to another aspect of the invention, there is provided a superconducting fault current limiter, comprising: at least one coil as defined above, wherein the conducting element comprises a superconducting material; and at least one vessel adapted to enclose said superconducting element at a temperature below the critical temperature of the superconducting material.

According to another aspect of the invention, there is provided a superconducting fault current limiter, comprising: at least one coil assembly as defined above, wherein the conducting element comprises a superconducting material; at least one vessel adapted to enclose at least said superconducting element at a temperature below the critical temperature of the superconducting material; and cooling means in thermal contact with said supports for removing heat from said coil assembly.

According to another aspect of the invention, there is provided a thermal anchor for electrically isolating and
thermally connecting an electrical conductor with respect to a thermally conducting element, the thermal anchor comprising:

an electrically insulating part having:

a first surface having a first area for thermal contact with the electrical conductor, and

a second surface, opposite to said first surface, having a second area for thermal contact with the thermally conducting element;

wherein said first surface comprises an electrically-conducting material and is concave such that it extends away from said first and second areas.

By arranging said first surface to comprise an electrically-conducting material and to be concave such that it extends away from said first and second areas, the present invention moves the meeting point of the electrical conductor, electrically insulating part, and vacuum away from the location of highest electrical field, thereby reducing the likelihood of flashover.

The second surface may comprise an electrically-conducting material and be concave such that it extends away from said first and second areas.

The electrically insulating part may comprise alumina.

The electrically-conducting material may comprise copper.

30 BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the present invention will now be described, by way of example only and not in any limitative sense, with reference to the accompanying drawings, in which:

Figure 1 shows a prior art bifilar helical winding;
Figure 2 shows a prior art bifilar spiral winding;

Figures 3 a and 3 b illustrate a winding pattern for a coil according to a first embodiment of the present invention, and show two alternative arrangements for making connections to the coil;

Figures 4 a to 4 h illustrate the winding pattern for a coil according to the first embodiment;

Figures 5 a and 5 b illustrate two alternative arrangements for the exit path of the conducting element of a coil according to the first embodiment;

Figure 6 shows an arrangement of formers and supports for winding a coil according to the first embodiment;

Figures 7 a to 7 c illustrate a calculation of the length of the conducting element of one layer of the coil of the first embodiment;

Figure 8 illustrates a winding arrangement for a coil according to a second embodiment of the present invention;

Figures 9 a to 9 d illustrate a winding pattern for a coil according to the second embodiment;

Figure 10 illustrates a winding arrangement for a coil according to a third embodiment of the present invention;

Figures 11 a to 11 d illustrate the winding pattern for a coil according to the third embodiment;

Figure 12 illustrates a superconducting fault current limiter according to the fourth embodiment;

Figures 13 a to 13 d show a winding arrangement of a fifth embodiment of the invention;

Figure 14 shows a winding arrangement of a sixth embodiment of the invention;

Figure 15 shows the arrangement of the windings of Figures 13 a to 13 d or Figure 14 in a superconducting fault current limiter;

Figures 16 a-j illustrate a winding arrangement for a coil according to a seventh embodiment of the present invention;
Figure 17 shows a plan view of an arrangement of formers around which three coils according to the seventh embodiment may be wound in a superconducting fault current limiter; Figure 18 shows a perspective view of the arrangement of Figure 17; Figure 19 illustrates a cooling arrangement for coils of the seventh embodiment in a superconducting fault current limiter; Figure 20 illustrates a former for use in the cooling arrangement of Figure 19; Figure 21 illustrates a current lead for use in the cooling arrangement of Figure 19; Figure 22 illustrates a thermal anchor for use in the cooling arrangement of Figure 19; Figures 23 a-c illustrate an electrically insulating part of the thermal anchor of Figure 22; and Figure 24 illustrates how the design of the thermal anchor of Figure 22 shifts the triple point away from regions of highest electric field.

DETAILED DESCRIPTION OF THE EMBODIMENTS

A first embodiment of the invention will be described with reference to Figure 3a, Figures 4a to 4h, and Figure 5a. Figure 3a shows a low-inductance coil assembly 10 comprising a coil 12, two cylindrical formers 14, 16, and two hemicylindrical supports 24, 26. The coil 12 comprises a conducting element 18, in the form of a conducting wire or tape, for example a superconducting wire or tape. The conducting element 18 defines a first subcoil 20 comprising a plurality of turns around a first axis XI, and a second subcoil 22 comprising a plurality of turns around a second axis X2, each plurality of turns being distributed along the length of the respective subcoil 20, 22. The two subcoils 20, 22 have substantially parallel axes XI, X2. The turns of each
subcoil 20, 22 are arranged such that, when a current flows in the conducting element 18, adjacent turns of each subcoil 20, 22 carry the current in opposite senses about the respective axis XI, X2.

As will be explained in detail below, adjacent pairs of turns of the first subcoil 20 are connected in series via at least one turn of the second subcoil 22. In other words, the conducting element 18 comprises a plurality of first portions which contribute to the first subcoil 20, and a plurality of second portions which contribute to the second subcoil 22, such that the first and second portions alternate along the length of the conducting element 18. In the present embodiment, this is achieved by a figure-of-eight type winding pattern, in which each layer of the figure-of-eight is wound in an opposite sense.

Figures 4a to 4h illustrate the winding arrangement of the coil 12 according to the first embodiment. Each successive turn on each of the two formers 14, 16 is in the direction opposite to that of the previous turn on the same former 14, 16. This causes cancellation of the magnetic field generated by a current flowing in adjacent turns, resulting in the arrangement having low inductance. Having each subsequent turn in the opposite direction to the previous turn also results in the most even distribution of electromagnetically generated force between the turns.

Figure 4a shows the point of entry of the conducting element 18 to the coil 12, and its route around support 24. Figure 4b shows the subsequent route of the conducting element as it passes clockwise around former 16, passes between the supports 24, 26 and then passes anticlockwise around former 14. Figure 4c shows the route of conducting element 18 around support 26 and Figure 4d shows the subsequent route of the conducting element as it passes anticlockwise around former 16, passes between the supports 24, 26 and then passes clockwise around former 14.
Thus Figures 4a to 4d illustrate the first two layers of the winding pattern. The next two layers of the winding pattern are illustrated by Figures 4e to 4h. The winding pattern can continue in this manner for as many layers as required, depending on the length of conducting element 18 to be accommodated, or the length of coil 12 desired. It is preferred that the coil 12 comprises an even number of complete layers, such that each subcoil 20, 22 comprises an equal number of turns in each sense in order to minimise the inductance of the coil 12. Once the required number of layers of the winding pattern have been completed, the conducting element 18 exits the coil 12 as shown in Figure 5a.

The turns around former 14 form a first subcoil 20, and the turns around former 16 form a second subcoil 22. If we consider the turns of the first subcoil 20, we can see that the first, second, third and fourth turns of subcoil 20 are anticlockwise, clockwise, anticlockwise, and clockwise respectively. Therefore, a current flowing through the conducting element will flow in opposite senses through adjacent turns of the first subcoil 20. This results in cancellation of the magnetic field created by current in the turns, and thus a low inductance. Similarly, if we consider the turns of the second subcoil 22, we can see that the first, second, third and fourth turns of subcoil 22 are, clockwise, anticlockwise, clockwise and anticlockwise respectively, such that the net magnetic field and inductance of the second subcoil 22 is also close to zero.

In addition, the portions of the coil 12 in the region between the first and second subcoils 20, 22, are arranged so that adjacent layers of the coil cancel each other in this region. In Figures 4a to 4h, an arrow at the right hand side of each figure indicates the path and direction of a segment of conducting element 18 which passes between the two formers 14 and 16. The segments of the conducting element 18 which are "non-crossing" between the two formers (Figures 4a, c, e
and g) always travel in the same direction and therefore produce magnetic fields which add to each other. Likewise, the segments which "cross" between the two formers (Figures 4b, d, f and h) always travel generally from right to left and thus also generate magnetic fields which add to each other. However, cancellation of the magnetic fields generated by these segments is achieved by shaping the path followed by the "crossing" and "non-crossing" segments of the conducting element 18 in this region so that they all pass through an axis X10 (shown in Figure 3, midway between supports 24 and 25), such that the "crossing" and "non-crossing" segments together cancel each other. For example, a "crossing" path from lower right to upper left (Figure 4b) is partially cancelled by a "non-crossing" path from upper left to upper right (Figure 4b) and partially cancelled by a "non-crossing" path from lower left to lower right, and so on. Thus the coil 12 of the first embodiment provides good cancellation of the magnetic field produced by a current in the conducting element 18 at all locations of the coil 12.

When the conducting element 18 enters and exits the coil 12 as shown in Figures 4a and 5a respectively, the ends of the conducting element 18 emerging from the coil 12 for electrical connection will be on opposite sides of the coil assembly 10, as shown in Figure 3a. Alternatively, the conducting element 18 may exit the coil 12 as shown in Figure 5b, so that the ends of the conducting element 18 emerging from the coil 12 for electrical connection will be on the same sides of the coil assembly 10, as shown in Figure 3b. Nonetheless, in both alternatives, the ends of the conducting element 18 emerging from the coil 12 for electrical connection will emerge from longitudinally-opposite ends of the coil 12.

From the above description, it can be seen that the present invention enables two adjacent turns on any given subcoil to be wound in opposite senses, without needing to reverse the local direction of the conducting element at any
point, by winding an intermediate portion of the conducting element around a second subcoil. Thus it is possible to realise a low-inductance coil using a monofilar winding, with the ends of the conducting element 18 emerging from opposite ends of the coil 12. Thus the voltage between adjacent turns of the coil 12 never exceeds the voltage drop associated with each layer of the coil 12 i.e. the applied voltage divided by the number of layers. This allows the turns of each subcoil to be spaced by an equal distance which is significantly smaller than the distance permissible in the section close to the terminals of a bifilar winding. This in turn allows a greater length of the conducting element 18 to be accommodated in a given volume.

In the first embodiment, the conducting element 18 is wound around formers 14, 16 and supports 24, 26, arranged as shown in Figure 6. The formers 14, 16 and supports 24, 25 have parallel axes, and are cylindrical/hemi-cylindrical respectively, and all have the same radius D/2. The supports 24 and 25 are spaced apart by a distance slightly greater than the diameter d of the conducting element 18. The formers 14, 16 are spaced apart from the supports 24, 25 by a similar distance. In this arrangement, the conducting element 18 is bent at a constant bend radius along the entire length of the coiled part of the conducting element, which can be close to or greater than the minimum bend radius allowable for the particular conducting element 18. By "bend radius", the magnitude of the radius of curvature is meant.

Figures 7a to 7c illustrate how the length of conducting element 18 occupying each layer of the coil 12 can be determined as a function of the diameter D of the formers 14, 16 and supports 24, 26. The segment of the conducting element 18 highlighted in Figure 7a has a length n*D*120/360. The segment highlighted in Figure 7b has a length n*D* (120/360 + 300/360). Thus the complete layer of the winding pattern highlighted in Figure 7c has a length 2*n*D* (120/360 +
300/360) = n*D*7/3. Thus eight layers of this winding pattern, using formers 14, 16 and supports 24, 26 having a diameter D of 205mm accommodates 12m of wire.

[Example]
Measurements have been made on a (non-superconducting) coil according to the first embodiment described above, and compared with a simple helical coil and a bifilar helical coil, each comprising the same length of conducting element.

A traditional single helical coil (i.e. a monofilar helical coil), a bifilar helical coil, and a coil according to the first embodiment described above were each wound from a 9.8m long insulated copper wire having a cross-section of 0.5mm².

Measurements were made using a Wayne-Kerr bridge from Tinsley Prism Instruments 6471 LCR Data Bridge (calibrated 2/4/2010, NAREC Asset NA40540, Serial Number 267826) on 15th April 2010.

The inductance of the traditional single helical coil was calculated to be 67µH and the resistance (assuming pure copper, precisely 0.5mm², 9.8m, 20°C) was expected to be 0.33Ω. At 100Hz test frequency, the traditional single helical coil was determined to have 0.369Ω pure resistance and 73.3µH inductance, the resistance agreeing (to one significant figure) with a measurement made using an uncalibrated Fluke multi-meter.

At 100Hz test frequency, the bifilar helical coil was determined to have an inductance of 3.5µH.

At 100Hz test frequency, the low inductance coil wound as for the first embodiment described above, was determined to have 0.366Ω pure resistance and 4.1µH inductance, the resistance agreeing with a measurement made using the uncalibrated Fluke multi-meter.

Thus the inductance of the coil of the first embodiment is much lower than that of a traditional monofilar helical
coil, and is comparable with that of a simple bifilar helical coil made from an identical length of conductor.

[Second embodiment]

A second embodiment of the invention will be described with reference to Figures 8 and 9a to 9d. Figure 8 shows a low-inductance coil assembly 110 comprising a coil 112 and two cylindrical formers 114, 116. The coil assembly 110 may also include supports (not shown) arranged in a similar manner to the supports 24, 26 of the first embodiment. The coil 112 comprises a conducting element 118, in the form of a conducting wire or tape, for example a superconducting wire or tape. The conducting element 118 defines a first subcoil 120 comprising a plurality of turns about a first axis X101 and a second subcoil 122 comprising a plurality of turns about a second axis X102, each plurality of turns being distributed along the length of the respective subcoil 120, 122. The turns of each subcoil 120, 122 are arranged such that, when a current flows in the conducting element 118, neighbouring groups of turns of each subcoil 120, 122 carry the current in opposite senses about the respective axis X101, X102. In Figure 8, the conducting element 118 is indicated as a dotted line where it passes behind one of the formers 114, 116. The conducting element 118 comprises alternating first and second portions, the first portions contributing to a first subcoil 120, and the second portions contributing to a second subcoil 122. In this way, at least two turns of the first subcoil 120 are connected in series via at least one turn of the second subcoil 122. This is achieved by a figure-of-eight type winding pattern, which is different from that of the first embodiment, as will be illustrated by Figures 9a to 9d.

Figure 9a shows the point of entry of the conducting element 118 to the coil 110, and its route as it passes clockwise around former 116, crosses between the formers 114 and 116, and then passes anticlockwise around former 114,
thereby completing the first layer of the winding pattern.

Figure 9b shows the second layer of the winding pattern, as the conducting element 118 passes anticlockwise around former 116, crosses between the formers 114 and 116 and then passes clockwise around former 114. These first two layers are the same as the first two layers of the winding pattern of the first embodiment, but the next two layers are different.

Figure 9c shows the third layer of the winding pattern, as the conducting element 118 passes anticlockwise around former 116, and then anticlockwise around former 114. Figure 9d shows the fourth layer of the winding pattern, as the conducting element 118 passes clockwise around former 116, and then clockwise around former 114. The pattern then repeats according to Figures 9a to 9d as many times as required. Again, it is preferred that the coil 112 comprises an even number of layers, so that each subcoil 120, 122 comprises an equal number of turns in each sense in order to minimise the inductance of the coil 112.

In the second embodiment, the first, second, third and fourth turns of the first subcoil 120 are anticlockwise, clockwise, anticlockwise, and clockwise respectively, the same as in the first embodiment. Therefore, a current flowing through the conducting element will flow in opposite senses in all pairs of adjacent turns of the first subcoil 120.

However, the first, second, third and fourth turns of the second subcoil 122 are, clockwise, anticlockwise, anticlockwise and clockwise respectively. Thus, a current will flows in opposite senses through neighbouring groups of turns of the second subcoil 122, where each group includes two adjacent turns. The net magnetic field and inductance of the second subcoil 122 will also be close to zero, but the electromagnetic forces between the turns of the coil 112 of the second embodiment will be greater than for the first embodiment, due to the presence of pairs of adjacent turns carrying current in the same sense around the second subcoil.
122.

For this reason, the first embodiment is preferred to the second embodiment. However, the second embodiment may be advantageous in that it provides better cancellation of the magnetic fields produced by the segments of the conducting element passing between the two formers 114 and 116. As described above, in Figures 4a to 4h illustrating the first embodiment, an arrow at the right hand side of each figure indicates the position and direction of a segment of conducting element 18 which passes between the two formers 14 and 16. It will be seen that the segments of the conducting element 18 which pass "straight" ("non-crossing") from one former to the other (Figures 4a, c, e and g) always travel in the same direction and therefore do not cancel each other.

Likewise, the segments which "cross" between the two formers (Figures 4b, d, f and h) always travel generally from right to left and do not cancel each other. In the first embodiment, cancellation of the magnetic fields generated by these segments is achieved by shaping the path followed by the "crossing" and "non-crossing" segments of the conducting element 18 so that they all pass through an axis X10 (midway between supports 24 and 25, see Figure 3a). In this way, the "crossing" segments overlap the "non-crossing" segments so that parts of the "crossing segments" cancel out the field generated by parts of the "non-crossing" segments and vice versa. In contrast, the second embodiment may be advantageous in that the corresponding segments of the conducting element 118 are arranged to provide better magnetic field cancellation in the region between the two subcoils 120, 122, even if the paths of these segments do not overlap as in the first embodiment. The paths followed by the segments of the conducting element 118 between the two subcoils 120, 122 are arranged so that the currents in each of these segments cancel out over four consecutive layers, even when, as shown in Figures 9a-9d, the crossing and non-crossing and non-crossing
segments do not overlap.

[Third embodiment]
A third embodiment of the invention will be described

with reference to Figures 10 and 11a to lid. Figure 10 shows
a low-inductance coil assembly 210 comprising a coil 212,
three cylindrical formers 214, 215, 216, two hemi-cylindrical
supports 224, 226 and a cylindrical support 217. The coil 212
comprises a conducting element 218, in the form of a
conducting wire or tape, for example a superconducting wire or
tape, formed into three subcoils 220, 221, 222 wound around
formers 214, 215 and 216 respectively. The conducting element
218 defines a first subcoil 220 comprising a plurality of
turns around a first axis X201, a second subcoil 221
comprising a plurality of turns around a second axis X202, and
a third subcoil 222 comprising a plurality of turns around a
third axis X203, the turns of each subcoil 220, 221, 222 being
distributed along the length of the respective subcoil 220,
221, 222. The turns of each subcoil 220, 221, 222 are
arranged such that, when a current flows in the conducting
element 218, adjacent turns of each subcoil 220, 221, and 222
carry the current in opposite senses about the respective axis
X201, X202, X203. As will be explained in detail below, the
conducting element 218 comprises alternating first and second
portions, the first portions contributing to a first subcoil
220, and the second portions contributing to a second and
third subcoils 221, 222. In this way, adjacent pairs of turns
around the first axis X201 are connected in series via turns
around the second and third axes X202, X203. This is achieved
by the winding pattern illustrated by Figures 11a to lid.

Figures 11a and 11b show the first layer of the winding
pattern. Figure 11a shows the point of entry of the conducting
element 218 to the coil 212 and its route as it passes around
support 224 and then performs two-thirds of a clockwise turn
around formers 215 and a complete clockwise turn around former
Figure 11b shows the route of the conducting element 218 as it performs two-thirds of an anticlockwise turn around support 217, followed by a clockwise turn around former 214.

Figure 11c and lid show the second layer of the winding pattern, as the conducting element 218 makes half a clockwise turn around support 217 and an anticlockwise turn around former 216 (Figure 11c), then two-thirds of an anticlockwise turn around former 215, an anticlockwise turn around former 214, and a sixth of a clockwise turn around support 217 (Figure lid). The pattern then repeats according to Figures 11a to lid as many times as required. Again, it is preferred that the coil 212 comprises an even number of layers, so that each subcoil 220, 221, 222 comprises an equal number of turns in each sense in order to minimise the inductance of the coil 212.

In the third embodiment, the turns around each of subcoils 220, 221, 222 alternate clockwise, anticlockwise, clockwise, anticlockwise, and so on. Therefore, a current flowing through the conducting element 218 will flow in opposite senses through adjacent turns of each of the subcoils 220, 221, 222. This results in cancellation of the magnetic field created by current in the turns of each subcoil 220, 221, 222, and thus a low inductance. It can also be seen that a partial subcoil 223 is formed by the partial turns around the cylindrical former 217. Adjacent turns around this partial subcoil 223 are also in opposite senses, alternating anticlockwise, clockwise, anticlockwise, clockwise, and so on. Thus the magnetic field created by current in the turns of the partial subcoil 223 is also substantially cancelled, resulting in a low inductance.

In the third embodiment, it can be seen that the path of the conducting element 218 follows a "loop" beginning and ending at an axis X210 indicated in Figure 10. The loop comprised turns of subcoils 221 and 222 around each of the axes X202 and X203 (formers 215 and 216) and turns of the
The turns of the subcoil 220, wound around axis X201 (former 214), are used for reversing the direction of the conducting element 218 so that it can be wound about the loop in successive layers in opposite senses. In other words, a loop in a clockwise sense via subcoils 212 and 222 (Figure 11a and first part winding shown in Figure 11b) is followed by a turn of subcoil 220 (second part of winding shown in Figure 11b), before repeating the loop around subcoils 212 and 222, but in an anticlockwise sense (Figure 11c and first part of winding shown in Figure 11d). This second loop, in the anticlockwise sense, is then followed by another turn of subcoil 220, in an anticlockwise sense. Thus successive layers of the "loop" are in opposite senses, and successive turns of the subcoil 220 are in opposite senses.

Importantly, the "loop" around subcoils 212, 222 and 223 begins and ends adjacent to the subcoil 220 so that each path around the loop, in either sense, can be followed immediately by a change-of-direction turn around subcoil 220. In this way, the number of turns around the subcoil 220 can be equal to the number of turns around the loop.

In particular, each layer of the "loop" begins and ends at an axis X210. The segments of the conducting element between the loop and subcoil 220 are curved around supports 224 and 217 so that the "crossing" segments (i.e. those connecting an anticlockwise (clockwise) loop with a clockwise (anticlockwise) turn of subcoil 220) and the "non-crossing" segments (i.e. those connecting an anticlockwise (clockwise) loop with an anticlockwise (clockwise) turn of subcoil 220) stack up directly above each other and cancel each other out. This is similar to the cancellation of the "crossing" and "non-crossing" segments of the figure-of-eight winding of the first embodiment (Figure 4).

By winding the conducting element 18, 118 into two subcoils 20, 22, 120, 122, as in the first and second
embodiments, the length of the coil 12, 112 is reduced as compared to a bifilar helical coil wound from an equivalent length of conducting element. By increasing the number of subcoils to three subcoils 220, 221, 222 (and a further partial subcoil 223) as in the third embodiment described above, the length of the coil 212 is reduced still further. Thus the present invention provides a means for adapting the length of the coil to different applications.

Although the first to third embodiments above are based on substantially cylindrical subcoils having the same diameter, and a coil may include subcoils having different or varying diameters. Also, the subcoils may have other shapes, for example elliptical, and a single coil may include subcoils having different shapes. Thus, the overall dimensions of the coil may be adapted for use in different applications. For example, when used in a superconducting fault current limiter, the length and cross-section of the coil may be adapted to increase the length of super-conducting element which may be accommodated in a given cryostat.

Arrangements which maintain the magnitude of the radius of curvature of the conducting element at a substantially constant value, as in the first to third embodiments, may be preferred, as this enables the conducting element to be wound at close to the minimum radius of curvature along its entire length, which may be useful in optimising the ratio of the length of the conducting element to the overall volume of the coil.

Although the above embodiments describe a coil assembly comprising a coil and various formers and supports, the coil may be used alone. Formers and/or supports may nonetheless be useful for winding the coil, even if they are removed subsequently.

[Fourth embodiment]

A fourth embodiment will be described with reference to
Figure 12 shows a superconducting fault current limiter 410, comprising a current limiting component 412 in the form of one or more low-inductance coils 12, 112, 212 according to any one of the first to third embodiments described above, wherein the conducting element 18, 118, 218 comprises a superconducting material, such as magnesium diboride wire. The current limiting component 412 is immersed in a liquid coolant (cryocoolant) 414 which is contained in a thermally insulated vessel 416. The thermal insulation of the vessel 416 is typically provided by a vacuum layer 418 surrounding the volume containing the cryocoolant 414. The vacuum-insulated vessel 416 is also sealed from the external atmosphere and is designed to withstand a predetermined change of the internal pressure. The vessel 416 may also be fitted with automatic pressure relief valves (not shown) because, in the event of a fault current, the "quenching" superconducting material of the current limiting component 412 generates sufficient heat to boil the cryocoolant 414 in its vicinity causing a pressure rise inside the vessel 416. Thermally insulated bushings 420 may be used to allow current leads 422 to pass into the vessel 416 causing minimal heat loss. A cooling machine 424 ensures that the cryocoolant 414 is kept at a sufficiently low temperature so that the superconducting parts of the current limiting component 412 maintain a superconducting state in the absence of fault current. Instead of a liquid cryocoolant 414, a solid or gaseous coolant may be used.

Advantageously, the low-inductance coils of the present invention enable a greater length of superconducting wire or tape to be accommodated in a cryostat of a given size, thereby reducing the costs of cooling the superconducting material to temperatures below the critical temperature of the material.

The superconducting fault current limiter 410 may comprise one or more low-inductance coils connected in series or parallel. The superconducting fault current limiter 410
may comprise one or more low-inductance coils for each phase of an electrical network to be protected.

[Fifth embodiment]

A fifth embodiment of the invention is shown in Figures 13a to 13d. A generally triangular arrangement 710 is formed by eight cylindrical formers 714 and eight part cylindrical supports 724, such that five of the cylindrical formers 714 are arranged within the perimeter of a circle 750 and three of the formers 714a, 714b, 714c are arranged outside of the circle 750 such that their centres form the corners of an equilateral triangle. Referring firstly to Figure 13a, the coil 712 passes in an anti-clockwise sense around an outermost former 714a, clockwise around part of the periphery of the circle 750, in a clockwise sense around a second outermost former 714b, and then around part of the periphery of each of the formers 714 arranged within the circle 750, before passing around a part cylindrical support 724a and in a clockwise sense around the third outermost former 714c. The coil 712 then passes clockwise around part of the periphery of the circle 750. The coil 712 then passes around one of the part cylindrical supports 724b as shown in Figure 13b and then passes around the formers 714, 714a, 714b, 714c as shown in Figure 13c to form the next layer, i.e. in a manner which is a mirror image of the arrangement shown in Figure 13a. The coil 712 then passes around one of the part cylindrical guides 724c as shown in Figure 13d, and then the process shown in Figures 13a to 13d is repeated for subsequent layers. It can be seen that the path followed in Figure 13c has identical radii of curvature in each portion to corresponding parts of the path followed in Figure 13a, but in an opposite sense so that the magnetic field generated by each turn of one layer is substantially cancelled by the field generated in the subsequent layer.

As described above in connection with the third
embodiment, the winding pattern of the fifth embodiment also comprises a "loop" including turns around each of the formers 714 located within the circle 750 and formers 714b and 714c. Turns around the former 714a are used to reverse the direction of the conductor 712 around the loop. Thus the "loop" begins and ends adjacent to the former 714a.

The arrangement shown in Figures 13a to 13d has the advantage that a very high packing density of the superconducting element 712 can be achieved, and the triangular arrangement of the turns enables the coil assemblies 710 to be easily inserted into a cylindrical tank of cryocoolant liquid, or into a cylindrical vacuum chamber. In particular, since the angle subtended by the apex of each triangular arrangement of turns is 60 degrees, this enables six arrangements of turns to be easily arranged in a cylindrical tank of coolant liquid such that there are two arrangements of turns for each phase, as shown in Figure 15. By using two triangular arrangements for each phase, it is possible for the connections to the windings for each phase to be located on the same side. For example, this can be achieved by winding one triangular arrangement from top to bottom and continuing the winding around another from bottom to top, so that the connectors to the conductor are both located at the top of the coil.

[Sixth embodiment]

A further embodiment is shown in Figure 14, in which instead of following parts of the perimeter of the circle 750 within which five of the formers 714 are arranged, the coil 712 passes around further part cylindrical supports 724 having substantially the same radius of curvature as the formers 714.

[Seventh embodiment]

A seventh embodiment of the invention will be described with reference to Figures 16a-j. Figures 16a-j illustrate the
winding pattern for a low inductance coil assembly 810 comprising a coil 812, five cylindrical formers 814, 815, 816, 817, 818 and two arc-shaped supports 825, 826. The coil 810 comprises a conducting element 813, in the form of a superconducting wire or tape, wound into five subcoils 820, 821, 822, 823, 824, each wound around a respective former 814, 815, 816, 817, 818. Each of the subcoils 820, 821, 822, 823, 824 comprises a respective plurality of turns around a respective axis X801, X802, X803, X804, X805 (see Figure 16b), the turns being distributed along the length of the respective subcoil 820, 821, 822, 823, 824.

Figure 16a shows the connection of the conducting element 813 at the lower end of the coil 812. A transition joint 830, integrally formed with the conducting element 813, connects the conducting element 813 to a current lead 832. The conducting element 813 follows a first turn anticlockwise around former 814.

Figure 16b shows a first (lowermost) layer of the winding pattern. The conducting element 813 follows a meandering path which comprises turns around each of the formers: 815, 816 and 817. The conducting element 813 then follows a clockwise turn around former 818, as shown in Figure 16c, in order to change direction. At this location, the conducting element 813 also changes height as it transitions from the first layer to the overlying second layer.

Figure 16d shows a second layer of the winding pattern, in which the conducting element 813 retracts the meandering path around each of the formers 815, 816 and 817, in the opposite direction from the first layer. In use, a current flows in opposite directions along the meandering path of the first and second layers, so that the magnetic fields generated by these portions of the coil 810 cancel each other. Note also that the leading end of the electrical conductor shown in Figure 16d lies directly above a corresponding portion of the first layer (Figure 16b), so that the first and second layers
generate opposed magnetic field in the region between the formers 814 and 815. The conducting element 813 then follows a clockwise turn around former 814, as shown in Figure 16e, in order to change direction once more. Again, the conducting element 813 changes height as it winds around former 814 as it transitions from the second to third layers.

Figure 16f shows a third layer of the winding pattern, in which the conducting element 813 repeats the meandering path around each of the formers 815, 816, 817, in the same direction as the first layer. Note also that the leading end of the electrical conductor shown in Figure 16f lies directly above a corresponding portion of the second layer (Figure 16d), so that the second and third layers generate opposed magnetic field in the region between the formers 817 and 818. The conducting element 813 then follows a clockwise turn around former 818, as shown in Figure 16g, in order to change direction once more.

Figure 16h shows a fourth layer of the winding pattern, in which the conducting element 813 repeats the meandering path around each of the formers 815, 816, 817, in the opposite direction to the third layer. Note also that the leading end of the electrical conductor shown in Figure 16h lies directly above a portion of the third layer (Figure 16f), so that the third and fourth layers generate opposed magnetic field in the region between the formers 814 and 815. The conducting element 813 then follows an anticlockwise turn around former 814, as shown in Figure 16i, in order to change direction once more.

The winding pattern then repeats, with the fifth to eighth layers being identical to the first to fourth layers, and so on. Figure 16j shows the connection of the conducting element 813 at the uppermost layer of the coil 812. A transition joint 834, integrally formed with the conducting element 813, connects the conducting element 813 to a current lead 836.
It can be seen that the winding pattern of this embodiment achieves cancellation every four layers. Adjacent turns around each of the formers 815, 816, 817 of the meander are in opposite directions and therefore cancel each other.

In this embodiment, the number of turns around the formers 814, 818 at the ends of the meander is only half the number of turns around the formers 815, 816, 817 of the meander. Nonetheless, adjacent turns around each of the end formers 814 and 818 are in opposite directions and also cancel each other.

In this embodiment, the end formers 814, 818 have a smaller radius (e.g. 250mm outer diameter) than the formers 815, 816, 187 of the meander (e.g. 320mm outer diameter). One reason for this is to improve the overall packing density of the conducting element 813, since the end formers 814, 818 carry only half as many turns compared to the formers 815, 816, 817 of the meander. Reducing the size of the end formers 814, 818 also reduces the amount of the material used in these formers. Using different diameters for the end formers 814, 818 also helps the overall shape of the coil assembly 810 to be designed to fit into a 120° sector of a cylindrical cryostat or vacuum chamber. In this way, three such coils 810, one per phase of a three-phase power connection, can be arranged compactly in a single cylindrical chamber 916, as shown in Figures 17 and 18.

[Eighth embodiment]

An eighth embodiment will now be described with reference to Figure 19. Figure 19 shows a portion of a superconducting fault current limiter 910, comprising three low-inductance coil assemblies 810, as described in connection with the seventh embodiment above, arranged in an evacuated vacuum chamber 916 as illustrated in Figures 17 and 18. It will be appreciated that the present embodiment may be adapted for use with the coils according to any of the other embodiments described above. The conducting element 813 of
the coils 812 comprises magnesium diboride wire. Current leads 832, 836 conduct current to and from the power supply to the conducting elements 813 of the coil assemblies 810 inside the vacuum chamber 916.

Cryocoolers are used to cool the conducting element 813 in order to maintain a superconducting state in the absence of fault current. This requires removal of heat that is radiated to, conducted to, and produced by the superconducting element 813 and current leads 832, 836 under normal operation. The superconducting element 813 of the fault current limiter 910 is at high voltage (e.g. up to 95kV during a lightning strike), whereas the cold head 918 of the cryocooler is at ground potential. It is therefore necessary to keep these potentials separated from each other. Therefore, the thermal connection between the cold heads 918 of the cryocoolers and the conducting elements 813 and/or current leads 832, 836 must simultaneously provide good thermal conductivity and high voltage isolation.

In this embodiment, a solid coolant is used to cool the magnesium diboride superconducting element 813 to its operating temperature (e.g. 20K). The solid coolant is provided by the formers 814, 815, 816, 817, 818, which conduct heat from the superconducting element 813 to the cold head 918 of the cryocooler via a copper thermal bus 920. As shown in Figure 20, the formers 814, 815, 816, 817, 818 comprise hollow tubes 924. In this embodiment, the tubes 924 are formed from alumina, which is selected as the solid coolant material for the superconductor as it has a relatively high thermal conductivity and specific heat capacity and a very high resistivity. However, other materials may be used provided they are good thermal conductors and good electrical insulators, for example beryllium oxide, sapphire, or aluminium nitride. Pure aluminium, in the form of 1mm thick aluminium strips 926, is bonded to the inside surfaces of the formers 814, 815, 816, 817, 818 to improve heat conduction. A
copper thermal bus 920 provides a thermal connection between the aluminium strips 926 and the cold head 918 of the cryocooler, and a central rod 928 provides mechanical support to the formers 814, 815, 816, 817, 818. The superconducting magnesium diboride wire 813 is bonded to the outside surface of the formers 814, 815, 816, 817, 818 using epoxy glue. The wire 813 may be provided in the form of a single tape (e.g. 5mm by 1mm) or as a multi-strand bundle of 48 or 96 strands of 0.2mm diameter. In this embodiment, the end formers 814, 818 have an outer diameter of 250mm, while the other formers 815, 916, 817 have an outer diameter of 320mm. Since the coil density is lower on the end formers 814, 818, the amount of coolant material used in the end formers can be reduced by using a smaller diameter, thereby reducing costs. The length of the formers 814, 815, 816, 817, 818 needs to be approximately 1 metre to accommodate approximately 400m of conducting element 813 with sufficient separation between adjacent turns on each former.

In addition, heat is conducted from each current lead 832, 836, using a two-stage cooling arrangement as shown in Figures 19 and 21. Each current lead 832, 836 comprises an insulated copper primary current lead 930a and a superconducting secondary current lead 930b formed from a high temperature superconductor. A first thermal anchor 934 conducts heat from the lower end of the primary current lead 930a and the upper end of the secondary current lead 930b to a copper thermal bus 922 connected to a cold head operating at a first temperature, at which the high temperature superconducting secondary current lead 930b can operate, for example 60K. A second thermal anchor 936 conducts heat from the lower end of the secondary current lead 930b and from the superconducting element 813 to a copper thermal bus 920 connected to a cold head operating at a temperature suitable for operation of the magnesium diboride conducting element 813 as a superconducting fault current limiting element, for
example 20K. The secondary current lead 930b comprises a ceramic superconductor which has very low thermal conductivity to minimise thermal conduction between the two thermal anchors 934, 936, and a low electrical resistivity so as to minimise resistive heat generation.

Although Figure 19 shows only a part of the superconducting fault current limiter 910, it will be appreciated that the superconducting fault current limiter 910 comprises further current leads 832, 834 for connections to each of the three coils 810, and a further cooling head connected to the first thermal bus 922 and operating at the first temperature (e.g. 60K).

The first thermal anchor 934 is further illustrated in Figure 22, and comprises an electrically insulating part 940, connected on each side to a respective copper block 946, 948. In this embodiment, the electrically insulating part 940 comprises a thermally conductive dielectric, such as alumina. However, other electrically insulating, thermally conductive materials may be used, such as beryllium oxide, sapphire or aluminium nitride. The electrically insulating part 940 has a double-dish shape, as shown in Figures 23 and 24. The inner dish-like or concave surfaces 942, 944 are plated with copper 950 and then attached to the copper blocks 946, 948 with a vacuum welding or similar process. On one side, the first copper block 946 is bolted or soldered to the copper busbar 922 for thermal connection to the cold head of the respective cryocooler operating at the first temperature (e.g. 60K). On the other side, the second copper block 948 is connected by flexible connections 952 to each of the primary and secondary current leads 930a and 930b. The flexible connections 952 allow for thermal expansion and contraction. The second thermal anchor 936 similarly comprises an electrically insulating part 940 connected on each side to a respective copper block 946, 948, with the first copper block 946 being bolted or soldered to the copper busbar 920 for thermal
connection to the cold head of the respective cryocooler operating at the second temperature (e.g. 20K), and the second copper block 948 being connected by flexible connections 952 to each of the secondary current lead 930b and superconducting element 813.

The shape of the electrically insulating part 940 is important in reducing the likelihood of flashover from the high potential conductor. Flashover is most likely to occur at a triple point, at which metal, dielectric and vacuum meet. This is particularly likely if the triple point is located at the point of maximum electric field. By arranging the surfaces 942 and 944 to be concave such that the plated ends extend away from the areas of contact with the copper blocks 946, 948, the present configuration shifts the triple point, at which copper, alumina and vacuum meet, away from the locations where the electric field is highest. Figure 23 shows the locations 960 of highest electric field, and the location 962 of the shifted triple point.

It will be appreciated by persons skilled in the art that the above embodiments have been described by way of example only, and not in any limitative sense, and that various alterations and modifications are possible without departure from the scope of the invention as defined by the appended claims.

For example, although the present invention has been described in connection with superconducting fault current limiters, the coil according to the present invention may have other applications where a compact or low-inductance coil is required.

Although monofilar coils have been described, and have particular advantages over bifilar coils, any of the coils of the first to third embodiments may be wound as bifilar coils. In this case, the reversal of direction between the two strands of the bifilar winding could be implemented as a
monofilar loop around one or more of the subcoils, the loop having a radius of curvature greater than a predetermined minimum radius of curvature. This would enable a bifilar coil to be wound more compactly using a continuous conducting element, avoiding the need for a connection between the two strands of the bifilar winding.
CLAIMS

1. A coil comprising an electrically conducting element defining:

4. A coil according to claim 3, wherein the curvature of the conducting element is about axes substantially parallel to said first and second axes.

5. A coil according to claim 3 or claim 4, wherein the path of the conducting element consists of a series of
6. A coil according to any one of the preceding claims, wherein the conducting element is wound in a figure-eight type pattern about one said first axis and one said second axis,

wherein a first turn about said first axis in a first sense is followed by a second turn about said second axis, then a first turn about the first axis in a second sense, opposite to said first sense;

wherein the path of the conducting element between the first and second turns always passes substantially through a third axis parallel to said first and second axes.

7. A coil according to claim 6, wherein said first turn about said first axis in said second sense is followed by a second turn about said second axis in a sense opposite to that of the previous second turn about the second axis.

8. A coil according to any of claims 1 to 5, wherein:

said coil comprises a group of respective pluralities of second turns around multiple respective second axes;

the path of said conducting element follows, in a first sense, a loop comprising at least one respective second turn around each said second axis of said group, followed by at least one respective first turn around said or each first axis, followed by another said loop in a second sense, opposite to said first sense; and

said pluralities of second turns of said group are arranged such that each said loop begins and ends adjacent said plurality of first turns.

9. A coil according to claim 8, wherein said loop in said second sense is followed by a first turn around said at least one first axis, in a sense opposite to that of the circular arcs.
previous turn around said first axis.

10. A coil according to claim 8 or claim 9, wherein each said loop begins and ends at an axis parallel to said first and second axes.

11. A coil according to any of claims 1 to 5, wherein:
said coil comprises a plurality of third turns around a respective third axis;
said coil comprises a group of respective pluralities of second turns around multiple respective second axes;
the path of said conducting element follows, in a first direction, a meander comprising at least one respective second turn around each said second axis of said group, followed by a turn around said first axis, followed by another said meander in a second direction opposite to said first direction, followed by a turn around said third first axis.

12. A coil according to claim 11, said path of said conducting element next follows said meander in said first direction, followed by a turn around said first axis in a sense opposite to the previous turn around said first axis, followed by another said meander in said second direction, followed by a turn around the third axis in a sense opposite to the previous turn around said third axis.

13. A coil according to any of the preceding claims, wherein:
said coil comprises multiple pluralities of second turns around multiple respective second axes;
said multiple pluralities of second turns are arranged radially inward of a periphery of a circle, said circle having a radius of curvature larger than a radius of curvature of said multiple pluralities of second turns; and
at least two further pluralities of second turns and
said plurality of first turns are arranged at separate locations radially outwards of the periphery of said circle.

14. A coil according to claim 13, wherein said at least two further pluralities of second turns and said plurality of first turns are arranged to define the corners of an equilateral triangle.

15. A coil according to any of the preceding claims, wherein:
   said coil comprises multiple pluralities of second turns around multiple respective second axes; and
   said multiple pluralities of second turns and said or each plurality of first turns are arranged substantially within an area defined by an equilateral triangle.

16. A coil according to any of the preceding claims, wherein:
   said coil comprises multiple pluralities of second turns around multiple respective second axes; and
   said multiple pluralities of second turns and said or each plurality of first turns are arranged substantially within an area defined by a 120 degree sector of a circle.

17. A coil according to any of the preceding claims, wherein the ends of the conducting element are located at or extend from locations spaced apart along at least one said first or second axis.

18. A coil according to any of the preceding claims, wherein the conducting element comprises at least one superconductive material.

19. A coil according to claim 18, wherein said superconducting material is continuous along the length of said
conducting element.

20. A coil according to any one of the preceding claims, wherein at least one first turn is connected to at least one second turn by a portion of the conducting element having a radius of curvature substantially equal in magnitude to a radius of curvature of said first and/or second turn.

21. A coil according to any one of the preceding claims, wherein at least one said plurality of first and/or second turns comprises a plurality of pairs of adjacent said first or second turns adapted to carry said current in opposite senses.

22. A coil according to any one of the preceding claims, wherein at least one said plurality of first and/or second turns comprises an equal number of turns in each sense about the respective first and/or second axis.

23. A coil according to any one of the preceding claims, wherein said first axis and at least one said second axis are substantially parallel.

24. A coil according to any one of the preceding claims, wherein a plurality of said first and/or second turns have a substantially constant radius of curvature.

25. A coil according to claim 24, wherein a plurality of said first and said second turns have a first radius of curvature and a plurality of said first and said second turns are arranged radially inward of the periphery of a circle having a second radius of curvature, larger than said first radius of curvature, and at least three said turns are arranged at separate locations radially outwards of the periphery of said circle.
26. A coil assembly, comprising:
a coil according to any one of the preceding claims; and
a plurality of formers;
wherein each said plurality of first and second turns is
wound on a respective former.

27. A coil assembly according to claim 26, further
comprising one or more supports for constraining the path of
the conducting element between two or more formers.

28. A coil assembly according to claim 27, wherein at
least one said support includes a support portion for engaging
the conducting element and having a radius of curvature
substantially equal to that of at least one said first and/or
said second turn.

29. A coil assembly according to any of claims 26 to
28, wherein said conducting element is in contact with at
least one said support and/or former along substantially all
the length of the conducting element.

30. A coil assembly according to any of claims 26 to
29, wherein at least two said supports and/or formers are
spaced apart by a distance slightly greater than the diameter
of the conducting element.

31. A superconducting fault current limiter,
comprising:
at least one coil according to any one of claims 1 to
25, wherein the conducting element comprises a super-
conducting material; and
at least one vessel adapted to enclose at least said
superconducting element at a temperature below the critical
temperature of the superconducting material.
32. A superconducting fault current limiter, comprising:
   at least one coil assembly according to any one of claims 26 to 30, wherein the conducting element comprises a super-conducting material;
   at least one vessel adapted to enclose at least said superconducting element at a temperature below the critical temperature of the superconducting material; and
   cooling means in thermal contact with said supports for removing heat from said coil assembly.

33. A thermal anchor for electrically isolating and thermally connecting an electrical conductor with respect to a thermally conducting element, the thermal anchor comprising:
   an electrically insulating part having
   a first surface having a first area for thermal contact with the electrical conductor, and
   a second surface, opposite to said first surface, having a second area for thermal contact with the thermally conducting element,
   wherein said first surface comprises an electrically-conducting material and is concave such that it extends away from said first and second areas.

34. A thermal anchor according to claim 33, wherein said second surface comprises an electrically-conducting material and is concave such that it extends away from said first and second areas.

35. A thermal anchor according to claim 33 or claim 34, wherein said electrically insulating part comprises alumina.

36. A thermal anchor according to any of claims 33 to
35, wherein said electrically-conducting material comprises copper.
Segment Length = \[\pi \times D \times \frac{120}{360}\]

Segment length = \[\pi \times D \times \left(\frac{120}{360} + \frac{300}{360}\right)\]

Full layer length
\[= \pi \times D \times \left(\frac{120}{360} + \frac{300}{360}\right) \times 2\]
\[= \pi \times D \times \frac{7}{3}\]
Figure 9c

Figure 9d
Layer 1
Clockwise

FIG. 14

FIG. 15