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**Reis et al.**

(10) **Patent No.: US 6,794,970 B2**
(45) **Date of Patent: Sep. 21, 2004**

(54) **LOW ALTERNATING CURRENT (AC) LOSS SUPERCONDUCTING COILS**

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PCT Pub. Date: **Apr. 4, 2002**

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**Related U.S. Application Data**

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(51) **Int. Cl.**[7] .................................................. **H01F 7/00**

(52) **U.S. Cl.** .................................... **335/216**; 174/125.1

(58) **Field of Search** ........................ 335/216; 174/125.1

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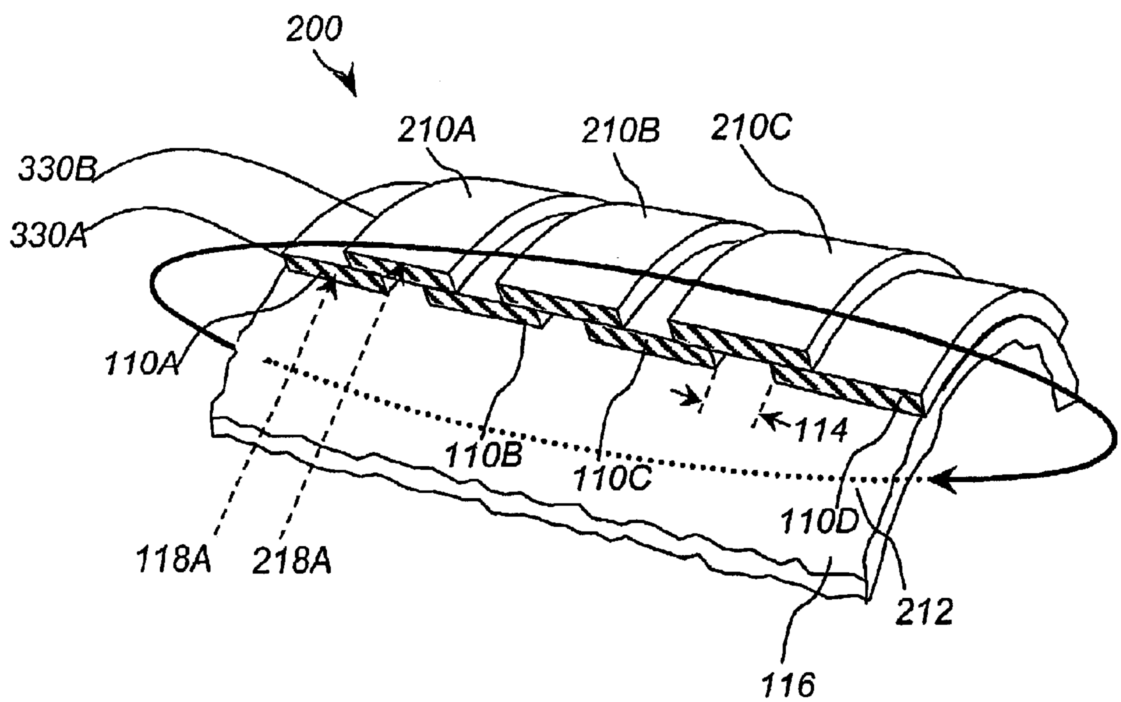
(57) **ABSTRACT**

The present invention relates to high-temperature low alternating current (AC) loss superconducting coil (**110**A–C), to methods of fabricating such superconducting coils (**110**A–C) and to devices which utilize high temperature superconductor [HTS] tape coils such as transformer, motors, generators, etc.

**18 Claims, 4 Drawing Sheets**



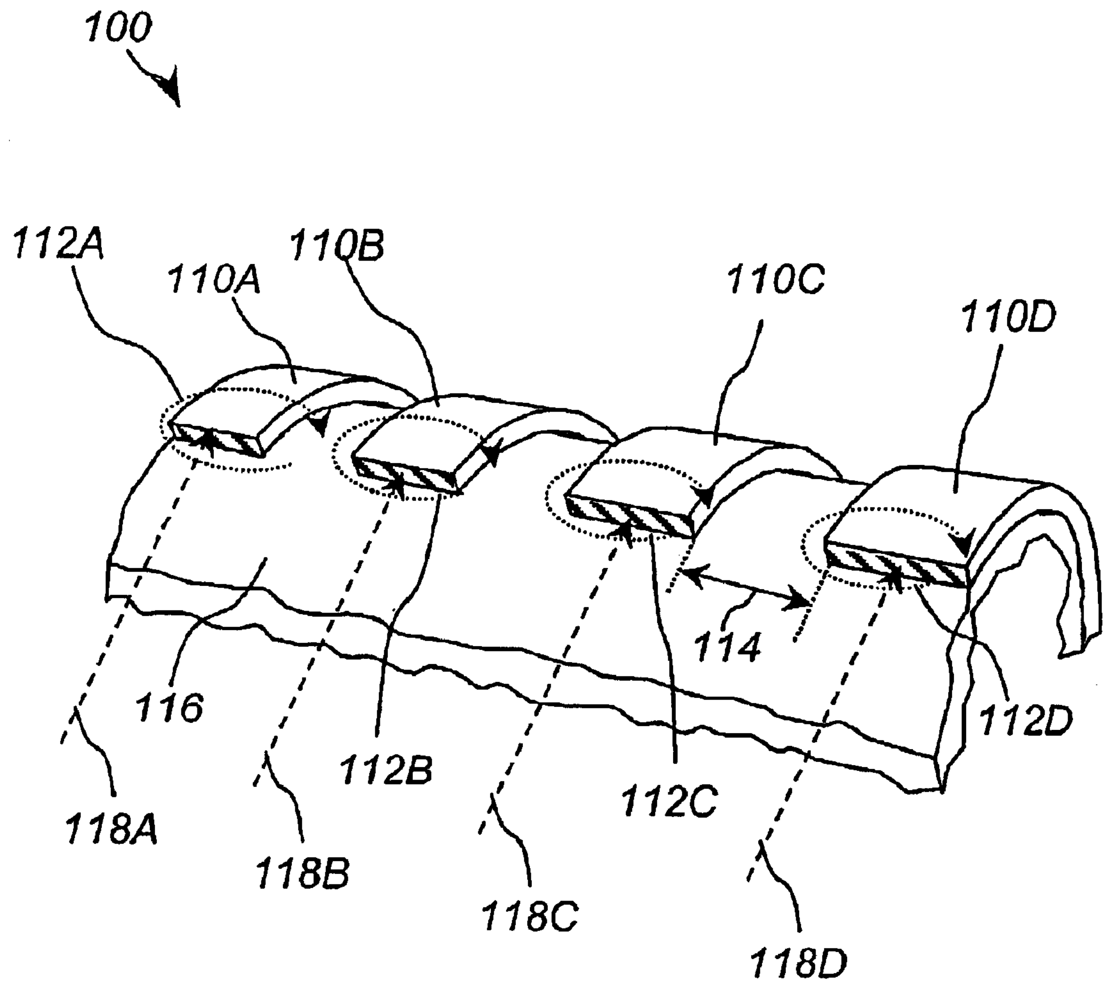

100
112A
110A
110B
110C
110D
116
112B
112C
114
112D
118A
118B
118C
118D

FIGURE 1

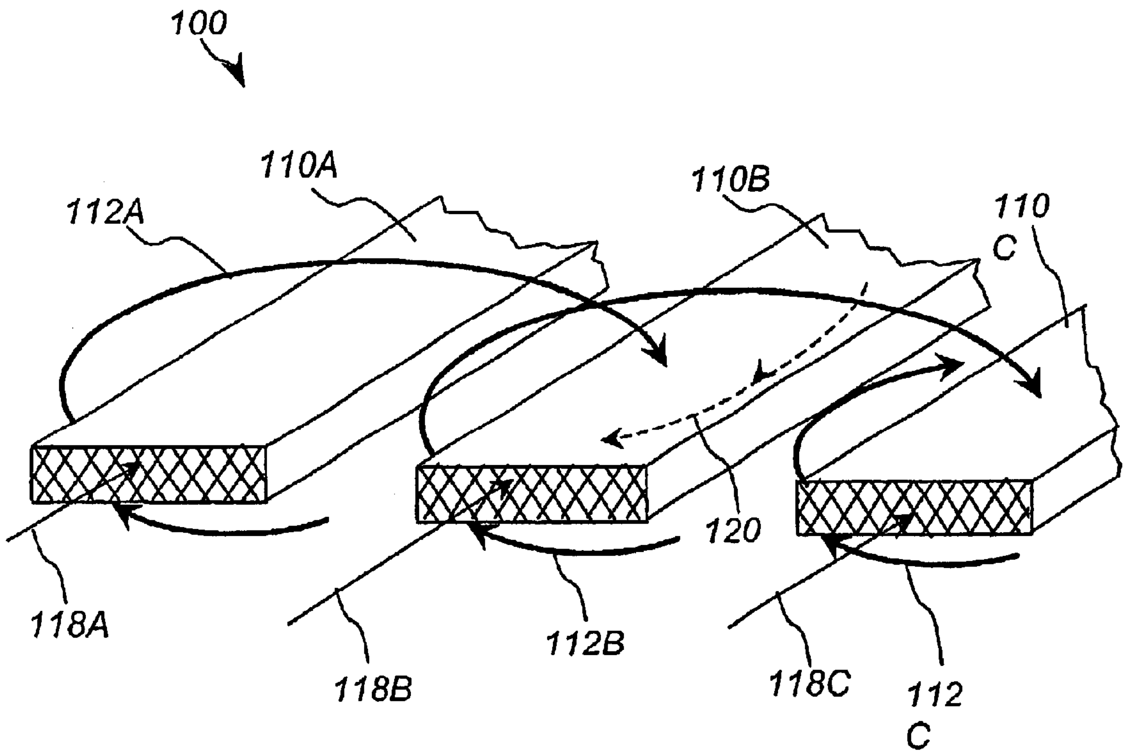



FIGURE 2

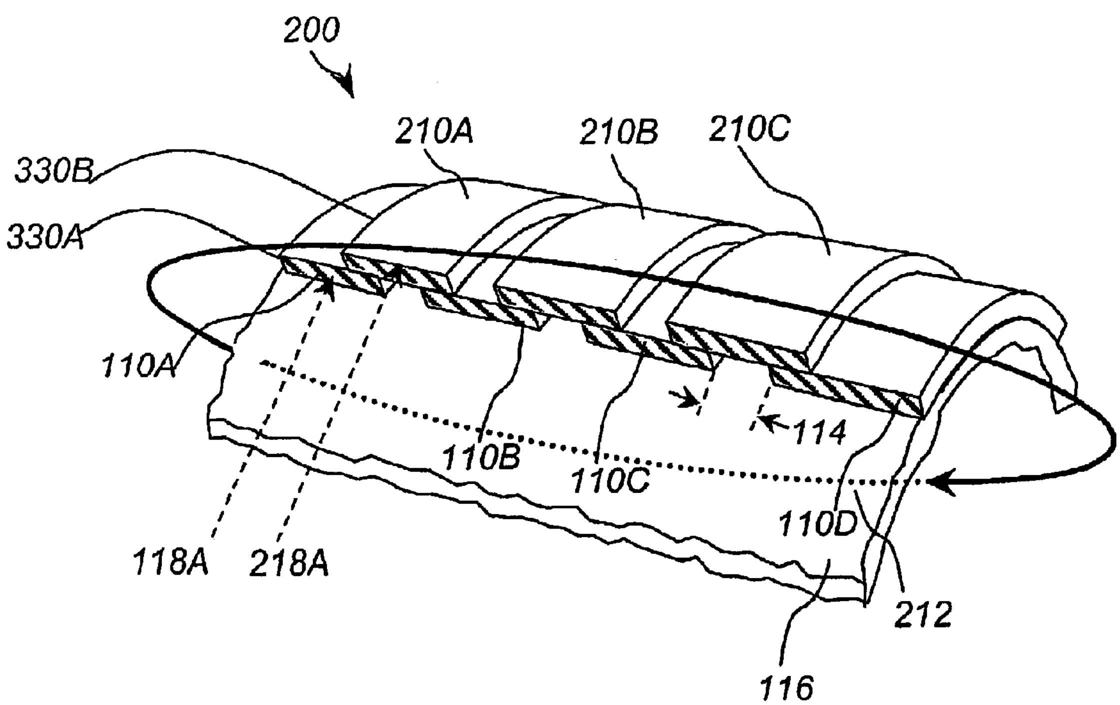

200
210A
210B
210C
330B
330A
110A
110B
110C
114
110D
118A
218A
212
116

FIGURE 3

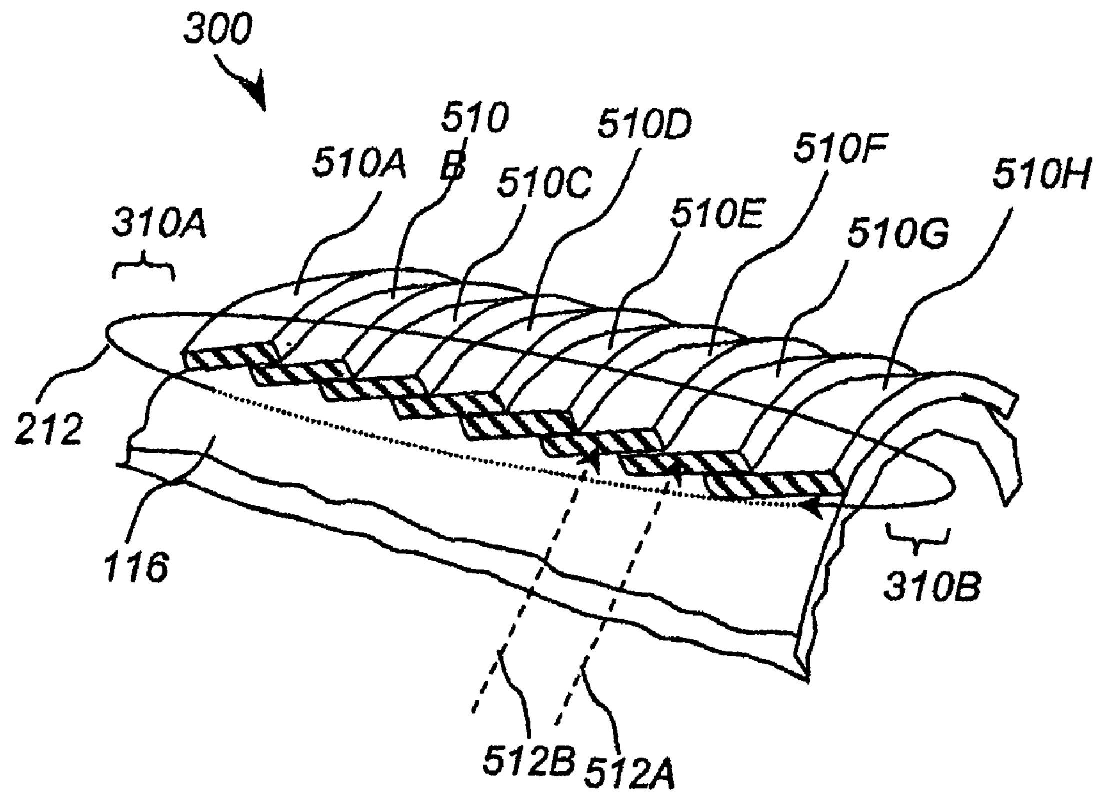

300
510
B
510D
510A
510C
510F
510H
510E
310A
510G
212
116
310B
512B
512A

FIGURE 4

# LOW ALTERNATING CURRENT (AC) LOSS SUPERCONDUCTING COILS

This application claims the benefit of Provisional Application Nos. 60/235,733, filed Sep. 27, 2000 and 60/241,592, filed Oct. 19, 2000.

## FIELD OF THE INVENTION

The present invention relates to low alternating current (AC) loss high temperature superconducting coils, to methods of fabricating such superconducting coils and to devices which utilize high temperature superconductor [HTS] tape coils such as transformers, motors, generators, etc.

## BACKGROUND OF THE INVENTION

Electrical conductors, such as copper wires, form the basic building block of the world's electric power system, i.e., wire in transformers, electric motors, generators, and alternators. The discovery of high-temperature superconducting compounds in 1986 has led to the development of their use in the power industry. This is the most fundamental advancement in conductor technology used for power systems in more than a century.

Over the past three decades, electric power use has risen about 25%–40% in the United States. With this rising demand for power comes an increased requirement for low-cost power. Because of the lack of DC resistance and the low AC losses of superconductors at operating temperatures, superconducting devices are being developed for application throughout the electric power industry.

The power industry's future use of superconductors depends on the overall cost and performance (low power loss) benefits that the superconductor wires offer. HTS tape technologies drive down the costs, increase the current-carrying capacity, and improve the reliability of the wiring system, thus impacting electric power systems in a variety of ways. These ways include the possibility of greatly reduced size and weight of the wires used in devices such as transformers, motors, and generators. Superconductor wires have many applications because of their efficiency for carrying electricity and their ability to carry much higher electrical currents than other conducting materials in less volume.

There exists the unmet technical challenge in the power industry of fabricating HTS coils and devices in such a way that they operate with negligible alternating current (AC) losses. These superconductors can carry direct current (DC) with negligible losses, but DC is rarely used in the power industry. AC is the dominant form in most of the world's power coil-based devices. AC applications of HTS tapes operate with non-negligible energy losses, the energy escaping in the form of heat. This impacts the efficiency of the system beyond the mere energy loss since the heat generated must be removed from the environment of the device.

Superconductors operate in the temperature range of 4°–85° K, far below ambient temperature (298° K). Thus, superconductors require refrigeration, and refrigeration requires continuous expenditure of energy. For example, if the heat caused by the electrical current flowing in superconductor wires is at 77° K and is dissipated at the rate of one watt, then refrigerators must be supplied with approximately 10–40 watts of electrical power to dissipate that generated heat. Absent this refrigeration, the superconductor material would warm itself to above its sukerconducting temperature and cease to operate as a superconductor, thereby eliminating any advantage and, in particular, providing worse performance than conventional copper conductors.

The heat generated must be eliminated to cost-effectively maintain the low temperatures required by the superconductor. Successful solution of this problem would reduce operating costs by reducing the added cooling energy needed.



The key problem of HTS tapes is that unwanted AC magnetic fields are generated by the current flowing in the neighboring HTS tapes, which causes AC losses. Because the HTS tape material and geometry is anisotropic, magnetic fields passing perpendicular to the preferred direction generate significantly greater losses than those of parallel fields. In the present invention, there are no perpendicular magnetic fields except for the very ends of the wiring structures, where different loss mechanisms apply. A discussion of AC losses caused by magnetic fields can be found in W. T. Norris, J. Phys. D 3 (1970) 489–507, or Superconducting Magnets by Martin N. Wilson, Oxford University Press, Oxford, UK 1983.

Kalsi et al., U.S. Pat. No. 6,081,987, entitled "Method of Making Fault Current Limiting Superconducting Coil," provides a multiple tape HTS system. Kalsi et al. describes a superconducting magnetic coil that includes a first superconductor formed of a first anisotropic superconducting material wire for providing a low-loss magnetic field characteristic for magnetic fields parallel to the longitudinal axis of the coil, and a second superconductor material wire having a low-loss magnetic field characteristic for magnetic fields, perpendicular to the longitudinal axis of the coil. The first superconductor has a normal state resistivity characteristic conducive for providing current limiting in the event that the second superconductivity wiring material of the magnetic coil is subjected to a current fault.

Kalsi et al. wires two superconductive HTS wiring tapes in parallel along the length (longitudinally) of the cable, but the two HTS wiring tapes are of different materials and one HTS wiring tape is used as a back up for fault tolerance. There is no mention of wiring configurations to reduce AC losses.

It would be highly beneficial to develop a superconductor configuration that reduces AC losses and associated very high refrigeration costs. Practical devices for AC applications could then be wound using wide flat superconductors, the most prevalent and desirable form of high temperature superconductors (HTS).

Thus, it is an object of this invention to provide a method of fabricating superconductor coils such that AC losses due to the presence of a localized perpendicular component of the self-field is eliminated or minimized.

It is another object of this invention to provide superconducting coils with minimized AC losses due to the presence of a localized self-field perpendicular field component.

It is yet another object of this invention to provide superconducting devices with minimized self-generated AC losses.

It is yet another object to reduce refrigeration requirements associated with the operation of a HTS tapes used in wiring coil-based devices by reducing the heat generated by perpendicular magnetic fields impinging on neighboring HTS tapes.

It is yet another object of this invention to use conventional HTS wiring tapes and conventional wiring methods in a new wiring configuration to create a low cost superconducting device.

## BRIEF SUMMARY OF THE PRESENT INVENTION

HTS tapes may be wound around coil structures in various ways described as "winding configurations". Winding configurations can be changed in a variety of ways by changing (1) the size of the superconductor wires (width, thickness, shape) on the coil structure, (2) the type of superconductor material used, and (3) the way the tape is wound on a coil structure itself (spacing to its neighboring wire).

Surprisingly, it has been determined that eliminating the gaps normally present when superconductor tapes are wound into coils prevents significant energy losses and limits the need for cooling of the superconductor. The present invention obtains low AC loss results by providing novel techniques of winding the tape on a coil stricture.

In most applications, the HTS tape is continuously in the presence of an AC field. The present invention is directed toward HTS tape-winding configurations used in applications where the AC frequency is typically in the range of 50–60 Hz (normal operating frequency in the power industry). By using HTS tapes instead of standard copper wires, better performance (lower power losses) and lower cost are achieved. However, HTS tapes require cooling, which uses power. The present invention is directed to HTS tape wiring configurations designed to achieve low AC losses, thereby reducing refrigeration requirements and enabling superconducting wiring structures to achieve their higher performance at lower cost.

A significant source of AC loss is the loss caused by the magnetic fields of the neighboring HTS tapes, said field being generated by AC current traveling through HTS tapes. In particular, the magnetic self-fields that are allowed to form because of gaps between the HTS tapes.

It has now been discovered the superconductors composed of conventional materials but wound in specified configurations eliminate certain energy losses commonly present in HTS applications. The invention applies broadly to a superconductor winding configuration that eliminates local perpendicular field components.

This new HTS tape configuration approximates a single current "sheet", which produces minimal magnetic fields perpendicular to the current flow, thus significantly reducing AC losses.

The invention comprises a method of fabricating superconductor coils that minimize the AC losses in the main body of the superconducting coil and low AC loss superconducting coils. The beneficial results of the invention are obtained by fabricating superconducting coils such that superconductors overlap one another so that gaps between the superconductors are covered by another superconductor.

Because there are no uncovered gaps, the individual turns of the HTS tapes approximate a single long former of current, forcing the magnetic field to be primarily parallel to the surface of the former and surface of the superconductor. This is a preferential orientation because it minimizes or eliminates the component of the magnetic field perpendicular to the surface of the superconductor. With no substantial perpendicular field component, the high perpendicular field losses in the superconductor are eliminated.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a sectional view of a typical prior art device illustrating the general effects of magnetic self field of one HTS tape on a neighboring HTS tape.

FIG. **2** is a magnified view of a typical prior art device illustrating the general effects of magnetic self field of one HTS tape on a neighboring HTS tape.

FIG. **3** is a sectional view of a typical inventive device illustrating a staggered winding configuration in a HTS tape wire assembly of the present invention.

FIG. **4** is a sectional view of a typical inventive device illustrating a lapped winding configuration in a HTS tape wiring assembly of the present invention.

## DETAILED DESCRIPTION OF THIS INVENTION

The present invention relates to superconductor tapes, fabrication methods and configurations that are designed to minimize the AC losses in a superconducting device or assembly. Superconducting tapes of various compositions are well known. Suitable high-temperature superconductor tapes are for example Bi-2223 superconducting tapes, and include, but are not limited to, those superconductor tapes that are formed from any of the following families of superconductive materials: cuprates (such as YBCO or BSCCO), diborides, or metallic superconductors.

Suitable HTS tapes can be flat and can also be elliptical, or rectangular. HTS tapes are typically from about 0.001 mm to about 10 mm thick and from about 0.5 mm to as wide as convenient for the design of the superconducting assembly. The HTS tapes can be either monocore or multifilament, thin or thick film, powder-in-tube or surface-coated, or any variety of high-temperature superconductors where the final form is flat, elliptical, or rectangular.

A single layer of HTS tape may be used in the lapped embodiment of the invention; a minimum of two HTS layers are required to achieve the benefits of the invention in other embodiments, but it is possible to have as many layers as are required by design considerations.

The HTS tapes are wound on a "former," which is used to support the HTS tapes. The former may be cylindrical, rectangular, or other shape. This former structure can range from 1 inch to several yards in diameter and can range from several inches to several yards in length. HTS tapes are preferably wound very nearly perpendicular to the longitudinal axis of the total former structure to create a coil and to maximize its effectiveness electrically and physically. HTS tapes can also be wound at different angles relative to the longitudinal axis of the former structure to create a coil with different electrical and physical requirements. The tapes are wound on the former using conventional fabrication techniques. Any conventional former can be utilized in the process; upon completion of tape wrapping the former may remain or may be removed.

These tapes are configured so that they overlap one another such that all gaps between HTS tapes are covered by another HTS tape. The HTS tapes are essentially parallel conductors terminated together at the ends of the superconducting device

FIGS. **1** and **2** illustrate, in very general terms, how prior art high-temperature superconductor wires or HTS tapes in the presence of magnetic fields create AC losses in prior art devices.

FIG. **1** shows an example of a general view **100** of prior art HTS tapes on a former. The former **116**, supports the HTS tapes. A cutaway portion of four HTS tapes **110**A–D is also shown. HTS tapes **110** A–D can be either separate tapes, different cross-sections of the same tape, or a combination thereof. The former **116**, shown in FIG. **1**, is a small section of a cylindrical, rectangular, elliptical or other shape of a total former structure that HTS tapes **110**A–D are wound around. HTS tapes **110**A–D are shown wound very nearly perpendicular to the longitudinal axis of the total former structure but can also be wound at different angles relative to the longitudinal axis of the total former **116** structure.

The electrical current direction flowing in each HTS tape **110**A–D is shown as **118**A–D, respectively. Current **118**A flowing in HTS tape **110**A shows the direction of a magnetic self-field loop **112**A. Magnetic field loops **112**B, **112**C, and **112**D are also shown for currents **118**B, **118**C, and **118**D, respectively. Also shown in FIG. **1** is a gap **114** between HTS tapes **110**C and **110**D. Note that this gap **114** exists between HTS tapes **110**A and **110**B and between HTS tapes **110**B and **110**C as well, but is not annotated. Because gaps **114** exist, the magnetic self-fields are able to complete their magnetic loops. Although FIG. **1** portrays magnetic self-field loops **112**A–D as single discrete loops, it should be noted that the magnetic field is infinitely continuous, although the field strength diminishes as one moves away from HTS tape **110**A–D.

FIG. **2** shows a more detailed view of FIG. **1** with further detail regarding magnetic fields in prior art devices. The detail view shows three separate HTS tapes **110**A–C. The electrical current direction flowing in each HTS tape **110**A–C is shown as **118**A–C, respectively. AC current **118**A flowing in HTS tape **110**A shows the direction of AC magnetic self-field loop **112**A. AC magnetic self-field loop **112**B for current **118**B is also shown. AC magnetic self-field loop **112**A is shown to impinge HTS tape **110**B. This impinging of field lines on HTS tape **110**B can range from angles that are perpendicular to the surface of HTS tape **110**B to angles that are parallel to HTS tape **110**B.

The impinging of perpendicular component of the AC magnetic self-field **112**A on HTS tape **110**B, when it is near perpendicular to HTS tape **110**B, induces a deleterious current flow **120** in HTS tape **110**B that creates AC loss. For further discussion, see W. T. Norris, J. Phys. D 3 (1970) 489–507, or Superconducting Magnets by Martin N. Wilson, Oxford University Press, Oxford, UK 1983. Also shown is how each HTS tape **110**, like HTS tape **110**B with current **118**B, has its magnetic self-field **112**B, which impinges on its nearest neighbor HTS tape **110**C.

Decreasing or eliminating the perpendicular component of the magnetic field that is created by the local magnetic self-field **112**A, as shown in FIG. **1**, substantially reduces AC losses. HTS tapes are anisotropic and therefore much higher losses are induced from peipendicular magnetic fields than from parallel magnetic fields. Present winding techniques allow for winding of an HTS tape into superconducting coils and devices in a manner that causes gaps to form between the HTS tapes. As current flows through the HTS tapes, these gaps allow perpendicular magnetic fields to form around the HTS tapes, and these field lines penetrate into adjacent HTS tapes, and thus create AC losses.

The HTS tapes **110**A–D and HTS tapes **210**A–C, represented in FIG. **3**, depicting an inventive device, are individual high-temperature superconductor tapes. In the figure, HTS tapes **110**A–D and **210**A–C are shown as flat, but suitable HTS tapes can also be elliptical, or rectangular. In FIG. **3**, only two layers are shown, first HTS tape level **330**A and second HTS tape layer **330**B, but it is possible to have as many layers as are required by design considerations.

Above a given magnitude of current, called the "critical current" flowing in the superconductor, the superconductor will go normal, that is, no longer be superconducting. For currents at or less than the critical current of the superconducting material, this staggered configuration approximates a single-turn current sheet, forcing the collective fields to be mainly parallel to the surface of the superconductor winding, a preferential orientation. Therefore, with no substantial perpendicular field component, the high AC losses caused by perpendicular magnetic fields penetrating adjacent HTS tapes are eliminated in the main body of the superconducting assembly.

When transport currents are at, or less than the critical current of the superconductor, this approximates a single-turn current sheet with a constant transport current per unit of axial length along the coil, a situation that substantially minimizes the perpendicular field (with the exception of the end-trim regions). The collective magnetic field loop **212** of FIG. **3** surrounding the approximated single-turn current sheet is almost completely parallel to the surface of the HTS tapes in the main body of the windings.

A first preferred embodiment of the invention is the staggered winding embodiment. The staggered winding embodiment of the invention is described more clearly with



reference to FIG. **3** which shows a cutaway section of staggered winding configuration **200** for a first embodiment of the present invention. FIG. **3** shows HTS tapes **110**A–D on former **116**. HTS tapes **110**A–D are separated by spaces or gaps **114** (one is shown for demonstration purposes). HTS tapes **110**A–D are shown on a first HTS tape layer **330**A. A plurality of HTS tapes **210**A–**210**C of a second HTS tape layer **330**B are shown arranged on top of first HTS tape layer **330**A. Each HTS tape **210** of second HTS tape level **330**B overlaps gaps **114** in first HTS tape layer **330**A. For instance, HTS tape **210**C covers gap **114** between HTS tape **110**C and HTS tape **110**D. Current **118**A shows the direction of current flow in HTS tape **110**A of first HTS tape layer **330**A, whereas a current **218**A shows the direction of current flow in HTS tape **210**A of second HTS tape layer **330**B. All current flows in identical directions in all HTS tapes at both first HTS tape layer **330**A and second HTS tape layer **330**B. A magnetic field loop **212** is created by the composite of the current flow shown in current flow directions **118**A and **218**A in all HTS tapes **110**A–D and all HTS tapes **210**A–C, respectively. Note that magnetic field loop **212** is parallel to all HTS tapes **110**A–D and HTS tapes **210**A–C.

In a second preferred embodiment, as is more clearly described by reference to FIG. **4**, a lapped winding configuration **300** is used. Winding an HTS tape such that one edge of the HTS tape rests on the surface of a former and the opposite edge rests on an adjacent HTS tape creates the lapped configuration.

As shown in FIG. **4**, a plurality of HTS tapes **510**A–H are wound on former **116**. A current direction **512**A and a current direction **512**B show the direction of current in HTS tapes **510**G and **510**F, respectively. Not shown are all the other current flow lines, which are all in the same direction as current directions **512**A and **512**B. The magnetic field loop **212**, caused by the composite current flow in HTS tapes **510**A–H, runs mostly parallel to HTS tapes **510**A–H. An end region **310**A and an end region **310**B show magnetic field loop **212** being completed at the outer regions of the superconductor assembly. As described above, there is some perpendicular component of magnetic field loop **212** in some end winding HTS tapes **512**A and **512**H, which may cause AC losses. However, in this lapped winding configuration **300** there is virtually no perpendicular component to magnetic self-field **212** for HTS tapes not at the ends, and therefore minimal AC losses.

The winding sections of HTS tapes **510**A–H, in the present embodiment, are winding sections of an individual, high-temperature superconductor tape, but could be any number of tapes in parallel. HTS tapes **510**A–H are shown flat, but may be made elliptical or rectangular. HTS tapes **510**A–H are preferably wound around former **116** in a nearly perpendicular path relative to the longitudinal axis of former **116**.

What is claimed is:

**1**. A low alternating current loss superconducting coil comprising a plurality of superconductor tapes, a portion of such tapes being individually positioned in a first layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between the superconductive material in adjacent tapes of such first layer, and at least one second layer formed of a portion of such plurality of tapes each individually positioned in a second layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between superconductive material in adjacent tapes of the at least one second layer, the superconductive material of the at least one second layer overlapping the gaps in the first layer.

**2**. A low alternating current loss superconducting coil as in claim **1**, wherein the first layer and at least one second layers are mostly circular in cross section and concentric, the at least one second layer having superconductive material that collectively entirely overlaps the gaps in said first layer.

**3**. A superconducting coil as in claim **2**, wherein the tapes are at least flat in cross section.

**4**. A low alternating current loss superconducting coil, comprising a plurality of superconductor tapes, each tape being individually positioned in a first layer around a longitudinal axis and extending longitudinally with said axis, each tape in being located between two immediately adjacent tapes, one lateral edge of each tape underlapping one associated adjacent tape and the other lateral edge of each said tape overlapping the other associated adjacent tape, such that at least a minor portion of the superconductive part of the superconductor tape under or overlaps an associated adjacent tape.

**5**. A superconducting coil as in claim **4**, wherein said lapped tapes provide a continuous circumferential loop of superconducting material around said axis.

**6**. A low alternating current loss producing superconductor coil comprising HTS superconducting tape wrapped in a gap free lapped configuration on an annular substrate.

**7**. A method of preparing a low alternating current loss superconducting coil comprising wrapping a cylindrical former section with at least one superconductor, such superconductor being positioned around the longitudinal axis of such former such that at least 1% of each winding of such superconductor around such former overlaps an associated adjacent winding.

**8**. The method of claim **7** wherein the superconductor overlaps at least 75%.

**9**. A method of fabricating low current loss superconducting coils comprising winding a coil of superconducting tape around a former, where the superconducting coil comprises a plurality of superconductor tapes,

individually positioning each tape in a first layer around a longitudinal axis and extending longitudinally with said axis,

locating each tape between two immediately adjacent tapes, one lateral edge of each tape underlapping one associated adjacent tape and the other lateral edge of each said tape overlapping the other associated adjacent tape, such that at least a minor portion of the superconductive part of the superconductor tape under or overlaps an associated adjacent tape.

**10**. An alternate current handling electrical device containing a low alternating current loss superconducting coil, such coil comprising a plurality of superconductor tapes, each tape being individually positioned in a first layer around a longitudinal axis and extending longitudinally with said axis, each tape in being located between two immediately adjacent tapes, one lateral edge of each tape underlapping one associated adjacent tape and the other lateral edge of each said tape overlapping the other associated adjacent tape, such that at least a minor portion of the superconductive part of the superconductor tape under or overlaps an associated adjacent tape.

**11**. The device of claim **10** that is selected from the group consisting of transformers, fault current limiters, electric motors, generators, and alternators.

**12**. An alternate current handling electrical device containing a low alternating current loss superconducting coil, such coil comprising a plurality of superconductor tapes, a portion of such tapes being individually positioned in a first layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between the superconductive material in adjacent tapes of such first layer, and at least one second layer formed of a portion of such plurality of tapes each individually positioned in a second layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between superconductive material in adjacent tapes of the at least one second layer, the superconductive material of the at least one second layer overlapping the gaps in the first layer.

**13**. The device of claim **12** that is selected from the group consisting of transformers, fault current limiters, electric motors, generators, and alternators.

**14**. A low alternating current loss superconducting coil comprising a plurality of superconductor tapes, where

a portion of such tapes is individually positioned in a first layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between the superconductive material in adjacent tapes of such first layer, and at least one second layer is formed of a portion of such plurality of tapes each individually positioned in a second layer around a longitudinal axis and extending longitudinally with such axis, gaps being present between superconductive material in adjacent tapes of the at least one second layer, the superconductive material of the at least one second layer overlapping the gaps in the first layer, or

each tape is individually positioned in a first layer around a longitudinal axis and extending longitudinally with said axis, each tape being located between two immediately adjacent tapes, one lateral edge of each tape underlapping one associated adjacent tape and the other lateral edge of each said tape overlapping the other associated adjacent tape, such that at least a minor portion of the superconductive part of the superconductor tape under or overlaps an associated adjacent tape.

**15**. The coil of claim **14** wherein the superconducting tape is selected from a member of the group consisting of cuprate based, diboride based and metallic superconducting tapes.

**16**. The coil of claim **14** wherein the superconducting tape is a tape selected from the group consisting of monocore, multifilament, thin film, thick film, powder-in-tube and surface-coated superconducting tapes.

**17**. The coil of claim **14** wherein the superconducting tape is a tape selected from the group consisting of elliptical, and rectangular superconducting tapes.

**18**. The coil of claim **14** wherein the superconducting tape has a thickness of from about 0.001 mm to about 10 mm thick.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 6,794,970 B2 

DATED : September 21, 2004

INVENTOR(S) : Chandra T. Reis and Michael S. Walker

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

<u>Column 1,</u>

Line 7, insert the following:

-- This invention was made with government support under Contract No. DE-FC36-98GO10282 awarded by the Department of Energy. The government has certain rights in this invention. --

Signed and Sealed this

Fifth Day of April, 2005

JON W. DUDAS

*Director of the United States Patent and Trademark Office*