United States Patent

Waterman

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[54] ELECTRICAL WINDING OF SHEET CONDUCTOR

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[73] Assignee: **Allis-Chalmers Manufacturing Company,** Milwaukee, Wis.

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[52] **U.S. Cl.**.....**336/187,** 336/60, 336/223

[51] **Int. Cl.**.....**H01f 27/28**

[58] **Field of Search**.....336/186, 187, 223, 60, 185, 336/180

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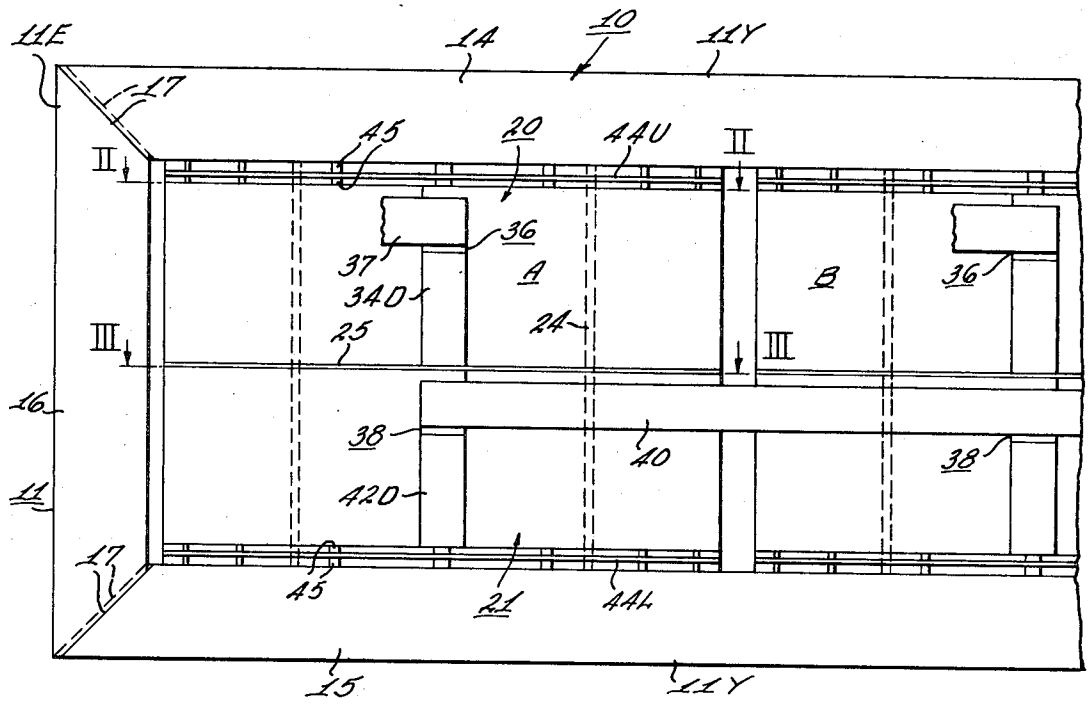
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[57] **ABSTRACT**

A high-current capacity winding of sheet conductor for stationary induction apparatus which substantially reduces eddy current and circulating current losses has a plurality of coaxial coils each of which is spirally wound from a plurality of conductor sheets in parallel that extend the entire coil height with insulation between paralleled sheets and between spiral turns. Crossover connector strips extending parallel to the winding axis connect paralleled conductor sheets in the plurality of coils in series relation and so that the innermost and outermost of the paralleled conductor sheets of different coils are transposed and the net flux linkages of the plurality of flux paths are approximately equal.

2 Claims, 10 Drawing Figures



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SHEET 1 OF 3

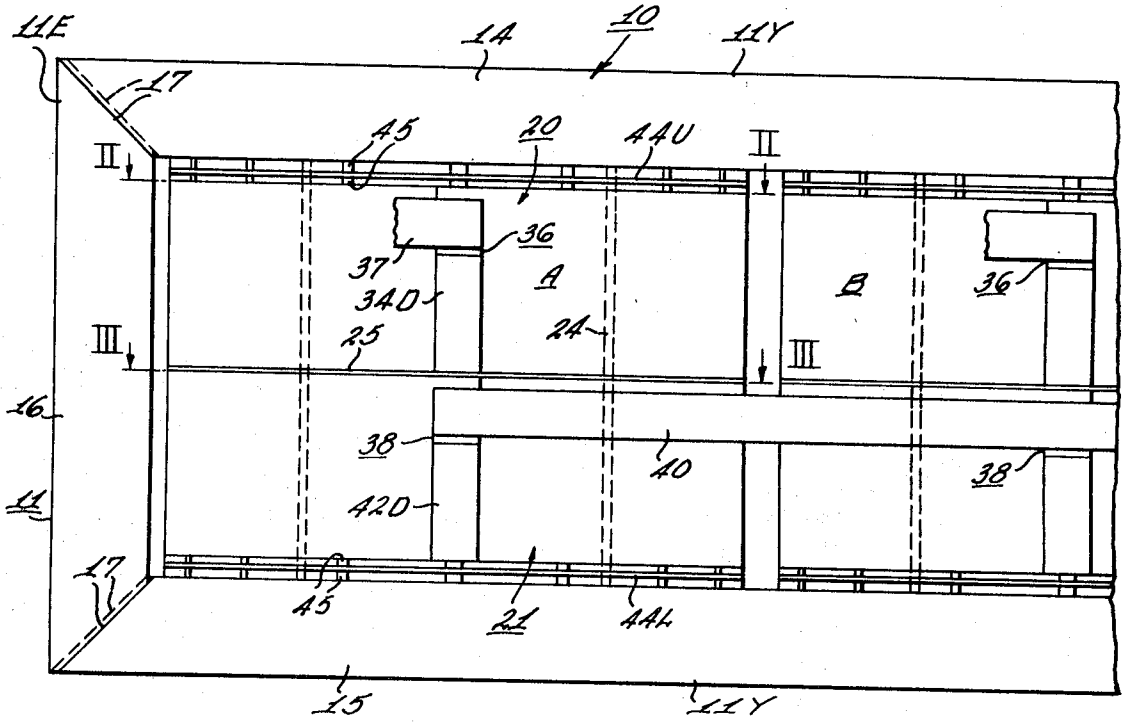


Fig.-1

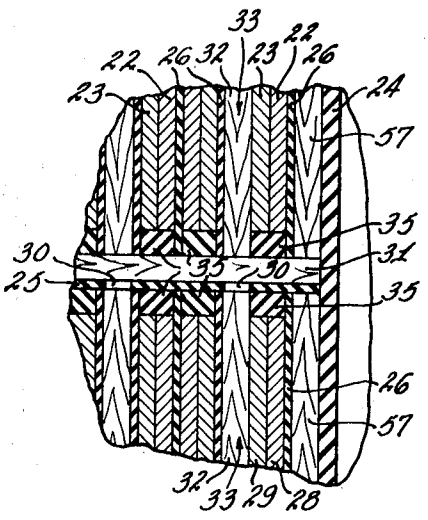


Fig.9

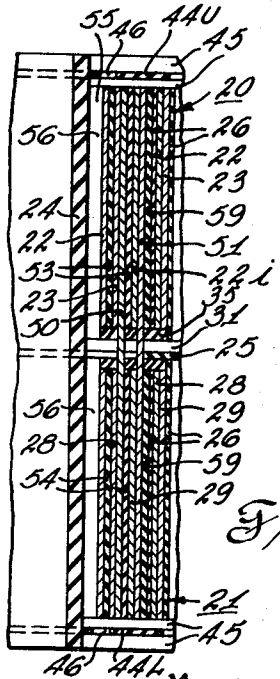


Fig.-10

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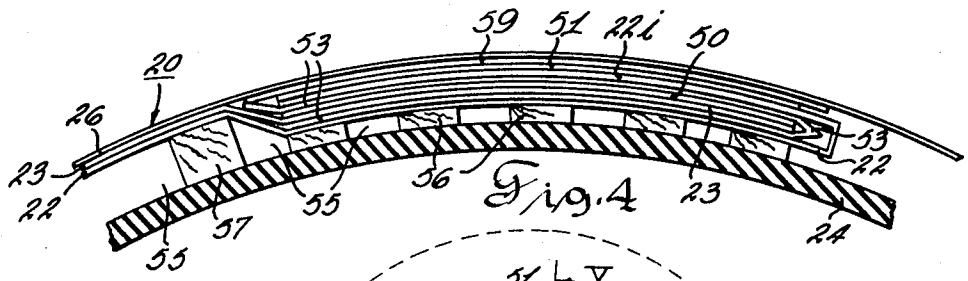


Fig. 4

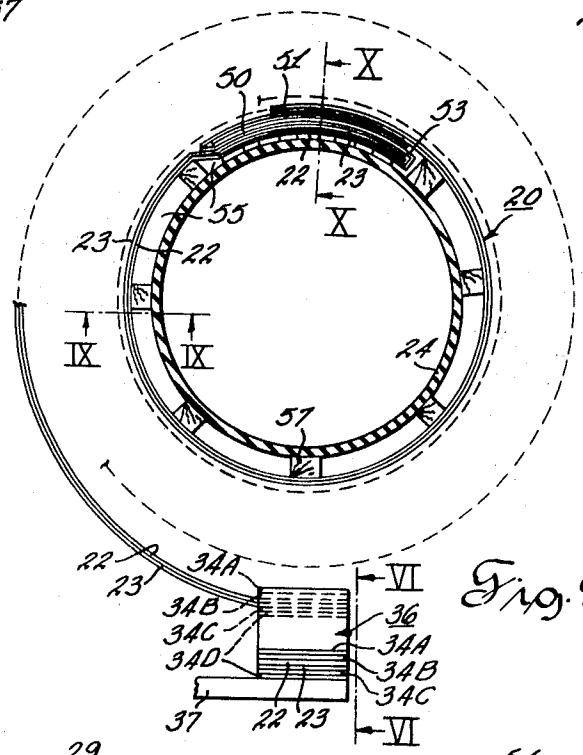


Fig. 2

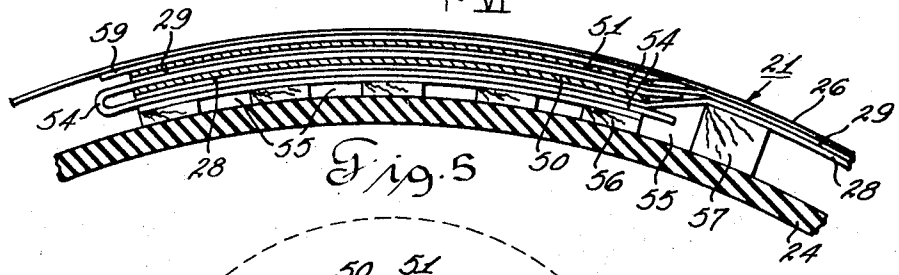


Fig. 5

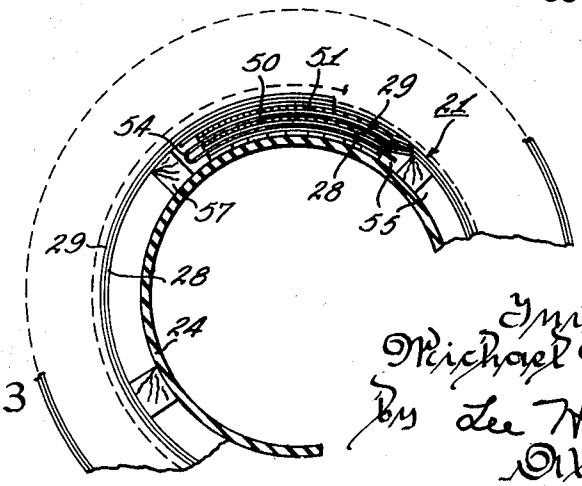


Fig. 3

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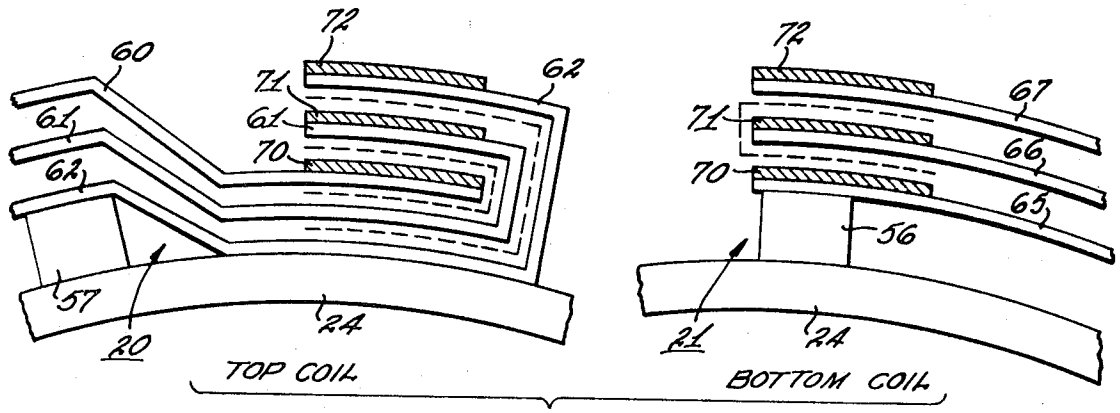


Fig. 7

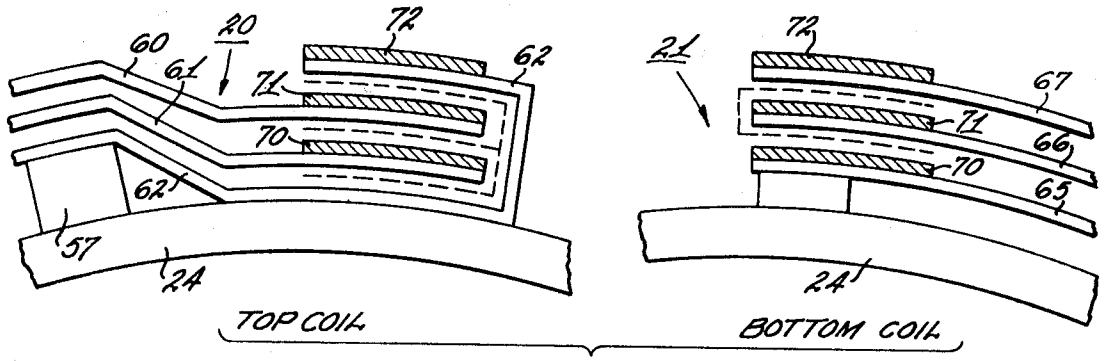


Fig. 8

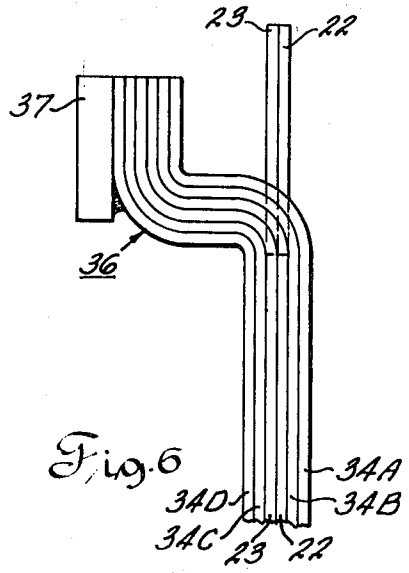


Fig. 6

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ELECTRICAL WINDING OF SHEET CONDUCTOR

This invention relates to electrical windings for stationary induction apparatus and in particular to electrical windings of sheet conductor for stationary induction apparatus such as shunt reactors.

BACKGROUND OF THE INVENTION

Shunt reactors may be used in high voltage, alternating current power transmission and distribution lines to compensate for line charging current and to allow the charge remaining in the line to bleed to ground when the line is opened. A reactor is often immersed in oil within a tank, and the reactor may be constructed without any magnetic material for a core so that it will have high-magnetizing current. Such an air-core reactor sets up a large magnetic field, and a problem with large size high voltage reactors is that the magnetic flux near the ends of the reactor winding deviates from the axial direction and has a cross direction relative to the winding axis. This cross flux interacts with the current in the conductor turns of the windings to cause high eddy current losses and to produce high axial compressive forces on the winding. Cross flux and its disadvantages are substantially eliminated in the extra high-voltage (EHV) shunt reactor disclosed in U.S. Pat. No. 3,362,000, in which I am a joint inventor with William C. Sealey, wherein a closed magnetic yoke having laminations in planes parallel to the axis of the reactor winding surrounds the winding to reduce the reluctance of the magnetic circuit external to the winding to reduce the reluctance of the magnetic circuit external to the winding and has portions closely adjacent the axial ends of the winding to straighten the lines of magnetic flux within the winding. The reactor winding is short in an axial direction and preferably has a high ratio of winding radius to winding axial height which further increases the inductance. The reactor winding disclosed in said patent comprises a plurality of axially aligned pancake coils disposed in a stack and arranged in two similar groups of series connected coils wound in opposite directions, and the patent discloses that the pancake coils may be wound from rectangular conductor having a substantially wider dimension in the axial direction than in the radial direction to improve the space factor. Reactors are also known wherein the reactor winding is wound from a board ribbon of conductive material which extends the entire axial height of the winding such as disclosed in U.S. Pat. No. 3,014,189 to McKinnon et al. However, it has heretofore been impracticable to use such wide conductor ribbon in large kv./a. shunt reactor windings requiring conductor of large cross section because of the high eddy current losses which vary with the square of the dimension of the conductor at right angles to the direction of the magnetic flux.

It is an object of the invention to provide an improved high current capacity electrical winding for stationary induction apparatus which, in comparison to known structures, has reduced eddy current and circulating current losses, has a high space factor and increased short strength, and is simpler and less costly to manufacture.

BRIEF DESCRIPTION OF THE DRAWINGS

This and other objects and advantages of the invention will be more readily apparent from the following detailed description when considered in conjunction with the accompanying drawing wherein:

FIG. 1 is a partial elevation view of a polyphase shunt reactor yoke and winding assembly incorporating a preferred embodiment of the invention;

FIGS. 2 and 3 are views taken along lines II—II and III—III respectively of FIG. 1;

FIGS. 4 and 5 are enlarged partial views of FIGS. 2 and 3 respectively showing the crossover connectors;

FIG. 6 is a view taken along lines VI—VI of FIG. 2;

FIG. 7 and 8 are views similar to FIGS. 4 and 5 schematically illustrating alternative embodiments of the invention wherein a greater number of conductor sheets are wound in parallel than in the FIG. 1 embodiment;

FIG. 9 is an enlarged sectional view taken along line IX—IX of FIG. 2 adjacent the abutting surfaces of the upper and lower coils; and

FIG. 10 is an enlarges sectional view taken along line X—X of FIG. 2.

DESCRIPTION OF PREFERRED EMBODIMENT

Referring to the drawing, a polyphase shunt reactor yoke and winding assembly incorporating a preferred embodiment of the invention has a plurality of cylindrical phase windings A, B and C (of which only windings A and B are shown) arranged with their axes vertical and aligned in a common vertical plane. The phase windings A, B and C are surrounded by a closed magnetic yoke **10** which provides a low reluctance magnetic circuit external to the windings. Yoke **10** has magnetic steel laminations **11** disposed in vertical planes with upper and lower horizontal yoke portions **14** and **15** respectively closely adjacent the axial ends of all phase windings A, B and C and connected by vertical end portions **16**. The laminations **11Y** of the upper and lower yoke portions **14** and **15** may have overlap miter joints **17** with the laminations **11E** of the end portions **16**, and the number of laminations may vary in a horizontal direction in the manner disclosed in U.S. Pat. No. **3,466,582**, in which I am a joint inventor with William C. Sealey, so that the magnetic flux density is approximately uniform in any cross section through yoke **10**.

The three phase windings A, B and C are identical, and only winding A will be described. Winding A comprises an upper coil **20** wound from sheet, or strip conductor such as aluminum as wide as the axial length thereof and a lower coil **21** also wound from sheet, or strip conductor such as aluminum as wide as the axial length thereof. The upper and lower coils **20** and **21** are coaxial and connected in electrical series relation and both are wound on the same insulating support tube **24** with an annular horizontal insulating washer **25** disposed therebetween. Washer **25** may have apertures **30** therethrough (see FIG. **9**) and radial insulating spacers **31** affixed to the upper surface thereof.

Upper coil **20** comprises inner and outer conductor sheets, or strips **22** and **23** having a width substantially equal to the axial height of upper coil **20** spirally wound counterclockwise in parallel. The large number of spiral turns of strips **22** and **23** cannot be shown in FIGS. **2** and **3**, and only the inner turn and a portion of the outer turn are illustrated with a dotted line representation of the spiral convolutions connecting the inner and outer turns. Conductor sheets **22** and **23** may be covered with an insulating film (not shown) such as epoxy resin or, alternatively, layer insulation (not shown) of suitable material such as kraft paper sheet may be wound between conductor sheets **22** and **23**. Layer insulation **26** (see FIG. **4**) of suitable material such as sheet kraft paper is wound between the spiral multilayer turns of paralleled sheet conductors **22** and **23**. Lower coil **21** similarly comprises inner and outer conductor sheets **28** and **29** covered with an insulating film (not shown) and having a width substantially equal to the axial height of lower coil **21** spirally wound clockwise in parallel with sheet layer insulation **26** between spiral multilayer turns so that the direction of magnetic flux generated in the upper and lower coils **20** and **21** is the same. The conductor strips **22**, **23**, **28** and **29** may be slightly narrower in an axial direction than the layer insulation **26**, and keepback insulation **35** may be disposed between washer **25** and the edges of the strips **22**, **23**, **28** and **29** to increase the dielectric breakdown strength between upper and lower coils **20** and **21**. Elongated wooden spacer sticks **32** (see FIG. **9**) extending parallel to the winding axis are inserted at circumferentially spaced positions between the spiral multilayer turns of the paralleled conductor sheets **22–23** of the upper coil **20** and also between spiral turns of paralleled conductor sheets **28–29** of lower coil **21** and form vertical ducts **33** for cooling fluid which extend through both the upper coil **20** and the lower coil **21** and communicate with the horizontal ducts formed by the radial spacers **31** and also with the apertures **30** in insulating washer **25**.

The insulation film is removed from conductor sheets **22** and **23** at the outward end thereof so that the outer ends of the sheet conductors **22** and **23** are electrically connected together, and a START terminal **36** (see FIGS. **1**, **2** and **6**) for winding A is provided on upper coil **20** and may comprise a plurality of superimposed elongated strips **34** of conductive material such as aluminum welded to the outer ends of the conductor sheets **22** and **23** where they engage and are electrically connected together. As shown in FIGS. **2** and **6**, two elongated aluminum strips **34A** and **34B** are disposed radially inward from the ends of the radially outer turn of the conductor sheets **22** and **23** and two elongated aluminum sheets **34C** and **34D** are disposed radially outward from the conductor sheets **22** and **23** adjacent the ends of the outer turn thereof, and the six layers of conductor **34A**, **34B**, **22**, **23**, **34C** and **34D** are welded together. The superimposed elongated conductors **34A**, **34B**, **34C** and **34D** are bent outwardly and upwardly adjacent the upper edge of the conductor sheets **22** and **23** to form START terminal **36** for phase winding A of the shunt reactor. A horizontal phase bus bar **37** may be welded to the START terminal **36**.

A FINISH terminal **38** for phase winding A of the shunt reactor is provided adjacent the upper edge of lower coil **21** and is similar to START terminal **36**. FINISH terminal **38** may be affixed to a horizontal bus bar **40** which is electrically connected to similar FINISH terminals on the other shunt reactor phase coils B and C to electrically connect phase coils A, B and C in wye. The insulation film is removed between sheet conductors **28** and **29** at the ends of the outer turn thereof to electrically connect these conductor sheets together at their outer ends, and FINISH terminal **38** may comprise four elongated aluminum strips (not shown) welded to the outer ends of conductor sheets **28** and **29** where said sheets abut in a manner similar to START terminal **36**.

An annular insulating washer **44U** having a plurality of apertures **46** therethrough (see FIG. **10**) and elongated radial spacer members **45** affixed to both surfaces thereof is positioned between the upper end of upper coil **20** and the upper yoke portion **14** to form radial ducts in communication with the vertical ducts **33** and also with ducts **55** described hereinafter in coil **20**, and a similar insulating washer **44L** having apertures **46** therein is positioned between the lower end of lower coil **21** and the lower horizontal yoke portion **15** to form radial ducts communicating with the vertical ducts **33** and **55** in lower coil **21**.

Two elongated, straight, vertical aluminum crossover strip connectors **50** and **51** electrically connect the inner and outer sheets **22** and **23** of the top coil **20** to the outer and inner sheets **29** and **28** respectively of the lower coil **21**, while keeping the two conducting paths insulated from each other, to obtain the same net flex linkage for each conductor. Crossover connector **50** is disposed against outer sheet **23** of the upper coil **20** along its entire vertical height and adjacent the inner end thereof (see FIGS. **4** to **10**) and is also disposed against the radially inner sheet **28** of lower coil **21** along the entire vertical height thereof. Sheet insulation **53** is folded in U-shape around the abutting crossover connector **50** and the end of outer conductor sheet **23** in upper coil **20**, and the radially inner end **22***i* of inner conductor sheet **22** is bent around such U-shaped insulation **53** and abuts against crossover connector **51** along the entire vertical height of inner sheet **22**.

In bottom coil **21** crossover connectors **50** and **51** abut against the radial outer surface of inner and outer sheets **28** and **29** respectively adjacent the ends thereof. Sheet insulation **54** is folded in U-shape around the abutting portions of crossover connector **50** and inner sheet **28** in the lower coil **21** to isolate the two electrical paths. The inner conductor sheet **22** of top coil **20** is thus transposed so that it becomes the outer conductor sheet **29** of the lower coil **21**, and also the outer conductor sheet **23** of top coil **20** is thus transposed so that it becomes the outer conductor sheet **28** of the lower coil **21**. As described hereinbefore, the sheets **22** and **23** are electrically connected at their radial outer ends in upper coil **20**, and the sheets **28** and **29** are electrically connected at their radial outer ends in lower coil **21**. The disclosed structure thus provides a conductor having the same cross section but only one-half the thickness of the conductor sheet of a reactor such as U.S. Pat. No. 3,014,189 wherein the sheet conductor extends over the entire height of the reactor coil. It will be appreciated that such reduction in conductor thickness reduces to one-fourth the eddy current losses (which are proportional to the square of the conductor dimension perpendicular to the direction of magnetic flux). Further, inasmuch as the inner and outer conductor sheets are transposed so that they occur in different radial positions in the upper and lower coils, the disclosed structure averages out the fact that the self-inductance caused by the magnetic flux is different in the inner and outer conductor sheets. Consequently, the circulating current generated by voltage inducted in the inner conductor sheet in one coil is canceled by the circulating current generated by the voltage induced in the outer conductor sheet in the other coil.

As shown in FIGS. **4** and **5**, cooling ducts **55** for an insulating fluid may be provided between the support tube **24** and the first spiral multilayer turn of the paralleled conductor sheets, and the vertical elongated wooden spacers **56** which form such ducts **55** and are in alignment with the crossover connectors **50** and **51** are thinner in a radial direction than the vertical wooden spacers **57** which form such ducts **55** in the other parts of the coil to prevent the crossover connectors **50** and **51** from causing a bulge in the coil. It will be appreciated that the radial thickness of such spacers **56** and **57** must be exaggerated in the drawing. Further, an elongated insulation pad **59** may be provided between the crossover connector **51** and the first spiral turn of paralleled conductor sheets in both coils **20** and **21** to electrically isolate the two current paths.

FIG. **7** schematically illustrates an embodiment of the invention wherein three conductor sheets **60**, **61** and **62** are spirally wound in parallel in the upper coil **20**, similarly three conductor sheets **65**, **66** and **67** are spirally wound in parallel in the lower coil **21**, and three straight vertical crossover strip connectors **70**, **71** and **72** electrically connect and transpose the sheet conductors so that the outermost sheet **60** of the top coil **20** is connected to the innermost sheet **65** of the bottom coil by crossover connector **70**; the innermost sheet **62** of the top coil **20** is connected to the outermost sheet **67** of the bottom coil **21** by crossover connector **72**; and the center sheet **61** of top coil **20** is connected to the center sheet **66** of bottom coil **21** by crossover connector **71**. Such transposition of the inner and outer sheets in the upper and lower coils results in substantially equal flux linkages for all three conductors and in nearly total cancellation of circulating currents due to the magnetic flux. U-shaped insulating members schematically shown in dotted lines electrically isolate the three current paths at the positions where the crossover connectors **70**, **71**, and **72** connect coils **20** and **21** in series. The folded portions at the inner ends of sheet conductors **61** and **62** permit use of simple straight crossover connectors **70**, **71** and **72** which are easy to fabricate and connect to the conductor sheets and without causing bulges in the coils.

FIG. **8** schematically illustrates an embodiment similar to FIG. **7** wherein three conductor sheets are spirally wound in parallel in both top coil **20** and lower coil **21** but only one conductor is transposed. Inner sheet conductor **62** of top coil **20** is bent in U-shape at its inner end so that it abuts and is electrically connected to the upper end of crossover strip connector **72** which, at its lower end, abuts and is electrically connected to the outer sheet conductor **67** of lower coil **21**. This construction results in substantial, but not perfect, cancellation of the circulating currents in the two coils **20** and **21** due to the magnetic flux. The structure shown in FIG. **8** would result in equal net flux linkages for the three conductors and the total cancellation of circulating current if it were used to connect three coils in series each of which is spirally wound with three conductor sheets in parallel.

Although the invention has been illustrated and described as embodied in a shunt reactor winding, it will be appreciated

that the invention is also applicable to electrical windings for other stationary induction apparatus such as power transformers.

It should thus be understood that I do not intend to be limited to the particular embodiments shown and described, for many modifications and variations will be obvious to those skilled in the art.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A shunt reactor winding having high-current capacity comprising, in combination,

a plurality of superimposed coaxial coils each of which is spirally wound from a plurality of conductor sheets in parallel terminating together at their radially outer ends and which terminate at their radially inner ends in a common radial plane and which sheets extend substantially the entire axial height of said coil, insulation between paralleled conductor sheets in each coil and between the spiral turns of paralleled sheets,

a START terminal on one of said coils electrically connecting said radially outer ends of the paralleled sheets of said one coil together and a FINISH terminal on another of said coils electrically connecting said radially outer ends of the paralleled sheets of said another of said coils together,

said plurality of coils being wound so that the direction of magnetic flux is the same in all of said coils, and

means including a plurality of elongated flat crossover connector strips disposed in a common radial plane extending between adjacent coils at the radially inner coil periphery in a direction parallel to the coil axis and joining oppositely disposed radially inner conductor sheet ends in said adjacent coils for electrically connecting said paralleled sheets in said plurality of coils in series relation,

the radially inner ends of certain of said conductor sheets in one of said adjacent coils being offset in a radial direction and joined to crossover connector strips affixed to conductor sheets occupying different radial positions in said adjacent coil so that the net flux linkages of the plurality of conductor paths formed by said series connected conductor sheets are approximately equal.

2. An electrical winding in accordance with claim 1 wherein the radially inner end of the radially inner conductor sheet in said one coil is bent in U-shape to a different radial position so that it is joined to a conductor strip affixed to the radially inner end of the radially outer conductor sheet of said adjacent coil.

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