Oct. 17, 1967 E. P. BAKER ET AL 3,348,182

WINDING TRANSPOSITION

Filed Oct. 13, 1965

FIG. 1.

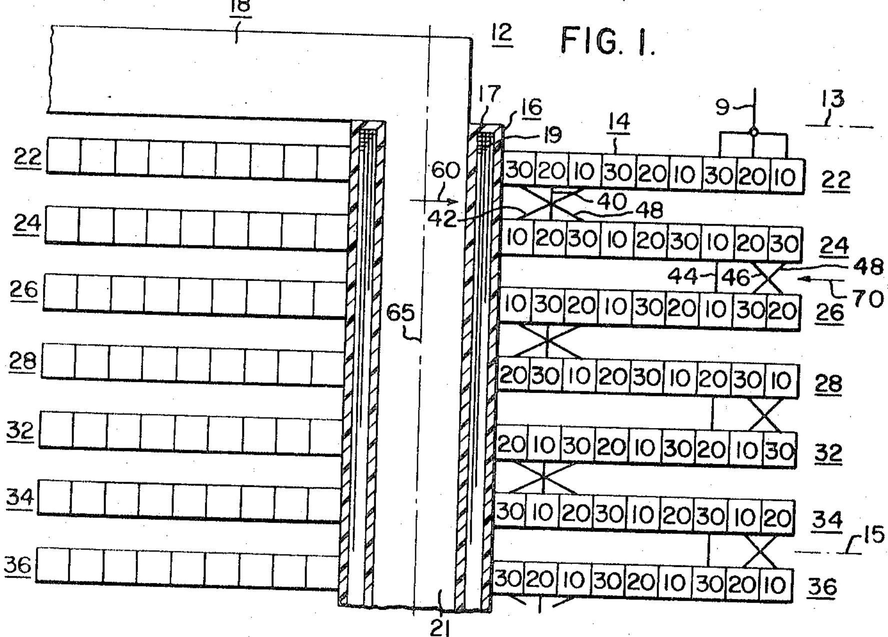


FIG. 2.

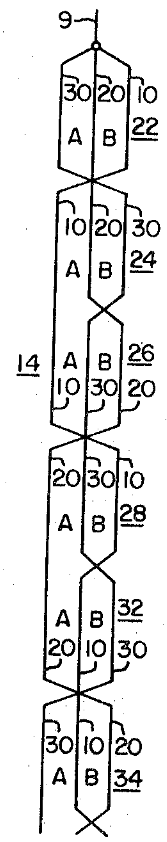


FIG. 3.

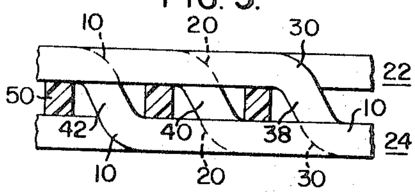


FIG. 4.

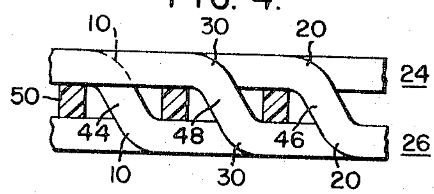


FIG. 5.

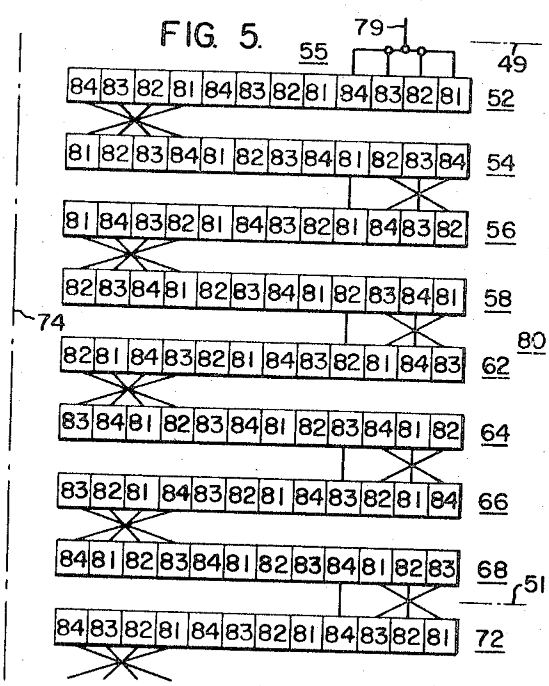
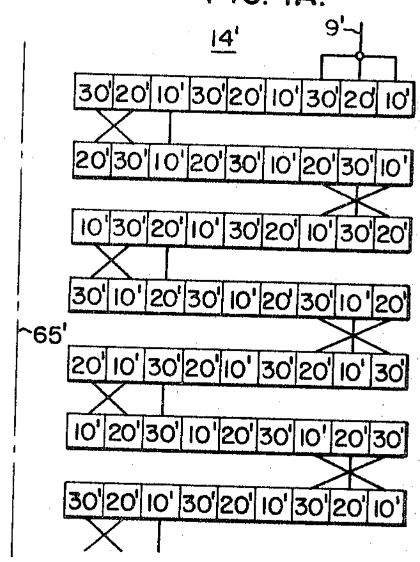


FIG. 1A.



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WINDING TRANSPOSITION

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ABSTRACT OF THE DISCLOSURE

A transposing arrangement for stranded electrical conductor having three or more strands. A complete transposition of all of the strands is achieved, wherein each strand occupies the positions of all of the other strands, by repeating a sequence, which includes first and second transpositions, at least as many times as there are conductive strands. One of the transposition points is a standard transposition, which reverses the positions of the strands, and the other transposition point is a partial standard transposition, in which one of the strands at a predetermined edge of the conductor continues in its same position, without a transposition, and the remaining strands are transposed with a standard transposition, to reverse their positions. Repeating this sequence as many times as there are conductive strands, causes each strand to occupy all strand positions, it subjects each strand to substantially the same net leakage flux, and it makes the strands all substantially the same length.

The electrical conductor which forms the turns of the windings of electrical inductive appartus is usually stranded or subdivided into a plurality of electrically insulated, parallel connected strands, in order to reduce the dimension of the electrical conductor at right angles to the leakage flux, and thus reduce eddy current losses in the apparatus. The stranded conductor, however, may introduce a substantial increase in losses due to currents circulating in the parallel connected strands. In an effort to reduce losses due to circulating currents in the conductor, the strands are transposed or have their positions periodically changed relative to one another, in an effort to equalize the induced voltages in the various strands and produce a net induced voltage around each loop of substantially zero.

Many different methods of transposing the strands of an electrical conductor have been used. However, each method is tailored for a specific number of strands, or, the transposition produced is not perfect, i.e., each conductive strand does not occupy the position of each of the other conductive strands for the same length, or the transposition possesses both of these disadvantages.

Thus, it would be desirable to provide a new and improved transposing arrangement for stranded electrical conductors which has an easy to follow repetitive sequence that is applicable to three or more strands, and which subjects each strand to the same net flux linkages. In other words, the transposing arrangement must apply equally to even and odd numbered strands, and each strand must occupy the position of all the other strands and for substantially the same lengths, in order to be subjected to the same leakage flux linkages and reduce circulating currents to a minimum.

Accordingly, it is an object of the invention to provide a new and improved transposing arrangement for stranded electrical conductor.

Another object of the invention is to provide a new and improved transposing arrangement for stranded electrical conductor having three or more strands, in which

the same repetitive sequence may be used on conductors having an even or odd number of strands to obtain a perfect transposition.

A further object of the invention is to provide a new and improved transposing arrangement for stranded electrical conductors having three or more strands, in which each strand occupies the position of all the other strands, and all strands are subjected to the same net flux linkages.

Briefly, the present invention accomplishes the above cited objects by following the repetitive sequence of transposing the strands with a standard transposition, which reverses the positions of the strands, and then at the next transposition point, continue one strand at a predetermined edge of the conductor without any transposition, and transpose the remaining strands with a standard transposition to reverse their sequence. This sequence, which includes two transposition points, is repeated at least as many times as there are conductive strands. Each strand will occupy each strand position twice, each strand will have substantially the same length, and each strand will have substantially the same net flux linkages, which insures the reduction of circulating currents to a minimum.

Further objects and advantages of the invention will become apparent as the following description proceeds and features of novelty which characterize the invention will be pointed out in particularity in the claims annexed to and forming a part of this specification.

For a better understanding of the invention, reference may be had to the following detailed description taken in connection with the accompanying drawings, in which:

FIGURE 1 is a partial sectional elevation of a transformer having a winding constructed according to the teachings of the invention;

FIG. 1A illustrates the high voltage winding of FIG. 1 constructed according to another embodiment of the invention;

FIG. 2 is a schematic diagram of the winding shown in FIG. 1, illustrating that each conductor is subjected to the same net flux linkages;

FIGS. 3 and 4 are diagrams illustrating the arrangement of the connections at the inner and outer transposition points of the winding shown in FIG. 1; and

FIG. 5 is a diagrammatic view illustrating another winding arrangement embodying the teachings of the invention.

Referring now to the drawings, and FIG. 1 in particular, there is illustrated a partial elevational view of a transformer **12**, shown in section, illustrating an embodiment of the invention. Transformer **12** includes high and low voltage winding assemblies, **14** and **16**, respectively, disposed in inductive relation with a leg **21** of magnetic core assembly **18**. Low voltage winding assembly **16** comprises a plurality of conductor turns **19** disposed about leg member **21**, and insulated from magnetic core assembly **18** and high voltage winding **14** by insulating means **17**. The high voltage winding **14** comprises a plurality of pancake or disc type coils **22, 24, 26, 28, 32, 34** and **36** disposed in concentric relation with low voltage winding assembly **16** about leg member **21**. Pancake coils **22, 24, 26, 28, 32, 34** and **36** are stacked in predetermined spaced relation with their openings for receiving magnetic core assembly **18** aligned, and are connected in series circuit relation with alternate start-to-start and finish-to-finish connections, to form the complete high voltage winding assembly **14**.

Each of the coils, such as coil **22** of high voltage winding assembly **14**, includes a plurality of turns of electrically insulated stranded conductor wound about a common central axis **65**, with the strands being electrically connected in parallel at the start and finish of winding assembly **14**. For purposes of example, each coil in FIG.

1 has three turns of a stranded electrical conductor having three conductive strands **10**, **20** and **30** disposed in side-by-side relation to form a conductor having first and second outer edges. The strands **10**, **20** and **30** are electrically connected at the upper end of the winding to form primary terminal conductor **9**, which is adapted for connection to one of the phases or lines of an electrical power system (not shown). The lower end of the high voltage winding **14** illustrates the conductors or conductive strands **10**, **20** and **30** in the position to connect coil **36** to an additional plurality of coils (not shown) as required in a particular application; and, after forming the last coil in the stack of coils in winding assembly **14**, the conductive strands **10**, **20** and **30** are electrically connected to complete their parallel connection.

Strands **10**, **20** and **30** of each coil are disposed in side-by-side insulated relation, with the resulting conductor being wound on edge to form the desired number of turns.

For purposes of explaining the interconnections of the various coils of winding assembly **14**, the ends of the conductive strands **10**, **20** and **30** of the turn which is adjacent magnetic core leg **21** will be called the start of the coil, and the finish of the coil will then be the ends of the strands **10**, **20** and **30** of the outermost turn of the coil. In order to connect the plurality of coils in electrical series, the coils are alternately connected start-to-start, with the remaining connections being finish-to-finish. In other words, the ends of the innermost turns of coils **22** and **24** are connected together, and the ends of the outermost turns of coils **24** and **26** are connected together, with this pattern being repeated until all of the coils of high voltage winding assembly **14** are serially connected.

As hereinbefore stated, each conductor turn is divided into a plurality of conductive strands in an effort to reduce eddy current losses, as eddy current losses in a winding vary with the square of the dimension of the conductor at right angles to the direction of the leakage flux. This remedy for reducing eddy currents, however, may introduce offsetting losses due to circulating currents in the parallel connected strands, unless some means is incorporated to provide the same net flux linkages for each strand.

The generally accepted method for reducing circulating currents in parallel connected strands of an electrical conductor is to periodically transpose the relative positions of the strands with respect to the direction of the leakage flux.

The so-called standard transposition, wherein the position of the strands of a single layer conductor are reversed into a mirror image position is commonly used. However, this transposition only provides a perfect transposition for a conductor having two strands. A perfect transposition being one in which each strand successively occupies the positions of all of the other strands for the same length, thus subjecting each strand to substantially the same next flux linkages. Other transposing arrangements have been used, tailored specifically for a certain number of strands, or which do not provide perfect transpositions. Thus, it would be desirable to provide a transposing arrangement which has an easy to follow sequence which provides a perfect transposition for three or more strands, and which is equally applicable to an odd or even number of strands.

FIG. 1 illustrates high voltage winding assembly **14** in which the conductive strands are transposed between coils to provide a perfect transposition, in which each conductive strand occupies the position of all the other conductive strands. More specifically, each coil **22**, **24**, **26**, **28**, **32**, **34** and **36** is spirally wound about leg member **21** of magnetic core assembly **18**, with the conductive strands of each turn forming three separate circuits through each coil. Giving the three strands in coil **22** the reference numerals **10**, **20** and **30**, the inner strand, with respect to centerline **65**, is conductor **30**, the middle strand is conductor **20**, and the outer strand is conductor **10**. Since, in this instance, the line is connected to what is normally called the finish end of the winding, coil **22** is connected to coil **24** with a start-to-start connection. The strands **10**, **20** and **30** of coil **22** are transposed as they are connected to coil **24** with a standard transposition, reversing the sequence of the strands. Thus, the inner strand with respect to center line **65** is now conductive strand **10**, the middle strand is still conductive strand **20** and the outer strand is conductive strand **30**. At the finish end of coil **24**, the strands **10**, **20** and **30** are connected to the finish end of coil **26**. A strand at a preselected edge of the conductor turn is connected to the same position in coil **26** that it occupied in coil **24**. The remaining strands are transposed with a standard transposition to reverse their sequence. In the connection between coils **24** and **26**, the innermost conductive strand **10** has been selected to be connected to the same relative position in coil **26** that it occupied in coil **24**, and the middle and outermost conductors exchange positions or sequence from coil **24** and **26**. Once a conductive strand at a predetermined edge of the conductor has been selected to occupy the same position in the two adjacent coils for this particular transposition, the conductive strand on this same edge must be used for this same transposition throughout the winding. This sequence, which comprises two transposition points, is then repeated for the remaining coils, with as many of these complete sequences being required for a perfect transposition as there are conductive strands. Thus, there are twice as many transposition points required as there are conductive strands to be transposed, in order to form a perfect transposition in which each strand occupies each strand position.

Thus, a perfect transposition may be made according to the teachings of the invention by following a repetitive sequence which includes a standard transposition, and a transposition which will be called a partial standard transposition, in which the strand on a predetermined edge of the conductor proceeds to occupy the same position it previously occupied, and the remaining strands are transposed with the standard transposition to reverse their previous positions. The first transposition point of a winding may use the standard transposition, as shown between coils **22** and **24** of FIG. 1, or the first transposition point may be the partial standard transposition, shown between coils **24** and **26**. However, once one type of transposition is used to start the transposing arrangement, the remaining sequence is set, requiring that the two types of transpositions, the standard and the partial standard, alternate. Thus, one perfect transposition according to the teachings of the invention comprises, as shown in FIG. 1, conductor **9** connected to conductive strands **10**, **20** and **30**, which are disposed in side-by-side relation to form a conductor, which is wound spirally to form coil **22**. The normal start connection of coil **22** is connected to the normal start connection of coil **24**, with the conductive strands **10**, **20** and **30** being transposed in a standard transposition between the coils to reverse their sequence. Thus, the outermost strand **10** of the innerturn of coil **22** becomes the innermost strand of the innerturn in coil **24**, the innermost strand in coil **22** becomes the outermost strand in coil **24**, and the middle or central strand **20** occupies the same relative position in both coils. Since in FIG. 1 the standard transposition was chosen to start the transposing arrangement, the next transposition point, which in this case is the finish-finish connection between coils **24** and **26**, must be a partial standard transposition. As shown in FIG. 1, the innermost strand **10** of coil **24**, relative to centerline **65**, is selected to occupy the same position in coil **26**, and strands **20** and **30** are transposed with a standard transposition to exchange positions, with the outermost strand **30** of coil **24** becoming the central strand in coil **26**, and the central strand **20** of coil **24** becoming the outermost strand in coil **26**. The next transposition point, which is the start-start connection between coils **26** and **28**, reverses the sequence of the strands with a standard transposition. The next transposition point is the finish-finish connection between coils **28** and **32**, with the innermost strand **20**, since it was the one selected for the partial standard transposition, proceeding to the same position in coil **32** that it occupies in coil **28**, and strands **30** and **10** are transposed to reverse their sequence. The next transposition point is the start-start connection between coils **32** and **34**, which is a standard transposition to reverse the sequence of the strands. The final transposition point is the finish-finish connection between coils **34** and **36**, which is a partial standard transposition, and brings the conductive strands back to the same relative position at which they started in coil **22**. It will be noted that in the coils **22**, **24**, **26**, **28**, **32** and **34**, shown between lines **13** and **15** in FIG. 1, each conductive strand has occupied the position of each of the other conductive strands for substantially the same distance, thus subjecting each conductive strand to the same net flux linkages and reducing circulating currents to a minimum.

In order to more clearly illustrate that each conductive strand is subjected to the same net flux linkages as the other conductive strands, FIG. 2 schematically illustrates the coils **22**, **24**, **26**, **28**, **32**, **34** and **36** of FIG. 1 unwound, illustrating the respective positions of each conductive strand in each coil, and designating the radial leakage flux in each coil between the innermost and central strand as A, and the leakage flux between the central and outermost strand as B. The leakage flux between conductive strands **30** and **20** is equal to A in coil **22**, B in coil **24**, B in coil **26**, A in coil **28**, $A+B$ in coil **32**, and $A+B$ in coil **34**, for a total of $4A+4B$. In like manner, the leakage flux between conductors **30** and **10** is equal to $A+B$ in coil **22**, $A+B$ in coil **24**, A in coil **26**, B in coil **28**, B in coil **32** and A in coil **34**, for a total of $4A+4B$. The leakage flux between conductors **20** and **10** is equal to B in coil **22**, A in coil **24**, $A+B$ in coil **26**, $A+B$ in coil **28**, A in coil **32** and B in coil **34**, for a total of $4A+4B$. Thus, since all of the conductors are subjected to the same net radial flux linkages, and all the conductive strands are substantially the same length, the differences in potential between the parallel connected strands is a minimum, thus reducing circulating currents to a negligible value.

It should be noted that the strands are only connected together at the start and finish of the complete winding assembly, and not at the termination of each coil. However, it would be satisfactory to connect the strands together after a perfect transposition has been completed, but generally it is more desirable to make the only common connections at the start and finish of the winding, as the longer the parallel loops the higher the resistance of the loop, thus requiring a greater difference of potential to force circulating currents through the loops.

FIGS. 3 and 4 illustrate start-start and finish-finish connections that may be used between the various pancake coils of winding **14**, respectively. FIG. 3 illustrates the start-start connection between coils **22** and **24** of FIG. 1, taken in the direction of arrow **60**. An electrical conductor **42** is connected from the end of the outermost conductive strand of the innermost turn of coil **22** to the innermost conductive strand in the inner turn of coil **24**, electrical conductor **40** connects the end of the central conductive strand **20** of coil **22** to the end of the central conductive strand of coil **24**, and conductor **38** connects the end of the innermost strand of coil **22** with the end of the outermost strand of the inner turn of coil **24**. Insulating spacer member **50** may be disposed between the coils adjacent the interconnecting conductors **38**, **40** and **42**, for insulating purposes and for providing ducts between the coils for circulation of cooling fluid.

FIG. 4 illustrates the finish-finish connection between coils **24** and **26**, taken in the direction of arrow **70**. An electrical conductor **44** connects the end of the innermost strand of the outermost turn of coil **24** with the end of the innermost strand of the outermost turn of coil **26**, electrical conductor **48** connects the end of the outermost strand of the outermost turn of coil **24** with the end of the central strand of coil **26**, and electrical conductor **46** connects the end of the central strand of coil **24** with the end of the outermost strand of coil **26**. Similar to the start-start connection shown in FIG. 3, insulating spacer members **50** may be disposed adjacent the connecting conductors **44**, **46** and **48** for insulating and duct forming purposes.

FIG. 1A illustrates the high voltage winding assembly **14** of FIG. 1, with the added modifications of starting the transposition with the partial standard transposition instead of with the standard transposition, and the selection of the outermost strand with respect to the center line **65'** for the strand of the partial standard transposition that occupies the same position in each coil. The reference numerals in FIG. 1A are the same as in FIG. 1, except with the addition of a prime mark. It will be noted that the above mentioned modifications do not change the results, producing a perfect transposition with six transposition points, whereby each strand twice occupies all strand positions and for the same length. In other words, it is immaterial which type of transposition is used to start the transposing arrangement, either the standard or partial standard, but once started with one or the other the transposing arrangement must alternate between the two types. Further, it is not important which strand on an edge of the conductor is selected to occupy the same position in adjacent coils while making the partial standard transposition. Thus, the inner strand with respect to the center line **65'**, or the outer strand with respect to the center line **65**, may be selected to continue to the same position on each side of the partial standard transposition. However, once the inner or outer strands are selected in the first partial standard transposition, the strand in the same relative position must be used in all subsequent partial standard transpositions.

FIG. 1 illustrates the application of the teachings of the invention to a conductor having an odd number of strands. As hereinbefore stated, the teachings of the invention are equally applicable to an even numbered plurality of strands. For example, FIG. 5 illustrates a winding assembly **55** having a plurality of coils **52**, **54**, **56**, **58**, **62**, **64**, **66**, **68** and **72**, each having a plurality of turns formed of an electrical conductor having four conductive strands, **81**, **82**, **83**, and **84**. The start of winding **55** is connected to conductor **79** which is adapted for connection to a line or phase of an electrical power distribution system (not shown), and comprises a plurality of stacked pancake type coils, with only the number of coils being illustrated which are required to perform one perfect transposition wherein each conductive strand occupies each strand position.

Since each repetitive sequence involves two transposition points for each strand in the conductor, a total of eight transposition points are required to provide a perfect transposition for a conductor having four conductive strands. More specifically, winding **55** starts the transposing arrangement between the normal starting points of coils **52** and **54**. As illustrated in FIG. 5, the transposition between coils **52** and **54** is the standard transposition, but as hereinbefore stated the partial standard transposition could also be used to start the transposition arrangement. Thus, using the standard transposition to transpose the conductive strands between coils **52** and **54**, the sequence of the strands in coil **54** are reversed from their previous location. Coils **54** and **56** are interconnected at their finish ends, with the innermost conductor **81** of the outermost turn of coil **54** being selected to proceed to the same relative position in coil **56** that it occupied in coil **54**, and the sequence of the remaining strands in coil **54** are reversed in coil **56**. The same two transposition arrangements are then repeated in the same order until eight transposition points have been completed, between lines 49 and 51, in which each strand occupies each strand position twice throughout the serially connected coils of winding 55. It will be noted that the eight transposition points return the conductive strands in the next coil 72 to the same sequence that they occupied in the first coil 52. Thus, the same transposition arrangement may be followed for a conductor having three or more strands, and it is equally applicable to an even or odd number plurality of strands, always providing a perfect transposition wherein each conductive strand occupies each strand position and each strand is substantially the same length as all the other strands.

While the invention has been illustrated with reference to the high voltage winding of inductive apparatus having concentrically disposed high and low voltage windings, it will be understood that the transposing arrangements disclosed herein are equally applicable to any type of electrical apparatus whereby it is necessary to transpose a plurality of conductive strands of an electrical conductor in order to reduce circulating currents. For example, the teachings of the invention may be applied to shell form type transformer construction wherein all of the windings are stacked in side-by-side relation, or they may be applied to transposition points made within an electrical coil instead of between coils.

In summary, there has been disclosed a new and improved winding arrangement which provides an easy to follow repeatable sequence for transposing a plurality of conductive strands of an electrical conductor, which directs each strand into all strand positions and thus insures that the net flux linkages of each strand with the leakage flux are substantially equal. Thus, the difference in potential between the strands when they are connected into parallel loops is substantially zero, minimizing losses due to circulating current. Further, the teachings of the invention apply equally to an odd or even numbered plurality of strands, and provide a perfect transposition in either case.

Since numerous changes may be made in the above described apparatus and different embodiments of the invention may be made without departing from the spirit thereof, it is intended that all matter contained in the foregoing description or shown in the accompanying drawings shall be interpreted as illustrative, and not in a limiting sense.

We claim as our invention:

1. An electrical conductor comprising at least three insulated conductive strands disposed in side-by-side relation to form a conductor having first and second outer edges, said conductive strands being transposed with only first and second transpositions, at first and second spaced transposition points, respectively, the sequence of said conductive strands being reversed at said first transposition point, the conductive strand at the first outer edge of the conductor occupying the same strand position before and after said second transposition point, the sequence of the remaining strands being reversed at said second transposition point, said first and second transpositions being repeated sequentially, at least as many times as there are conductive strands, to dispose each conductive strand in each strand position.

2. The electrical conductor of claim 1 wherein the strands are electrically connected at each end of the conductor to form a plurality of parallel loops.

3. An electrical winding for electrical inductive apparatus comprising a plurality of coils disposed in spaced side-by-side relation each having start and finish ends, each of said coils being formed of an electrical conductor having at least three insulated conductive strands disposed in side-by-side relation to form a conductor having first and second outer edges, said winding having at least twice as many coils as there are conductive strands in said electrical conductor, said electrical coils being successively connected start-to-start and finish-to-finish to connect said coils in electrical series, alternate connections between said coils transposing said conductive strands by reversing their sequence, the remaining alternate connections between said coils transposing said conductive strands by retaining the position of a strand at a predetermined outer edge of the conductor, and reversing the sequence of the remaining strands.

4. The winding of claim 3 wherein said electrically conductive strands are connected together at least at the ends of the serially connected coils to form a plurality of parallel loops.

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