My invention relates to windings for electric induction apparatus, and particularly to windings formed of stranded conductor wherein a single helically wound conductor of high current carrying capacity is formed of a plurality of separately insulated conductor strands stacked together in radially superposed relation and electrically connected in parallel circuit relation.

In high current electric windings for power transformers, reactors and the like, it is a common practice to form the winding conductor of a plurality of strands, usually stacked in radial superposition to maximize the number of turns in a single cylindrical winding layer. The strands of such conductor are usually separately insulated even though all strands are connected together at their ends. Such insulation has the primary purpose of subdividing the conductor to minimize local eddy current losses due to magnetic fluxes traversing the conductor itself. The insulation of strands, however, creates another problem in that coils formed by radially outward strands include more flux than do coils formed by radially inner strands (i.e., with respect to the midpoint between the inner and outer peripheries of the helical conductor). The flux difference results in appreciable difference in the number of volts per turn in the radially spaced-apart strands of a single conductor, i.e., the reactive voltage drop per turn in a reactor or the induced volts per turn in a transformer winding is not the same for each of a plurality of radially stacked strands. Since the conductor strands are connected in parallel circuit relation at their ends, each pair of strands forms a conductive loop in which circulating current will be set up as a result of such voltage differences.

To reduce the circulating currents referred above, it is known to transpose the several radially stacked strands of a conductor between radially inner and radially outer positions in the stack in such a way that each conductor occupies a symmetrical succession of inner and outer positions as it traverses the axial length of the coil.

In transposing conductor strands as described, several known transposition sequences are generally used. Such sequences fall into two principal categories. One type of transposition known as a "progressive" transposition, moves each conductor strand through a consecutive succession of radial displacements in the same direction for each complete transposition. The other general type also locates each strand in a symmetrical succession of radially inner and radially outer positions in a stack of strands, but without progressive displacement in a single direction. Such non-consecutive transposition may, for example, be a complete reversal of strand positions either individually or in groups.

In prior transpositions of both the foregoing types it has been common practice to locate transposition points at equal axial intervals and to provide such a number of transpositions that each strand occupies a symmetrical succession of radially inner and radially outer positions for equal axial distances in each coil layer. While this disposition of conductor strands appreciably reduces circulating current it does not entirely eliminate such currents.

Accordingly, it is a principal object of my invention to further reduce power loss due to circulating currents in high current electric windings formed of multistrand conductor.

It is a more particular object of my invention to reduce circulating current power loss in stranded electric coil conductors which are radially transposed in progressive, or consecutive, sequence.

Another object of my invention is to reduce circulating current power loss in electric coil conductors of the transposed strand type by providing an optimum variation of transposition intervals for transposition sequences of both the progressive and non-progressive types.

My invention will be more fully understood and its several objects and advantages further appreciated by referring now to the following detailed specification taken in conjunction with the accompanying drawings in which:

FIG. 1 is a fragmentary cross-sectional view of an electric transformer having primary and secondary windings concentrically wound upon a single core leg to illustrate the origin of leakage flux between such windings;

FIG. 2 is a similar fragmentary cross-sectional view of a two-winding transformer showing in more detail the configuration of the leakage flux field;

FIG. 3 is a fragmentary cross-sectional view similar to those of FIGS. 1 and 2, but illustrating also a typical stranded winding conductor;

FIGS. 4 and 5 are detailed multiple cross-sectional views illustrating several transposition sequences for a multistrand winding such as shown at FIG. 3; and

FIG. 6 is a graphical representation showing one typical manner of varying transposition intervals in accordance with my invention; and

FIG. 7 is a fragmentary cross-sectional view of a multistrand winding transposed in accordance with my invention.

Referring now to the drawings, I have illustrated my invention by way of example in connection with a transformer of the concentric winding type as commonly used for large power transformers, such as furnace transformers and others having low voltage windings of high current-carrying capacity. At FIG. 1, I have shown in fragmentary cross-sectional view a transformer consisting of a magnetizable core including a core leg 10 and a yoke portion 11. The transformer leg 10 of FIG. 1, may of course, be one winding leg of a three-phase or other polyphase transformer. Upon the core leg 10 is wound a helical high voltage primary winding 12 and a concentric helical secondary winding 13 of high current carrying capacity. It will be understood by those skilled in the art that when both windings are carrying current under load conditions the voltages of the windings 12 and 13 are vectorially in substantially opposite phase relation and the currents in the windings are also in substantially opposite phase relation. The current in the primary winding 12 includes as a component thereof the exciting current. On amperturn basis this exciting current is the vectorial difference between the primary and secondary currents and has the effect of producing in the core 10, 11 a main flux represented at FIG. 1 by the single flux line $\phi_m$. 
Under load conditions an appreciable part of the flux generated by the current in the primary winding 12 does not pass through the core yoke 11, but fringes from the core leg 10 to encircle directly the primary and secondary windings 12 and 13 through a return path including the conductors, the winding insulation and both return paths of the primary and secondary windings. One return path of the primary winding 13 is shown having a common portion φp in the core leg 10 and two return paths outside the core leg. One return path φin encircles both the primary and secondary windings, and another return path φin is shown returning in the space between the primary and secondary windings. Similarly, the flux established by load current in the secondary winding 13 has a common portion φs passing through the core leg 10 and two return paths outside the core leg. One of these paths φin encircles both the primary and the secondary windings, and the second path φs returns in the space between the primary and secondary windings.

It will be noted from the directional arrows on the several flux paths referred to that the primary and secondary fluxes φp and φs within the core leg 10 are in opposite directions. It is the difference between the total primary and secondary flux which results in the main magnetizing flux φm. Similarly, the components of stray primary and stray secondary flux radially beyond both of the windings 12 and 13 are in opposite directions and tend to cancel each other. In the space between the primary and secondary windings, however, the stray flux from both the primary and secondary windings are in the same direction and reinforce each other to establish a flux of considerable proportion known as "leakage" flux and comprising the components φps and φsp.

At FIG. 2 I have shown similar cross-sectional views of the primary and secondary windings 12 and 13, and have illustrated the leakage flux components φps and φsp in schematic detail. Thus, omitting illustration of the mutual stray flux components φps and φsp, as illustrated at FIG. 2, the leakage flux components do not uniformly include within their loop paths all of the primary and secondary winding turns, but in fact fringes out appreciably at the axially remote ends of the windings so that the axial component of leakage flux at opposite ends of the windings are of considerably less intensity than the axial component of leakage flux at the axial midpoint of the windings. In addition it will be evident from FIG. 2 that the leakage flux traverses only the space between the primary and secondary windings but also passes through the conductors themselves, this being shown particularly with respect to the large cross-section conductors of the secondary winding 13.

At FIG. 3 I have shown a view similar to that of FIG. 2, but in which the high current capacity conductor of the low voltage winding 13 is shown composed of a plurality of separately insulated conductor strands 1 to 8. The strands are so disposed that each winding turn is formed of two stacks of radially superseded strands (1 to 4 and 5 to 8 at FIG. 3) with the two stacks axially juxtaposed in side-by-side relation. It will be understood by those skilled in the art that axialy remote turns of the ends the eight separately insulated conductor strands are electrically connected together, as illustrated by the lack of insulation therebetween in the axially endmost turns. In practice, of course, electrical connection of the ends of the conductors is made in the leads beyond the end turns of the windings.

At FIG. 4 I have shown by a plurality of successive cross-sectional views 4a to 4j inclusive, one sequence in which the eight conductor strands shown at FIG. 4 may be radially transposed with respect to each other at selected axially spaced-apart points along the length of the helical winding 13. Each cross-sectional view at FIG. 4 is of a single winding turn, but it will be understood by those skilled in the art that these turns, while axially spaced apart, are not ordinarily axially adjacent as shown, but are spaced axially at intervals along the winding. While I have shown only eight conductor strands for the purpose of illustration, it will be evident that any odd or even number of strands stacked radially in either one or more stacks comprising a single conductor may be utilized.

The transposition illustrated at FIG. 4 is of the so-called "progressive" type. In the illustrated case the stranded conductor comprises an even number of strands with four radially superimposed strands in each of two axially juxtaposed stacks. FIG. 4a shows the initial position of the strands as the conductor enters the first turn of the winding 13. FIG. 4b illustrates the case in which the stack of strands 1 to 4 has been shifted radially outward by one strand position with respect to the adjacent stack of strands 5 to 8. FIG. 4c shows a second transposition point at which the radially innermost and radially outermost strands 3 and 4, respectively, have been shifted in opposite directions axially to place each of them in the adjacent stack of conductors. FIG. 4d shows a succeeding transposition point at which the uppermost stack of conductors has been moved radially inward and back into radial alignment with the lower stack of strands. It will be observed that in this three-conductor portion of the conductor strands 1, 2 and 3 have been moved radially outward by one position, the conductors 6, 7 and 8 have been moved radially inward by one position, and the conductors 4 and 5 have been moved axially in opposite directions without changing their radial disposition. It will now be evident to those skilled in the art that by the three successive three-step transpositions shown at FIG. 4 the conductor strand 1 may be moved to its radially outermost position at FIG. 4j, while each of the other strands is moved in step-by-step progressive manner radially inward or radially outward until each strand has occupied each of the four available radially displaced strand positions. Similar progressive, or consecutive, transpositions may be continued until the conductor strand 1 has been moved continuously through all strand positions and back to its initial radially innermost and axially uppermost position.

In further connection with the progressive type transposition illustrated at FIG. 4, it will be understood by those skilled in the art that whether one complete radial transposition (illustrated at FIGS. 4a to 4j inclusive) is made or whether two or more such transpositions are made as the conductor traverses the full length of the helical winding 13, it is generally the practice to space the transplantion points 4b, 4c, etc. apart by equal axial (or peripheral) distances along the conductors. It will also be understood by those skilled in the art that a progressive type transposition may be carried out by transposing groups of strands radially in consecutive sequence rather than so transposing each strand individually. Thus, for example, if each stack included thirty-two strands rather than four and four radial transposition points were provided (as points 4b, 4d, 4f and 4j), each strand would be moved by eight positions at each such point rather than by one position as shown, but the transposition would still be "progressive," or consecutive, in that each radial displacement would be in the same direction and by any equal number of positions within the confines of one complete transposition.

The progressive type transposition illustrated at FIG. 4 and described above is illustrated also at page 63 of a book entitled "Transformer Engineering" by L. F. Bloom et al., published by John Wiley and Sons in its second edition in 1951.

It is understood by those skilled in the art that a high current capacity conductor formed of more than two axially juxtaposed stacks of conductor strands may be transposed progressively in like manner. See, for example, British Pat. 451,617 wherein the strands in three axially adjacent stacks are transposed in progressive sequence. If it is desired to utilize four axially adjacent stacks of strands, each pair of stacks may be progressively trans-
posed in the manner described in connection with FIG. 4 above.

To illustrate the manner in which a single stack radially superposed strands forming a winding conductor may be transposed in non-progressive sequence, I have illustrated in a succession of cross-sectional views at FIG. 5 two non-progressive types of transposition known in the art as the "standard" transposition and the "special" transposition. At FIGS. 5a and 5b, I have illustrated a so-called "standard" transposition in which strand positions 1, 2, 3 and 4 are completely reversed radially at a single transposition point between consecutive winding turns. Such a transposition is more fully described at column 3 of Pat. 2,710,380, DeBuda. At FIGS. 5c and 5d, I have illustrated a so-called "special" transposition in which similar reversal of strand position is accomplished at a single transposition point by transposing the conductors in groups rather than individually. More specifically at FIGS. 5e and 5f the strand group 1-2 is reversed in respect to the strand group 3-4. The radial positional reversals which characterize the standard and special transpositions and, of course, be carried out with any desired number of axially juxtaposed stacks constituting a small conductor.

It is known that a combination of the standard transposition shown at FIGS. 5a and 5b and the special transposition shown at FIGS. 5c and 5d may be utilized to place each conductor strand in each available radial position in non-progressive, or non-consecutive, sequence. For example, if a special transposition (FIGS. 5c, 5d) is utilized at the midpoint of the upper half of a winding, a standard transposition (FIGS. 5a, 5b) is utilized at the winding midpoint and another special transposition is utilized at the midpoint of the lower half of the winding, it is evident that each conductor strand occupies each of the four available radial positions for \( \frac{1}{4} \) the length of the winding.

Transpositions similar to the "standard" and the "special" as described above and shown at FIG. 5 may also be carried out by transposing the conductors in groups rather than individually, as described for example in the DeBuda patent identified above. Moreover, it will be understood that the transpositions shown at FIG. 5 may be carried out with a conductor formed of two or more radial stacks of strands, each radial stack of such a conductor being transposed as at FIG. 5 independently of the other stacks.

As previously described, it is accepted practice in transposing conductor strands in any of the sequences described above to space the transposition points uniformly along the axis of the coil. For example, utilizing special and standard transpositions it is the practice to locate the transposition points at the center and the \( \frac{1}{4} \) and \( \frac{3}{4} \) points of the winding length. In a progressive type transposition it is the practice to separate the transposition points by equal axial distances. It should now be noted that a progressive transposition is complete in regard to radial variation of included axial leakage flux for the several strand positions when each strand has been located once in each available radial position. Moreover, if a two-stack progressive transposition is carried through a second transposition sequence so that each strand traverses both of the juxtaposed stacks, the voltage equalization accomplished takes account also of axial variation of included leakage flux because of the spacing described in connection with FIGS. 2 and 3 above. In all such transpositions, however, uniform spacing of transposition points axially along the winding assumes that the axial component of leakage flux is of uniform intensity at all points along the winding axis. Such uniform intensity does not in general exist, and I have discovered that the circulating currents in a helical electric winding formed of transposed multistrand conductors may be further reduced by spacing the transposition points non-uniformly along the axial length of the winding. More specifically, I find that by increasing the distance between transposition points in moving from the axial midpoint toward the axially remote ends of the winding, greater uniformity in the volts per turn between adjacent conductor strands may be attained. For example, in a progressive type transposition with a relatively large number of transposition points, the spacing between transpositions is, according to my invention, progressively increased approaching each end of the winding, the transposition intervals being a minimum at the axial midpoint of the winding and a maximum at the axially remote ends therefrom. Similarly, in a non-progressive type transposition such as that shown in the DeBuda patent referred to above, the transposition points in the opposite halves of the winding are located axially somewhat closer to the center of the winding than to the adjacent end. Thus in each case the median position of the transposition points in each half of the winding on opposite sides of the axial midpoint is closer to the midpoint than to the adjacent end of the winding.

The degree of non-uniformity or asymmetry in respect to axial position of transposition points in each half of the winding will, of course, vary in accordance with the configuration of the leakage field in the particular winding under consideration. Where the fringing effect is slight, the inward displacement of the median transposition point will be slight, but where the fringing effect is greater, the inward displacement of such median point will be greater.

From the foregoing it will be apparent that the terms "median position of transposition points" and "median transposition point" have the same meaning. Such "median" position or point is that axial position at each side of the axial midpoint of the winding at which occurs the central one (or only one) of an odd number of transpositions on that side of the winding midpoint; or in the case of an even number of transpositions on each side of the winding midpoint it is that axial position at one side of the winding midpoint which is midway between the central pair of transpositions on that side of the winding midpoint.

By way of example, I have shown at FIG. 6 a specific graphical representation of non-uniformly displaced transposition points for a winding having a progressive type transposition.

At FIG. 6, the curve A represents the desired axial spacing of transposition points in a winding of the kind described at FIG. 4 in terms of the ratio of actual to average spacing at each point along the winding axis. The abscissa of curve A represents turn location along winding axis in percentage of winding length, the midpoint of the curve horizontally being the midpoint of the winding and representing a percentage of 50%. The ordinate of the curve A shown at FIG. 6 represents transposition point spacing in terms of ratio to an average or uniform spacing 1.00. The curve represents an optimum progression in the spacing of transposition points along a winding having an even number of complete progressive type transpositions and characterized by a leakage flux having approximately half the intensity at the axially remote ends of the winding that it has at the winding midpoint. As illustrated, the curve A shows that at the midpoint of the winding the spacing of transposition points is preferably about .92 of an average, or uniform spacing effect. As the distance is gradually increased from the center toward each end of the winding at a very gradual rate to positions approximately \( \frac{1}{4} \) the axial length from each end of the winding. For the last \( \frac{1}{4} \) of the axial distance at the axially remote ends, the spacing between transposition points increases sharply until the spacing reaches a maximum of approximately double the average axial spacing at each end of the winding.

As a further illustrated of my invention, I have shown at FIG. 7 a cross-section view (at only one side of the
of a multistrand winding transposed non-progressively in accordance with the invention. At FIG. 7 the axially remote ends of the windings are designated O—O and the midpoint as 50%. The quadrature points are designated 25% and 75%. A "standard" transposition of a four strand single stack conductor is shown at the midpoint and designated T₁. Near the quadrature points, but slightly displaced toward the midpoint, each axial half of the winding has a "special" transposition designated T₂. Thus, as indicated also for a progressive winding by the diagram of FIG. 6, the winding of FIG. 7 has the "median" transposition point in each axial half asymmetrically displaced toward the winding midpoint.

It may be noted at this point that in some transformers voltage taps are taken out from an axially intermediate region of the high voltage winding. In such cases the low voltage winding turns radially adjacent the taps are spread out axially. Such spreading results in a fringing effect similar to end fringing, and my invention may be utilized to counteract such an effect as well as to counteract fringing of the field at opposite ends of the winding. Accordingly, I intend that in the appended claims any reference to "ends" of a winding shall include such intermediate fringing points of a spread winding.

While I have described my invention in connection with a helical winding formed of a single cylindrical layer of winding conductor, it will of course be understood by those skilled in the art that, if desired, the winding built in accordance with my invention may comprise more than one cylindrical layer and that the spacing of strand transposition points may be made non-uniform and progressively greater approaching each end of the winding in either one or more of such several cylindrical winding layers. Moreover, it will be understood that, while I have shown my invention applied to the outer of two concentric windings, it is equally applicable to the inner winding of such a pair or the intermediate windings of a group of three or more concentric windings.

Thus while I have described a particular embodiment of my invention by way of illustration, many modifications will occur to those skilled in the art, and I therefore wish to have it understood that I intend in the appended claims to cover all such modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A helical winding for electric induction apparatus, a conductor helically wound in at least one cylindrical layer of turns extending at constant pitch along a central axis, said conductor being formed of a plurality of separately insulated strands electrically connected together at their ends and positioned in radially superposed groups forming at least two axially adjacent radially extending stacks of strands in each winding turn, the strands in adjacent pairs of said stacks being radially transposed at axially spaced points along said winding layer in progressive sequence, the number of transposition points along said winding being such that each strand in each said stack occupies a succession of radially inner and radially outer positions in said stack in symmetrical sequence throughout the length of said winding, the axial spacing of said transposition points being progressively greater as said conductor approaches opposite end of said winding than is the spacing at the axial midpoint of said winding.

2. A helical winding according to claim 1 wherein the number of transposition points is such that each said strand successively occupies each strand position in an adjacent pair of stacks at least once in a single traverse through the length of said winding.

3. In a helical winding for electric induction apparatus, a conductor helically wound in at least one cylindrical layer of turns extending at constant pitch along a central axis, said conductor being formed of a plurality of separately insulated strands electrically connected together at their ends and positioned in parallel side-by-side radially superposed relation forming at least one radial stack of strands in each winding turn, the strands in said stack being radially transposed at least three axially spaced apart points along the length of said winding, the median transposition point in each axial half of said winding being closer to the axial midpoint of said winding than to the adjacent end thereof.

4. A winding for electric induction apparatus according to claim 3 wherein the strands in each said radial stack of strands are radially transposed in progressive positional sequence at axially spaced-apart points along said winding layer and the number of transposition points is such that each strand of said radial stack occupies every radially discrete strand position at least once in the course of a single traverse through said winding layer.

5. A winding for electric induction apparatus according to claim 3 wherein the strands of said radial stack are transposed radially in progressive positional sequence at axially spaced-apart points along said winding layers, the number of transposition points being such that each strand of said radial stack occupies a succession of radially inner and radially outer positions in the stack as said conductor traverses the length of said winding, the axial spacing between said points of transposition being a minimum at the axial midpoint of said winding and being progressively greater as said conductor approaches axially opposite ends of said winding.

6. A winding for electric induction apparatus according to claim 3 wherein said conductor consists of a single radially superposed stack of conductor strands transposed in fully inverse relationship at the axial midpoints of winding and having a single point of transposition in each axial half of said winding positioned closer to said midpoint than to the adjacent axial end thereof.

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