July 29, 1958 W. H. DOHERTY 2,845,473

ELECTRICAL CONDUCTOR HAVING TRANSPOSED CONDUCTING MEMBERS

Filed Dec. 29, 1955

FIG. 1

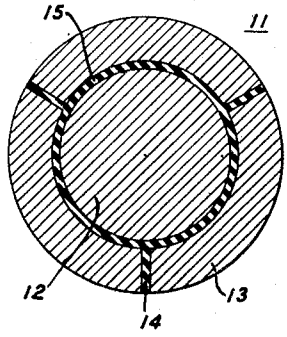


FIG. 2

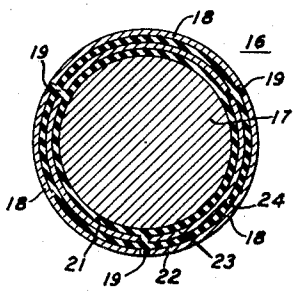


FIG. 3

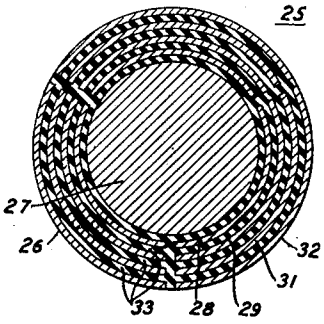


FIG. 4

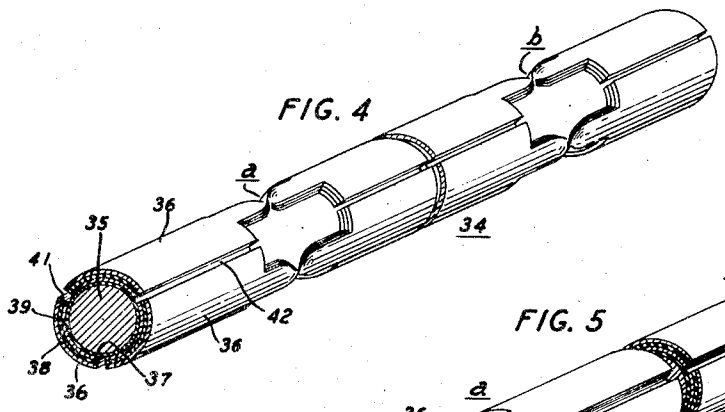


FIG. 5

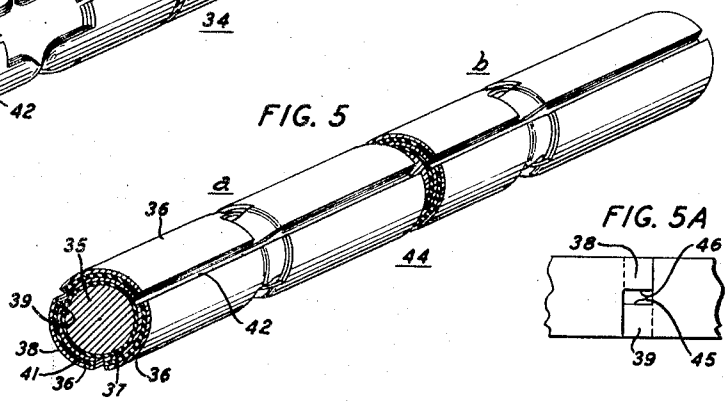
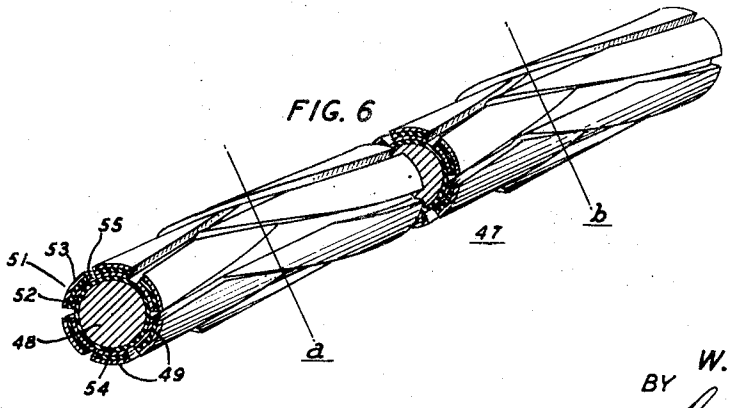


FIG. 5A

FIG. 6



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2,845,473

ELECTRICAL CONDUCTOR HAVING TRANSPOSED CONDUCTING MEMBERS

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4 Claims. (Cl. 174—34)

This invention relates to electrical conductors, and, more particularly, to electrical conductors of the type used in cables, wherein the conductor comprises a plurality of conducting elements.

Conductors of the type used in cables for the transmission of electromagnetic energy comprise, in general, a central core member of conducting material surrounded by a plurality of flat tapes of conducting material which extend longitudinally along the core. The flat tapes, which are more popularly known in the art as "surrounds," are, in general, laid on the central core in a manner such that each one spirals around the core, in the manner shown in United States Patent 2,066,525 of J. J. Gilbert which issued on January 5, 1937. Each of the surrounds contributes materially to the conduction of current, and, when the conductor is used at the higher frequencies, the surrounds carry substantially all of the current. By insulating the core and the spirally disposed surrounds from one another, the losses due to proximity effect, in cases where such proximity effect is present due to the presence of a neighboring conductor, are minimized, since each surround carries its own share of current. While losses resulting from proximity effect may be minimized in this manner, losses resulting from skin effect and other phenomena must be minimized in a different manner, such as, for example, by transposing the conducting elements of the multi-element conductor.

The term "transposed conducting elements" is used to refer to a plurality of conducting elements whose positions are shifted relative to each other and to an axis of the conductor. Transposition may take the form of frequent shifting of a large number of conducting strands, as in the case of Litz wire, or it may be an orderly change of position of a few conducting elements, such as, for example, the type shown in my copending United States patent applications Serial No. 366,510, filed July 7, 1953, now Patent Number 2,812,502, and Serial No. 519,206, filed June 30, 1955.

It is well known to workers in the art that substantial reductions in losses resulting from skin effect over a band of frequencies can be obtained by transposing the conducting elements of a multielement conductor. However, it is important that the manner of transposition be such as to minimize the difficulties of manufacture. In my copending applications identified above and others, there are disclosed various transposition schemes which facilitate manufacture. The present invention similarly relates to transposed conductors, but more particularly to such conductors of special advantage for use in submarine cables.

It is an object of this invention to provide an electrical conductor whose alternating-current resistance is less dependent upon frequency changes over a band of frequencies than that of conventional conductors.

It is another object of this invention to provide an electrical conductor for use in a submarine cable in which the losses due to nonuniformity of current distribution in the conductor are minimized.

It is still another object of this invention to provide a low loss electrical conductor which is simple and inexpensive to manufacture, and which lends itself readily to volume production.

At very low frequencies, the current in a conductor is substantially uniformly distributed throughout the cross sectional area of the conductor. As frequency is increased, however, the current distribution becomes nonuniform, current density becoming a maximum at the surface of the conductor exposed to the main field of the waves, and decreasing as distance from the field increases, i. e., towards the center of a solid conductor. The rate at which the current density decreases is dependent upon the frequency and the material of the conductor, and, for most conducting materials, at high frequencies the current density at the center of the conductor becomes negligible while the current density at the conductor surface is a maximum. This phenomenon is commonly known as "skin effect," and a "skin depth" is defined as the distance measured inwardly from the surface of the conductor in which the current density in the conductor will decrease by one neper, i. e., the current density becomes

$$\frac{1}{e}$$

times the density at the surface of the conductor, where e is the natural logarithm base. Because of the skin effect phenomenon, the alternating-current resistance of conductors increases as the frequency increases, necessitating frequent amplification of the signal along the transmission path.

It has long been recognized that the alternating-current resistance of a conductor to high frequencies can be substantially reduced over a substantial band of frequencies if the conductor is formed of a number of conducting elements connected in parallel and transposed often enough so that each conductor receives its share of exposure to the main field. This amounts to forcing the current to distribute itself over the entire cross sectional area of the composite of individual conducting elements, thereby increasing the total current carrying area. It follows then that the alternating-current resistance is decreased substantially, and the frequency dependency of the alternating-current resistance is likewise decreased within the frequency band.

In accordance with the present invention, an electrical conductor suitable for use in cables transmitting electromagnetic energy is provided which is a great improvement in many respects over conductors currently in use, and which is quite simple and inexpensive to manufacture. In an illustrative embodiment of the invention, a solid inner member of conducting material has disposed around its circumference a plurality of composite surrounds which are insulated from the inner member and from each other. Each surround comprises an elongated flat sandwich formed by interposing a thin sheet of dielectric material between two thin sheets or tapes of conducting material. At intervals along the length of the conductor the thin conducting sheets which form each surround are transposed relative to each other by imparting to the surround a 180 degree twist, the inner conducting sheet becoming the outer, and the outer conducting sheet becoming the inner.

The invention will be more readily understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a cross sectional view of a conductor for use in submarine cables of the kind shown in the aforementioned Gilbert patent;

Fig. 2 is a cross sectional view of a conductor suitable

for use in cables embodying features of the present invention;

Fig. 3 is a cross sectional view of another conductor suitable for use in cables embodying features of the present invention;

Fig. 4 is a perspective view of a preferred embodiment of the present invention;

Fig. 5 is a perspective view of another conductor embodying the principles of the present invention;

Fig. 5A is a plan view of a small portion of one of the surrounds of the conductor of Fig. 5, showing details of the transposition; and

Fig. 6 is a perspective view of still another conductor embodying the principles of the invention.

Turning now to Fig. 1 there is shown a conductor **11** for use in cables of the type disclosed in United States Patent 1,756,546 to J. J. Gilbert, filed December 12, 1923, and issued April 29, 1930, and United States Patent 2,066,525 to J. J. Gilbert, filed March 29, 1929, and issued January 5, 1937. Conductor **11** comprises a solid inner core **12** of conducting material which is surrounded by a plurality of conducting members or surrounds **13**. The surrounds extend longitudinally along the conductor and preferably spiral about the conductor. While conductor **11** is shown with only three surrounds, it is obvious that a large number of surrounds may be used. Surrounds **13** are insulated from each other by insulating material 14 and from the central core 12 by insulating material **15**. As disclosed in the aforementioned Gilbert patents the insulation may comprise a layer of copper oxide, or it may be any one of a number of insulating materials known in the art. When conductor **11** is used in a submarine cable system or in any cable system, the surrounds carry a substantial portion of the current, and their contribution to the total conduction of the conductor increases with frequency. When frequencies become so high that skin effect becomes a factor, the resistance of the conductor increases, becoming frequency dependent, as previously explained.

In Fig. 2 there is shown a conductor **16** of the same general type as conductor **11** of Fig. 1 which, however, is constructed in accordance with the present invention so that the frequency dependency of the resistance of the conductor may be substantially overcome. Conductor **16** comprises a solid inner core member **17** of conducting material which is surrounded by a plurality of composite surrounds **18** which, as pointed out in the foregoing, may spiral around the core. The surrounds are insulated from each other by insulating material **19** and from the core **17** by insulating material **21**. Each surround comprises two thin elongated members **22** and **23** of conducting material which are separated from each other by a thin layer of insulating material **24**. Conducting members **22** and **23** are preferably of the order of a skin depth in thickness at the highest frequency of operation of the conductor, although this dimension is not altogether critical.

In Fig. 3 there is shown a conductor **25** which is substantially similar to conductor **16** of Fig. 2 with the exception that each of the surrounds **26** which surround core **27** comprises four conducting members **28**, **29**, **31** and **32** separated by thin layers of insulating material **33**. While conductor **16** of Fig. 2 and conductor **25** of Fig. 3 are shown with the surrounds made up of two and four thin layers of conducting material respectively, the surrounds may comprise any number of thin layers of conducting material so long as the surrounds do not become so unwieldy as to prevent the mechanical manipulation to be disclosed hereinafter.

In Fig. 4 there is shown a perspective view of a composite conductor **34** embodying the principles of the present invention. Conductor **34** comprises a solid cylindrical core member **35** of conducting material. Surrounding core **35** are a plurality of composite surrounds **36** which are separated from core **35** by a thin layer of insulation **37**. In the particular embodiment shown in Fig. 4, for simplicity the surrounds are shown as comprising two thin layers **38** and **39** of conducting material separated by a thin layer **41** of insulating material. It is obvious from the disclosures of Figs. 2 and 3 that the surrounds may comprise a large number of thin layers of conducting material instead of the two here shown. The surrounds are disposed around core **35** and extend longitudinally thereof in parallel relationship to each other, being separated from each other by gaps **42** which may be simply air gaps or may be filled with suitable insulating material. At periodic intervals along the length of the composite conductor **34** the width of the surrounds is narrowed as at points *a* and *b* in Fig. 4 and each surround is twisted 180 degrees. The inner and outer conducting members reverse position relative to the core. As shown at point *a* the conducting member **39** becomes the outer conducting member and conducting member **38** becomes the inner, thus effectively transposing the members **38** and **39** relative to each other and to the core member **35**. It is preferable that the surrounds be narrowed as at points *a* and *b* sufficiently to facilitate twisting thereof. It is obvious, however, that if a large number of surrounds is used instead of three, as shown in Fig. 4, each one will be sufficiently narrow and flexible to permit twisting without decreasing the width at the point of transposition. It is obvious that if, for example, the main field along the conductor is at the outer surface thereof and if the intervals between transpositions, that is, the distance between points *a* and *b*, remains the same throughout the entire length of the conductor, the conducting members **38** and **39** will be made to share equally exposure to the main field, whereby the current will be evenly distributed between the two conducting members.

The effectiveness of transposition of conducting elements in a conductor depends to a considerable extent upon a judicious selection of the transposition interval, that is, the distance between points *a* and *b* in Fig. 4. It is desirable to transpose at close enough intervals to insure a substantial reduction in losses, yet, on the other hand, in the interest of ease and low cost of fabrication it is desirable that the conducting elements be transposed no more frequently than is necessary. As long as the currents carried by the conducting elements are approximately equal, losses such as those resulting from unequal current distribution in a conductor will be minimized, hence it is necessary to transpose only often enough to maintain this condition of approximate equality of current in the conducting elements. In the drawings of the present invention the particular embodiments shown are neither to scale nor to proportion inasmuch as the transposition interval may be quite long as compared to that portion of the length of the conductor over which the transposition is accomplished.

In Fig. 5 there is shown a composite conductor **44** which is similar to conductor **34** of Fig. 4. For clarity the elements of conductor **44** which correspond to like elements of conductor **34** have been numbered the same. Elements **38** and **39** of each surround are periodically transposed at points along the length of conductor **44**, such as points *a* and *b* in Fig. 5. Conducting members **39** have a notch **45** cut therein, and conducting members **38** have a notch **46** cut therein as best seen in Fig. 5A. Notches **46** and **45** are cut in their respective conducting members in opposite sense and conducting member **39** is bent upward so that it is shifted to the outside of conducting member **38**, conducting member **38** being bent downward at the notch and passing under conducting member **39**, thereby accomplishing transposition of conducting members **38** and **39**. Preferably, members **38** and **39** are coated with a suitable insulating layer on both sides so that after each transposition they are still insulated from each other.

While the embodiments thus far shown in Figs. 4, 5 and 5A have had the surrounds disposed around the

circumference of the conducting core member in parallel relationship to each other and to the axis of the core, it is to be understood that they may be disposed around the core member parallel to each other but in a spiral relationship relative to the axis of the conductor as disclosed in the aforementioned Gilbert patents. Such an arrangement will, as explained in the foregoing, materially decrease losses resulting from proximity effect if the conductors are to be used in other than coaxial arrangements.

In Fig. 6 there is shown a conductor **47** which effectively reduces losses resulting from both proximity effect and skin effect. Conductor **47** comprises a solid core member **48** of conducting material having disposed around the circumference thereof a multiplicity of surrounds **49**. Surrounds **49** in the embodiment shown in Fig. 6 are of the type disclosed in Figs. 2, 4 and 5 although, as mentioned in the foregoing, they may be made up of large numbers of conducting elements. Each surround **49** is made up of two thin layers of conducting material **51** and **52** separated by a thin layer of insulating material **53**. The surrounds are insulated from core member **48** by a layer of insulating material **54** and from each other by gaps **55** which may be simply air gaps or filled with suitable insulating material. Surrounds **49** extend parallel to each other along the length of conductor **47** and spiral relative to the axis of conductor **47**. At intervals along the length of conductor **47** such as at points *a* and *b*, each surround is folded over upon itself so that it commences to spiral in opposite direction relative to the axis of conductor **47**. It can readily be seen from an examination of Fig. 6 that at the point where a surround **49** is folded over upon itself the outer conductor, for instance conductor **51**, becomes the inner conductor and the inner conductor **52** becomes the outer conductor, thereby effectively transposing the conductors. The spiral disposition of the surrounds **49** of conductor **47** will cause each one to occupy over a given length, depending upon the lay of the spiral, every point on the circumference of the core member **48**. If another conductor is in the vicinity each surround will therefore occupy within this length the nearest and farthest points as well as the intermediate points of conductor **47** relative to the other conductor. The current will be prevented, therefore, from crowding to one side or the other of the conductor due to proximity effect inasmuch as each of the surrounds will have an equal exposure to the field of the current in the other conductor. In addition, since each conducting element of each surround is made to occupy both inner and outer positions relative to the axis of conductor **47**, each element will therefore share equal exposure to the main field of the waves and prevent crowding of the current toward the outer layer of conductor **47**. As a result of this configuration conductor **47** exhibits less loss resulting from proximity effect and from skin effect.

In all of the embodiments of the invention herein shown the use of insulating material surrounding the conductor is permissible, a showing thereof having been eliminated for clarity's sake inasmuch as various insulating methods and practices are well known in the art. It is to be understood that the above described arrangements are merely illustrative of the principles of the invention

and applicant does not intend to limit his invention to the particular embodiments described inasmuch as other embodiments may be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electrical conductor for the transmission of electromagnetic energy comprising an elongated core member of conducting material and a plurality of insulated composite conducting members each including a plurality of strips of conducting material separated by insulating material, disposed around the periphery of said core and extending longitudinally thereof, said composite members being equally spaced from said core over at least a portion of the length of said conductor and each having a 180 degree twist at intervals along the length of said conductor whereby the strips in each of said composite conducting members are transposed.

2. An electrical conductor for the transmission of electromagnetic energy comprising an elongated core member of conducting material and a plurality of insulated composite conducting members each including a plurality of strips of conducting material separated by insulating material, disposed spirally around the periphery of said core and extending longitudinally thereof, said composite members being equally spaced from said core over at least a portion of the length of said conductor and having 180 degree twists at intervals along the length of said conductor whereby the strips in each composite member are transposed.

3. An electrical conductor for the transmission of electromagnetic energy comprising an elongated core member of conducting material and a plurality of insulated composite conducting members each including a plurality of strips of conducting material separated by insulating material and having short sections of reduced width at intervals along the length of said composite members, disposed around the periphery of said core and extending longitudinally thereof, said composite members being equally spaced from said core over at least a portion of the length of said conductor and each including a 180 degree twist at each of the reduced width sections whereby said strips are transposed.

4. An electrical conductor for the transmission of electromagnetic energy comprising an elongated core member of conducting material and a plurality of insulated composite conducting members each including a plurality of strips of conducting material separated by insulating material and having short sections of reduced width at intervals along the length of said composite members, disposed spirally around the periphery of said core and extending longitudinally thereof, said composite members being equally spaced from said core over at least a portion of the length of said conductor and each including a 180 degree twist at each of the reduced width sections whereby said strips are transposed.

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