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W. W. SALISBURY

2,963,669

AIR-CORE TRANSFORMER

Filed Feb. 13, 1958

Fig. 1

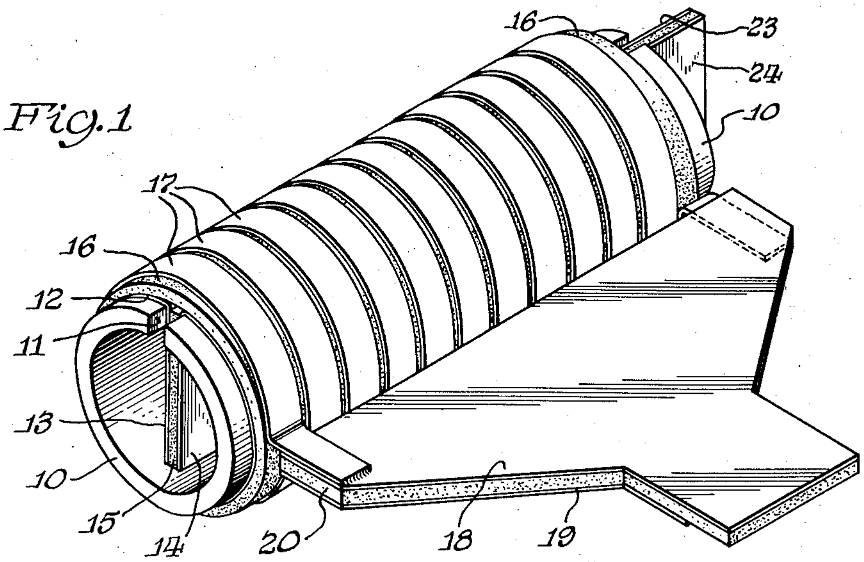


Fig. 2

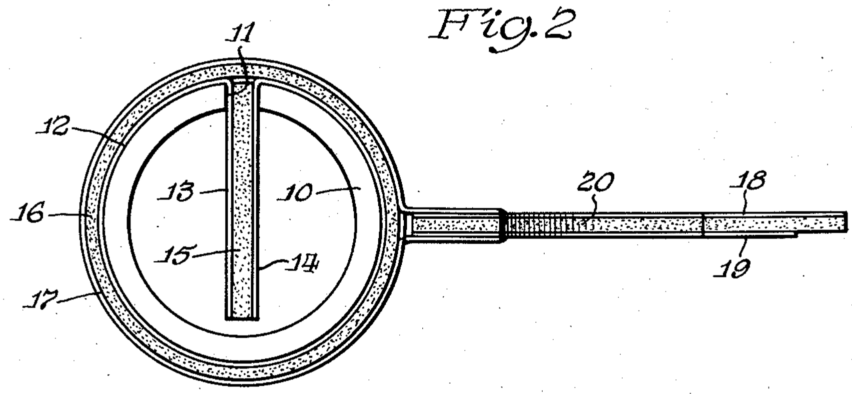
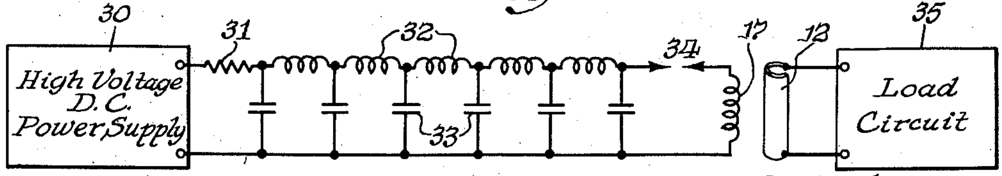


Fig. 3



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AIR-CORE TRANSFORMER

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9 Claims. (Cl. 336—192)

This invention relates in general to transformers and is particularly directed to transformers of the air-core type. The expression "air-core transformer" as used herein and in the appended claims means a transformer which has a core of non-magnetic and non-conductive material whether the core, in fact, be air or an insulating material employed to strengthen the structure mechanically.

Transformers, of course, have a myriad of applications and the desideratum in their design and construction has always been increased efficiency or greater and greater coupling coefficients of the windings with respect to one another. Two well known expedients have been resorted to in the past for the purpose of improving the transformer action: (1) the use of a magnetic core to concentrate the magnetic flux resulting from current flow in the windings and (2) the use of tuned windings. Neither is entirely satisfactory. Magnetic cores are objectionable because they introduce losses, specifically hysteresis losses, and they are subject to saturation which undesirably limits the current capacity of the transformer. Moreover, they impose frequency limitations especially for high-frequency installations. Tuned windings similarly impose severe frequency limitations and may be likened to a brute force method of increasing transformer action. The improvement results from resonance effects rather than from any increase in efficiency or co-efficient of coupling.

Transformers of the air-core type do avoid certain of the objectionable features of those employing magnetic cores but, as previously constructed, they have exhibited poor coupling coefficients and have not represented any real solution to the quest for a high-efficiency transformer. High efficiency, which is another expression for a high degree of coupling, is obviously desirable for any installation, but is essential in systems where the performance depends upon the attainment of "fast circuitry"; for example, in the field of controlled thermonuclear reaction.

Efforts have been made to obtain a thermonuclear reaction by confining a plasma of a suitable reactant within an exceedingly concentrated magnetic field fashioned to enclose a reactoin space and by pouring energy into that space. It is necessary in an apparatus pursuing this approach to nuclear reaction to supply enormous quantities of energy in short pulse intervals which may be in the order of 50 microseconds or less and that can be accomplished only through fast circuits. Such circuits are characterized by the fact that their inductance has been reduced as nearly as possible to an essential minimum.

In practice, the energy is delivered from condenser banks and condensers have been developed which have a very low internal inductance. Such a condenser is described and claimed in a copending application, Serial No. 711,376, filed January 27, 1958, in the name of Winfield W. Salisbury, and assigned to the same assignee as the present invention. Techniques have also been perfected for minimizing the inductance of the leads or conductors employed in constructing the system and a

switch for controlling current flow in the system, while of itself contributing a minimum of inductance, is the subject of another copending application, Serial No. 715,000, filed February 13, 1958, in the name of Leigh Curtis Foster and, likewise, assigned to the same assignee as the present invention. The remaining component of the system, which can be a major source of unwanted inductance, is the transformer desired to be employed for the purpose of achieving currents of extreme intensity in the magnetic structure. Transformers heretofore employed for this purpose have been of more or less conventional construction, exhibiting unnecessary leakage inductance and impairing optimum performance of the system by degrading its rise time.

It is an object of the present invention, therefore, to provide a transformer of the air core type particularly useful in high frequency applications.

It is another object of the invention to provide an air core transformer having a minimum of leakage inductance and exhibiting an extraordinary high coefficient of coupling and efficiency.

It is a specific object of the invention to provide an air core transformer having an improved coupling coefficient achieved primarily through geometrical or physical considerations of the structure itself as distinguished from the aid of magnetic cores or tuned windings.

A high frequency air core transformer, constructed in accordance with the invention, comprises a first winding including a plurality of helically wound turns of a flat-ribbon conductor having a width very much greater than its thickness and having a minimal spacing between turns. There is a secondary winding in concentric relation to the first winding, formed of a conductor having a width approximately equal to the axial length of the first winding, to constitute with the first winding an air core transformer having a winding thickness much less than the core diameter. Insulating material is interposed between the turns of the winding and a pair of terminal strips connect to opposite ends of the first winding. These terminal strips are formed of conductors having a width substantially greater than the conductor width of the first winding and extending in closely apposed mutually parallel relation. A second pair of terminal strips is connected to the opposite ends of the second winding, having a width much greater than their thickness and likewise extending from the second winding in closely apposed mutually parallel relation.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The organization and manner of operation of the invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in the several figures of which like reference numerals identify like elements, and in which:

Figure 1 is a perspetcive view of a transformer embodying the teachings of the invention;

Figure 2 is an end view of the structure of Figure 1; and

Figure 3 is a schematic representation of an electrical system to which the transformer may be applied with a special advantage.

Referring now more particularly to Figures 1 and 2, the structure there represented is an air core transformer which is especially suited for high frequency application. When employed in an electrical system in which the transformer is interposed between a condenser bank and a magnetic structure for the purpose of establishing intense magnetic fields in response to the discharge of the condenser bank, the discharge is of an oscillatory type and the frequency corresponds to the frequency of the oscillatory discharge. In thermonuclear systems this frequency is high, being in the neighborhood of one megacycle per second.

While the transformer may have a strictly air core, it is convenient to form the windings about a core 10 of nonmagnetic and nonconductive material but being mechanically strong in order to impart mechanical strength to the transformer structure. Such a core may be formed of a canvas base Bakelite, Lucite or other nonmagnetic and nonconductive material. Its axial length is preferably somewhat greater than the desired length of the transformer windings and, while taking the form of a hollow cylinder, it has a slot 11 extending completely along its length for a purpose to be made clear hereinafter. There is a winding 12 formed about core 10 to constitute one coil turn which is almost but not quite complete. The winding is made of a conductor having a width approximately equal to the desired axial lengths of the transformer windings. Electrically this winding may conveniently be employed as the secondary of the transformer and the free ends of the conductor from which it is wound are folded or bent across the coil turn, extending through slot 11 of core 10 and arranged in closely apposed mutually parallel relation. These end portions of the conductor are designated 13 and 14 and a layer 15 of insulating material is interposed between them.

A layer 16 of insulating material is wound over secondary winding 12 so as to be interposed between the primary and secondary windings. Preferably, layer 16 has a minimal thickness, that is to say, its thickness is as small as the electrical ratings and properties of the transformer permit. A layer thickness corresponding to one skin depth in the winding conductors at the operating frequency is desirable because it permits a condition of image currents in close physical proximity to be established in the primary and secondary windings.

The primary winding is formed over insulating layer 16 and includes a plurality of helically wound turns 17, 17 of a conductor having a width several times greater, than its thickness, and a spacing between turns which is as small as it can be made compatible with the electrical requirements of the winding. The primary and secondary windings may be formed of conductors having like thicknesses and their thickness dimension is selected with a view to obtaining an optimum compromise in respect of the magnetic properties, the electrical resistance and the mechanical strength of the windings.

In general, the thinner the winding conductor, the better is its magnetic property but its resistance is smallest for a thickness corresponding to one skin depth at the operating frequency. Skin depth is defined as follows:

$$\Delta = K\sqrt{\frac{\rho}{fu}} \qquad (1)$$

where:

Δ is the skin depth;
K is the constant;
ρ is the resistivity of the winding conductors;
f is the operating frequency; and
u is the permeability of the winding conductor.

Of course, the mechanical strength of the winding increases with the thickness of the conductor and this is seen to be in conflict with the requirement for best magnetic properties. For the case under consideration the primary and secondary windings are formed of conductors having a thickness of the order of one skin depth at the operating frequency.

Terminal strips connect to opposite ends or to the first and last turns of primary winding 17 and are themselves constructed to have a minimum inductance. To that end, the strips 18, 19 are formed from conductive strips having a width substantially greater than the width of the conductor from which the primary is formed and, additionally, the terminal strips extend in closely apposed mutually parallel relation, being insulated one from the other by a suitable layer 20 of insulation. To have the necessary cancellation of lead inductance, strips 18 and 19 should have a width exceeding half the axial length of the windings but preferably, and as represented in Figure 1, their width corresponds essentially to that of the lengths of the windings. Of course, each terminal strip, while being mechanically and electrically connected to an end turn of the primary is otherwise insulated from the winding turns. Where the terminal strips are formed from the same stock as the primary winding, their thickness will be approximately one skin depth.

As will be explained presently, the desired condition of low leakage inductance requires that currents flowing in the transformer structure, including its lead-ins, be in close physical proximity to image currents. To achieve that condition, at least so far as primary lead-ins 18, 19 are concerned, these lead-ins are to have the same size and shape and to be positioned for complete overlapping as represented in Figure 1.

It is of course essential that terminal strips be provided for making electrical connections to the inner or secondary winding of the transformer and this is accomplished by extending terminal sections 13, 14 of the secondary conductor, extending them axially from the winding as shown at 23, 24 in Figure 1. Terminal strips 23, 24 have a width much greater than their thickness and, more particularly, have a width approximately equal to the core diameter of the transformer. They are positioned in closely apposed mutually parallel relation and are insulated from one another by the insulating layer 15.

In general, the desirable properties of a transformer are that it be capable of transforming alternating current electric power from one voltage-current ratio to another without excessive power loss and with a minimum of interference in the phase relations which depend on the power utilizing load. For the described structure, the primary lead-ins 18, 19 represent a high voltage and relatively low current condition which may be transformed through the transformer action to a relatively low voltage but intense current available at the terminal strips 23, 24 of the secondary. The optimized value of conductor thickness, namely, a thickness in the order of one skin depth at the operating frequency, assures minimum power loss in the transformer itself while other physical characteristics of the structure contribute to an extraordinarily high coefficient of coupling or transformer efficiency.

The energy stored in common by a given current so as to be available to either winding of the transformer represents the energy which can be transferred from one to the other in each cycle and, accordingly, represents the open circuit or excitation inductance of the transformer while the energy stored in such a way as to be available to only one coil and not to the other represents leakage inductance. The ratio of leakage inductance to excitation inductance must be minimized to achieve high efficiency and coupling coefficients approaching unity. Primary conductor 17 is formed into a coil around a large conducting cylinder 12 so that the currents which flow in the cylinder are equal and opposite to those in the exciting coil and may be thought of as images of the exciting current. Such image currents are always so distributed as to reduce to a minimum possible value magnetic flux below the surface of the conducting cylinder. If the exciting conductors are close to the surface from which they induce images in terms of their width and if their width is large compared to a skin depth, the image currents are nearly true images of the exciting currents which is a necessary condition for minimizing leakage inductance. That condition is admirably satisfied by the described structure, especially when insulating layer 16 has a thickness as described, of the order of one skin depth. The structure achieves increased transformer action through considerations of its physical or geometrical construction as distinguished from prior art techniques wherein enhanced transformer action is accomplished through the use of magnetic cores and/or tuned windings with the limitations incident to such techniques discussed hereinabove.

One embodiment of the transformer structure which has been successfully employed had the following specification which, being given solely for the purpose of illustration, represents no limitation of the invention:

Primary conductor 17	A copper strip 1¼ inches wide and .040 inch thick.
Interturn spacing of the primary	⅛ of an inch.
Insulation 16	.010 inch of "Mylar."
Secondary conductor 12	A copper strip having a length equal to that of the primary and the same thickness as primary conductor 17.
Mean diameter	6½ inches.
Primary voltage	4 kilovolts.
Secondary current	200,000 amperes in a pulse interval of 50 microseconds.
Coefficient of coupling	75%.
Turns ratio of primary to secondary	4:1.
Axial length of transformer windings	12 inches.

Coefficients of coupling as high as 96% have been achieved with transformer constructions of the type described.

An electrical system characterized by fast circuitry and employing a transformer in accordance with the instant invention is represented schematically in Figure 3. It includes a high voltage D.C. power supply **30** of any conventional construction, coupled through a current limiting resistor **31** to an artificial transmission line constituted of series-connected inductors **32, 32** and parallel-connected condensers **33, 33**. The output terminals of the transmission line are connected through a switch **34**, represented as electrodes defining a spark-gap, to a transformer **12, 17** which may be considered to be the structure represented in Figures 1 and 2. The secondary winding of the transformer connects to a load circuit **35**. The load circuit may take any of a variety of forms and may, if thought of as a component of a thermonuclear reaction apparatus, be a magnetic structure for creating an intense magnetic field in response to the application of high intensity current pulses.

In operating intervals in which switch **34** is open, supply **30** charges condensers **33** to a high potential through current limiting resistor **31**. When the switch is closed through the expedient of establishing an arc between its electrodes, the transmission line discharges through the transformer **12, 17**. As a consequence, and in virtue of the current step-up properties of the transformer, a pulse of current of very high intensity is applied to the load **35**.

A system of this type renders its intended performance only to the extent that it is composed of fast circuits so as to have very sharp rise times. This necessary attribute may be realized by constructing condensers **33** in the manner described in the above-identified application of W. W. Salisbury and by employing a low inductance switch, of the type described in the aforeidentified Foster application, at component **34**. The low inductance condensers, low inductance switch and the current transformer of high coupling coefficient in minimized leakage inductance yield very sharp rise times for the system.

While particular embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a width much greater than its thickness and having a minimal spacing between turns; a second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

2. A high-frequency air-core transformer comprising: a first winding including a plurality of helically wound turns of a flat-ribbon conductor having a thickness of the order of one skin depth at the operating frequency, having a width much greater than its thickness and having a minimal spacing between turns; a second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

3. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a thickness of the order of one skin depth at the operating frequency, having a width much greater than its thickness and having a minimal spacing between turns; a second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding and a thickness of the order of one skin depth at the operating frequency, to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

4. A high-frequency air-core auto-transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a thickness of the order of one skin depth at the operating frequency, having a width much greater than its thickness and having a minimal spacing between turns; a single-turn second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding and a thickness of the order of one skin depth at the operating frequency, to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel rela-

tion; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

5. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a width much greater than its thickness and having a minimal spacing between turns; a second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than one-half the axial length of said windings and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

6. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a width much greater than its thickness and having a minimal spacing between turns; a second winding in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width approximately equal to the axial length of said windings and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending from said second winding in closely-apposed mutually-parallel relation.

7. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a width much greater than its thickness and having a minimal spacing between turns; a second winding disposed within and in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width much greater than the thickness and extending axially of said second winding in closely-apposed mutually-parallel relation.

8. A high-frequency air-core transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a width much greater than its thickness and having a minimal spacing between turns; a second winding disposed within and in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding to constitute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width substantially greater than the conductor width of said first winding and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width approximately equal to the core diameter of the transformer and extending axially of said second winding in closely-apposed mutually-parallel relation.

9. A high-frequency air-core auto-transformer comprising: a first winding including a plurality of helically-wound turns of a flat-ribbon conductor having a thickness of the order of one skin depth at the operating frequency, having a width much greater than its thickness and having a minimal spacing between turns; a single-turn second winding disposed within and in concentric relation to said first winding, formed of a conductor having a width approximately equal to the axial length of said first winding and a thickness of the order of one skin depth at the operating frequency, to consttiute with said first winding a transformer having a winding thickness much less than the core diameter; insulating material between said windings; a pair of terminal strips connected to opposite ends of said first winding formed of conductors having a width approximately equal to the axial length of said windings and extending in closely-apposed mutually-parallel relation; and a pair of terminal strips connected to the opposite ends of said second winding, having a width approximately equal to the core diameter of the transformer and extending axially of said second winding in closely-apposed mutually-parallel relation.

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