Oct. 19, 1948. H. A. WHEELER 2,451,596

UNITARY BALANCED INDUCTOR SYSTEM

Filed Dec. 31, 1942 2 Sheets-Sheet 1

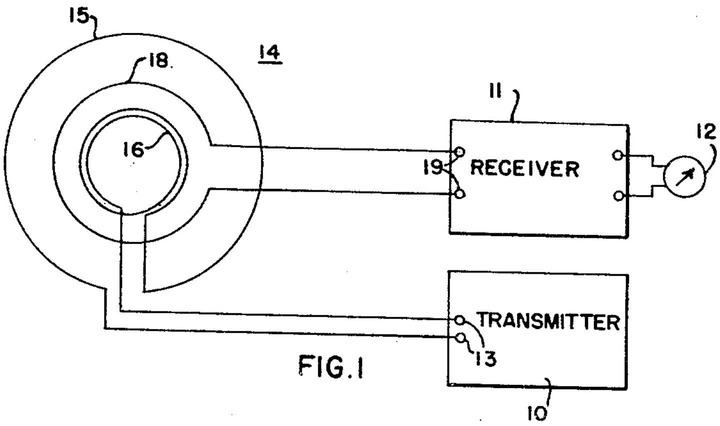

FIG. 1

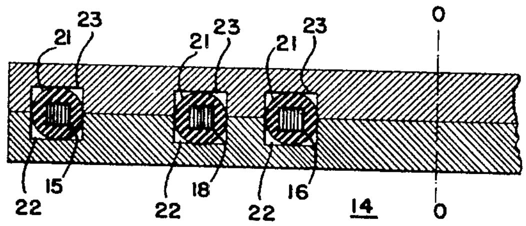

FIG. 2

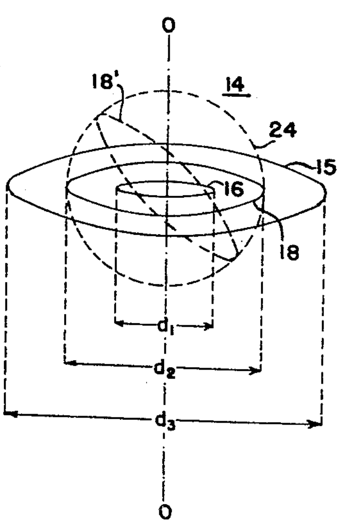

FIG. 3

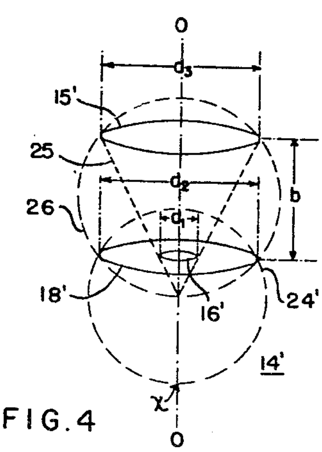

FIG. 4

INVENTOR
HAROLD A. WHEELER
BY Harry C. Page
ATTORNEY

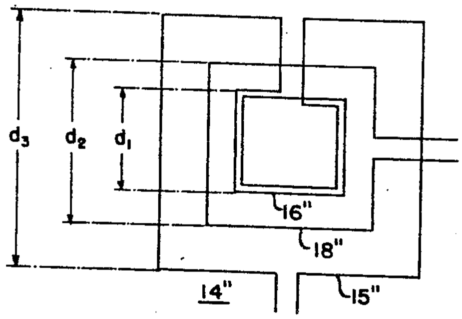

FIG. 5

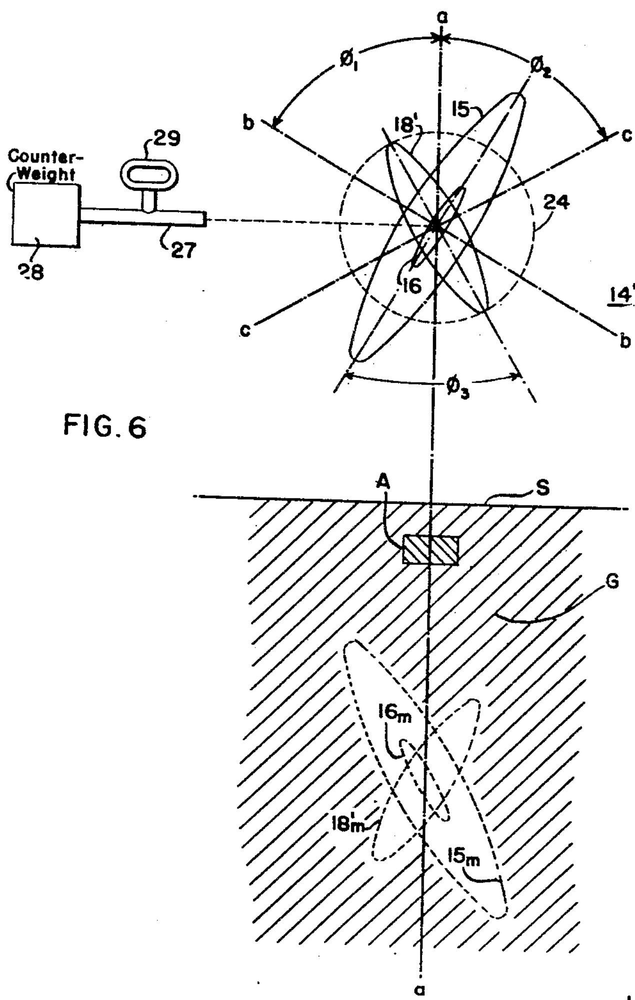

FIG. 6

INVENTOR
HAROLD A. WHEELER
BY Harry B. Page.
ATTORNEY

Patented Oct. 19, 1948

2,451,596

UNITED STATES PATENT OFFICE

2,451,596

UNITARY BALANCED-INDUCTOR SYSTEM

Harold A. Wheeler, Great Neck, N. Y., assignor, by mesne assignments, to Hazeltine Research, Inc., Chicago, Ill., a corporation of Illinois

Application December 31, 1942, Serial No. 470,785

6 Claims. (Cl. 175—182)

1

The present invention relates to unitary balanced-inductor systems and, particularly, to such systems of the type which has a plurality of inductors at least two of which are adapted to be connected in one electrical circuit and others in a second electrical circuit, the inductors being so wound and disposed relative to each other that alternating current flowing in one electrical circuit will produce a field in the vicinity of all of the inductors but normally will not induce any appreciable voltage in the other circuit until the inductive coupling between the inductors is disturbed by some external condition.

In certain applications, for example in some detectors of buried metallic objects or bodies of ore, it is desirable to provide an inductor system having at least two inductors individually connected in two electrical circuits of the detector system but normally providing no coupling between the circuits. When a magnetic or conductive body is brought into the vicinity of such an inductor system, the coupling between the inductors is modified and electrical energy is transferred from one electrical circuit of the detector system to the other. This transfer of energy between the circuits is used to actuate a suitable device to indicate the presence of the conductive body.

Perhaps the simplest prior inductor system of this nature comprises a pair of inductors crossed at right angles and included in individual electrical circuits of the detector system. Inductors relatively positioned in this manner have substantially zero mutual inductance and consequently are normally not effective to transfer energy between the circuits of the detector system. Another prior arrangement utilizes a pair of parallel inductors close together and connected in individual circuits of the detector system, the inductors being overlapped just sufficiently to provide zero mutual inductance. Both of these dual-inductor arrangements of the prior art involve some constructional difficulties because the inductors cannot be made coplanar. Furthermore, in the overlapping inductor arrangement, it is impossible to compute the position of the two inductors for zero mutual inductance and it is difficult to maintain such relation if the inductor system must be operated under conditions of varying temperature. The crossed-inductor system has the important disadvantages that it is unresponsive to a metallic object on the axis of either inductor and the inductors thereof become appreciably and undesirably coupled due to the presence of the earth for even slight variations of the inductors from the horizontal and vertical positions in which they normally are used.

An additional prior art inductor system includes three inductors of the same size supported in fixed coaxial relation with one inductor between the other two. The end inductors have equal numbers of turns and are serially connected with opposing magnetic fields, whereby the centrally positioned inductor is inductively coupled to either of the end inductors but is inductively uncoupled to both together. This inductor system has the disadvantage that the inductors, being of the same size, cannot be made coplanar to minimize the volume necessarily occupied by the inductor system. There is the additional disadvantage that the inductors of this arrangement cannot be made concentric and, consequently, the balance of coupling between the center inductor and the end inductors is critically sensitive to movement of any one of the inductors, such as might be experienced during initial construction of the inductor system or by unequal displacements of the inductors with changes of temperature. This inductor system, in common to those heretofore considered, has the additional important disadvantage that the system is incapable of providing a critical indication of the distance from the inductor system of any body which is effective to produce coupling between the inductors thereof, for example the distance below the earth's surface of a buried metallic object or a body of ore.

2

Yet another prior inductor system of this general type utilizes three coaxial inductors, two of which are laid on the ground and connected in one electrical circuit with opposing magnetic fields while the third inductor is positioned on a support above the ground and connected in a second electrical circuit. This arrangement of inductors has the disadvantage that the inductors cannot readily be moved or transported over the ground as a unitary inductor system. Additionally, it is quite difficult to position and arrange the several inductors to provide balanced mutual inductance between the elevated inductor and the two inductors which lie on the ground with the result that this desired condition of balance can only be attained by experiment after each new disposition of the inductors.

It is an object of the present invention, therefore, to provide a new and improved unitary balanced-inductor system which avoids one or more of the limitations and disadvantages of the prior art systems of this nature.

It is a further object of the invention to provide a new and improved unitary balanced-inductor system in which at least two of the inductors are adapted to be connected in one electrical circuit and other inductors in at least one additional electrical circuit and in which the relative positions and parameters of the inductors for substantially zero inductive coupling between the circuits are readily determined by computation even though some of the inductors are of unequal size.

It is an additional object of the invention to provide a new and improved unitary inductor system in which the exact relative positions and parameters of the inductors for balanced coupling therebetween may be determined by computation so that the inductor system is adapted to be initially constructed with the inductors supported in fixed positions relative to one another.

It is a further object of the invention to provide a new and improved unitary inductor system in which the desired mutual coupling between the inductors does not appreciably change with temperature and is not critical in respect to either the shape of the inductors or their centering.

It is an additional object of the invention to provide a unitary balanced-inductor system particularly suited for use in a system for locating buried masses of magnetic or conductive material or bodies of ore and one which is effective to determine the position and the depth at which the material or body is buried.

It is yet an additional object of the invention to provide a new and improved unitary inductor system adapted to be carried in proximity to a mass of material having a substantially flat surface and exhibiting an electrical characteristic, for example magnetic permeability, and one which is not only substantially unresponsive to variations of the distance of the system from the mass of material but additionally has greatly reduced response to undesirable slight departures in the orientation of the system from a predetermined normal orientation relative to the surface of the mass of material.

In accordance with the invention, therefore, a unitary balanced-inductor system comprises a first inductor having a predetermined shape and diameter d_1 and number of turns n_1, and a second inductor having the same predetermined shape but having a larger diameter d_3 and a number of turns n_3. The second inductor is positioned in fixed coaxial relation to the first inductor and the diameters and numbers of turns of the first and the second inductors are proportioned in accordance with the relation $n_1/n_3=\sqrt{d_3/d_1}$ so that alternating currents of equal magnitudes and opposite phases in the inductors produce a magnetic field which has zero normal component of intensity over a predetermined unbroken three-dimensional surface in space completely enclosing on all sides the smaller of the inductors but completely excluding the larger thereof. The system includes a third inductor having any number of turns and positioned in fixed relation to the first and second inductors and lying substantially in the aforesaid surface, whereby the third inductor has substantially zero inductive coupling to the first and second inductors when carrying the aforesaid alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to the first and second inductors in the presence of such bodies.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims.

Referring to the drawings, Fig. 1 is a circuit diagram, partly schematic, of a complete electrical indicating system embodying the present invention; Fig. 2 is a partial cross-sectional view representing a preferred construction of the unitary balanced-inductor system of the Fig. 1 arrangement; and Figs. 3, 4, 5 and 6 represent schematically certain modified forms of the inductor system of the present invention which are suitable for use in the Fig. 1 arrangement.

Referring now more particularly to Fig. 1 of the drawings, there is represented a circuit diagram, partly schematic, of a complete electrical indicating system which includes a unitary balanced-inductor system embodying the present invention in a preferred form. In general, this indicating system includes a transmitter 10 which may comprise any suitable form of oscillation generator and, if desired, one or more stages of amplification for amplifying the generated oscillations. The system also includes a receiver 11, adapted to receive the oscillations generated by the transmitter 10, which may comprise, in the order named, one or more stages of amplification, a detector for deriving a control signal from received oscillations, and one or more stages of amplification for amplifying the control signal. An indicating device 12 is coupled to the output circuit of the receiver 11 and is responsive to the control signal derived by the latter. The output circuit comprising output-circuit terminals 13 of the transmitter 10 is coupled to a unitary balanced-inductor system 14, presently to be described in greater detail. Briefly stated, the inductor system 14 includes a pair of inductors 15, 16 which are serially connected with opposing magnetic fields and are coupled in series to the output-circuit terminals 13 of the transmitter. The inductor system 14 also includes a third inductor 18 which is coupled to the input circuit, comprising input-circuit terminals 19, of the receiver 11.

Considering briefly the operation of the electrical indicating system just described, the inductor 18 of the inductor system 14 is so positioned with relation to the inductors 15 and 16 thereof that, while it is coupled to each of the latter inductors considered alone, it normally is uncoupled to both thereof. Consequently, the oscillations generated by the transmitter 10 and applied to the inductors 15 and 16 normally are not coupled through the inductor 18 to the input circuit of the receiver 11. No control signal is thus developed by the receiver 11 and no indication is, of course, provided under such conditions by the indicating device 12.

Now assume that a metallic object which exhibits electrical conductivity or magnetic permeability is brought into the vicinity of the balanced-inductor system 14. The metallic object unbalances or changes the coupling between the inductors of the latter with the result that the oscillations generated by the transmitter 10 are now applied to the input circuit of the receiver 11 and the control signal derived from the received oscillations is applied to the indicating device 12. The resultant indication provided by the indicating device indicates the presence of the metallic object in the vicinity of the inductor system 14.

Referring now more particularly to the portion of the indicating system embodying the present invention, the unitary balanced-inductor system 14 includes, as previously stated, the pair of inductors 15, 16. These inductors are positioned in fixed relation and have the same shape but substantially different sizes. The terms "shape" and "shape factor," as applied to the inductors of the system 14, are used throughout the present specification and claims in the usual and widely accepted technical sense with which the terms are used in the art. The effect of the "shape" or "shape factor" of an inductor both on its own value of self-inductance and on the value of its mutual inductance with another inductor of similar "shape" and "shape factor" was early analyzed and carefully explained at length in the United States National Bureau of Standards publication "Radio Instruments and Measurements, Circular C74," pages 242–311, inclusive (edition of March 10, 1924—reprinted January 1, 1937). As between two coupled inductors, the two inductors are said to have the same "shape factor" within the meaning of the present specification and claims insofar as the coefficient of mutual coupling between them is concerned if they have the same ratios of all dimensions that have a significant effect on the value of their mutual inductance. For example, if the winding cross section of one inductor has a maximum dimension which is much less than the winding diameter, the shape and size of the cross section of the inductor have no appreciable effect on its mutual inductance with another inductor and, hence, only its turns shape (i. e. the shape of its average or mean turn) is important in comparing its shape with that of another inductor. Again, by way of example, if the maximum dimension of the winding cross section of one inductor is not small with relation to the inductor diameter, then the shape and size of the cross section have a substantial effect on its mutual inductance with another inductor so its ratio of maximum cross-sectional dimension to inductor diameter is important in comparing its shape with that of another inductor. Two single-layer cylindrical inductors are thus said to have the same shape when they have the same ratio of length to diameter.

Specifically, the inductors 15, 16 have the same turns shape or ring shape of small cross section and as shown are planar circular inductors of different diameters and are positioned in fixed coaxial coplanar relation. As previously mentioned, the inductors 15 and 16 are connected in series-opposing relation; that is, are connected in series with opposing magnetic fields. In accordance with the invention, the inductors 15 and 16 have numbers of turns proportioned in the inverse ratio of the square root of their diameters so that alternating currents of predetermined relative magnitudes and phases produce a magnetic field which has zero normal component of intensity over a predetermined surface in space. In the particular arrangement of balanced-inductor system shown, the inductors 15 and 16 are serially included in the same electrical circuit so that the same alternating current flows through both of the inductors to produce a magnetic field which has zero normal component of intensity over a spherical surface in space, which surface has a diameter equal to the square root of the product of the diameters of inductors 15 and 16.

The third inductor 18 has the same shape as the pair of inductors 15, 16, for example a planar circular shape, and has a size intermediate that of the pair of inductors 15, 16. The third inductor 18 is shown as fixedly positioned in coplanar coaxial relation with respect to the pair of inductors 15, 16. It will, however, later be apparent that this coplanar arrangement of inductor 18 is a preferred, rather than an essential, form by virtue of several advantages which relate to the physical construction of the inductor system. Consequently, the inductor 18 is inductively coupled to each of the inductors 15, 16 but lies substantially in the aforementioned predetermined surface of zero normal component of magnetic-field intensity of the latter inductors and, hence, has substantially zero inductive coupling to both thereof. It may be noted at this point that this is likewise true for any inductor of any shape which lies substantially entirely on the surface of zero normal component of magnetic-field intensity. Thus, the indicator system 14 may include any desired number of inductors similar to the inductor 18 and all such inductors, if positioned in the manner described, have substantially zero inductive coupling to both of the inductors 15 and 16. When the third inductor 18 is coplanar and coaxial with relation to the inductors 15 and 16 as described, the diameter of the third inductor is equal to the geometric mean of the diameters of the inductors 15 and 16; that is, to the square root of the product of the diameters thereof. With the inductors 15, 16 and 18 positioned as described, all have a common center; that is, are in concentric relation.

The concentric coplanar arrangement of the inductors 15, 16 and 18 of the inductor system 14 is one which does not require critical centering of the inductors. This is a great advantage in that it facilitates the construction of the inductor system, particularly insofar as it concerns establishing and maintaining cancellation of the mutual inductance existing between the inductors 15 and 18 on the one hand and the inductors 16 and 18 on the other so that the inductor 18 has substantially zero inductive coupling to both of the inductors 15 and 16. The circular shape of the inductors 15, 16 and 18 has the additional advantage that the inductors are not very critical as to shape, whereby temperature variations have little effect on the desired cancellation of mutual inductance if all of the inductors are constructed of the same material and are maintained at substantially the same temperature.

This insensitiveness of the inductor system 14 to exact centering of the inductors and to slight variations of the relative shapes thereof permits the improved construction of Fig. 2, which represents a cross-sectional view of one-half of an inductor system embodying the Fig. 1 arrangement of the present invention. Elements of Fig. 2 corresponding to similar elements of Fig. 1 are designated by the same reference numerals. Each of the inductors 15, 16 and 18 is wound of a number of turns of very thin insulated copper or aluminum ribbon, aluminum being preferable from the standpoint of light weight. The ribbon winding is cemented together to provide a self-supporting inductor structure. Each inductor is mounted by flexible supports 21, preferably of soft resilient rubber in the form of spaced rubber beads, in concentric circular grooves 22, 23 which are cut in two flat plates of balsa wood or the like. These plates are cemented together with crossed grain to enclose the inductors. As thus arranged, the inductors are fixedly supported in coplanar relationship and are coaxial with relation to their common axis O—O, yet are permitted to move slightly to change their shape or centering with changes of temperature.

It has heretofore been stated that when the alternating currents flowing through the inductors 15, 16 of the inductor system 14 have predetermined relative magnitudes and phases, the inductors 15, 16 produce a magnetic field of which the locus of zero normal component of magnetic-field intensity is a predetermined surface in space, and that the third inductor 18 lies substantially in this surface, whereby the third inductor has substantially zero inductive coupling to both of the inductors 15, 16 when the latter carry such alternating currents. It can be shown that this condition holds when the parameters of the inductor system 14 are proportioned in accordance with the relations:

$$\frac{M_{12}}{M_{23}}=\frac{n_1}{n_3}\sqrt{\frac{d_1}{d_3}} \quad (1)$$

$$\frac{M_{12}}{M_{23}}=\frac{n_1 d_1}{n_3 d_2} \quad (2)$$

$$\frac{M_{12}}{M_{23}}=\frac{n_1 d_2}{n_3 d_3} \quad (3)$$

where

M_{12}=mutual inductance between inductors 16 and 18,
M_{23}=mutual inductance between inductors 18 and 15,
n_1=number of turns in inductor 16,
n_3=number of turns in inductor 15,
d_1=diameter of inductor 16,
d_2=diameter of inductor 18, and
d_3=diameter of inductor 15.

The mutual inductance between the inductors 16 and 18 is made equal to that between the inductors 15 and 18 by proportioning, in accordance with the invention, the numbers of turns and the diameters of these inductors. Under this condition, Equations 1, 2 and 3 simplify to the following equation, useful in computing the parameters of the inductors 15, 16 and 18 to provide the balanced-inductor system of the present invention:

$$\frac{n_1}{n_3}=\sqrt{\frac{d_3}{d_1}}=\frac{d_2}{d_1}=\frac{d_3}{d_2} \quad (4)$$

When the inductors 15, 16 and 18 of the balanced-inductor system 14 have numbers of turns and diameters proportioned in accordance with the relations given in Equation 4, the inductor 18 has substantially zero inductive coupling to both of the inductors 15 and 16 when the currents flowing therein have equal magnitude and have relative phases such that the magnetic fields produced by these currents are opposing. This latter condition is fulfilled in the arrangement of Fig. 1 by serially connecting the inductors 15 and 16 in the same electrical circuit, so that the same current flows through both but in opposite senses.

In general, two circular planar coaxial inductors which carry the same alternating current and are connected with opposing magnetic fields produce a magnetic field of which the locus of zero normal component of magnetic-field intensity is a spherical surface in space. Thus, as shown in Fig. 3, when the inductors 15 and 16 are coplanar concentric inductors with their numbers of turns and diameters proportioned in accordance with the relations expressed in Equation 4, the locus of zero normal component of magnetic-field intensity of their resultant magnetic field is a sphere 24, indicated in broken lines, with its center concentric with that of the inductors 15 and 16. The magnetic field of the inductor 15 predominates outside of this sphere 24 while that of the inductor 16 predominates within the sphere, the two fields neutralizing each other on the surface of the sphere insofar as the normal component of intensity is concerned. For convenience, therefore, it may be considered that no magnetic flux of either of the inductors 15 or 16 penetrates this spherical surface. For this reason, the spherical surface 24 is hereinafter referred to as a "neutral sphere." The neutral sphere has a diameter d_2 expressed by the relation:

$$d_2=\sqrt{d_1 d_3} \quad (5)$$

This is also the diameter of the inductor 18 of a coplanar inductor system since the latter inductor is located on the surface of the neutral sphere. In fact, any inductor which is located in any position lying wholly in this spherical surface, such as the inductor 18′ of Fig. 3, has substantially zero inductive coupling to both of the inductors 15 or 16. It will thus be apparent that the diameter of the inductor 18 as given in Equation 5 need apply only to the case where the inductor 18 is positioned in coaxial coplanar relation with the inductors 15 and 16. If the inductor 18 has a diameter smaller than that given by Equation 5, it can, nevertheless, be positioned to lie on the spherical surface 24, thus having zero inductive coupling to both of the inductors 15 and 16, but in this case cannot be positioned in coplanar relation with these inductors.

In general then, and in accordance with the invention, the two circular coaxial inductors 15 and 16 are connected in one electrical circuit with opposing magnetic fields and have numbers of turns inversely proportional to the square root of their diameters. The locus of zero normal component of magnetic-field intensity of the resultant magnetic field produced by the inductors is a spherical surface or neutral sphere in space in which either inductor is the image of the other. Any inductor located wholly on the surface of this sphere has no inductive coupling with the electrical circuit which includes the inductors 15 and 16.

The invention contemplates that the inductors 15 and 16 need not be coplanar. Thus as in Fig. 4, in which elements corresponding to similar elements of Fig. 1 are designated by similar reference numerals primed, the inductors 15′ and 16′ are coaxial but are fixedly positioned in parallel planes separated a distance b. Since the inductors have different diameters, they lie on the surface of a cone 25 and alternating currents flowing through the inductors may be adjusted in relative magnitudes and phases, as when the inductors are serially included in the same electrical circuit but are connected with opposing magnetic fields, to produce a magnetic field of which the locus of zero normal component of magnetic-field intensity is a spherical surface or neutral sphere 24′ with its center at the apex of the cone 25. The third inductor 18′ is fixedly positioned with relation to the inductors 15′ and 16′ and lies substantially entirely on the surface of the sphere 24′, whereby it has substantially zero inductive coupling to both of the inductors 15′ and 16′.

In the particular inductor system of Fig. 4, the inductor 18′ has the same diameter as the inductor 15′ and is included in a plane parallel therewith. In accordance with the invention, however, the inductor 18′ may have a diameter either smaller or larger than that of the inductor 15′ and the plane of the inductor 18′ may form any desired angle with the plane of the latter. Further, as in the arrangement of Figs. 1 and 3, any number of inductors similar to the inductor 18′ may be used and if located substantially entirely on the surface of the sphere 24′ have substantially zero inductive coupling to both of the inductors 15′ and 16′.

The particular arrangement of inductors shown in Fig. 4 has the advantage that it facilitates the construction of the balanced-inductor system, particularly in that the inductors 15′ and 18′, being of the same diameter, may be supported on the same cylindrical support and the inductor 16′, being coplanar with the inductor 18′, may be easily mounted at one end of the supporting structure. This arrangement has the additional advantage that a geometrical construction may be used to determine the diameter of the inductor 16′ if the diameters and spacing of the inductors 15′ and 18′ are known. This geometrical construction is accomplished in the following manner. Two coaxial circles are first drawn to scale with diameters d_2 and d_3 corresponding to the diameters of the respective inductors 18′ and 15′, these circles being spaced a scaled distance b. A sphere 26, Fig. 4, is then described through these two circles. Next, a cone is described through the circle corresponding to the inductor 15′ with the apex of the cone at the intersection of the sphere 26 and the axis O—O of the inductors. A circle corresponding to the inductor 16′ is then drawn to lie on the surface of the cone 25 and in a plane which includes the circle corresponding to the inductor 18′. The neutral sphere 24′ is then described through the circle corresponding to the inductor 18′ with the center of the sphere at the apex of the cone 25. This construction thus readily determines the scaled diameter of the inductor 16′ and establishes the position in space, relative to the several inductors, of the neutral sphere 24′. The numbers of turns of the inductors 15′ and 16′ are given by Equation 4 as in the arrangements previously described.

Each of the arrangements heretofore described possesses the important characteristic that a relatively concentrated body exhibiting magnetic permeability or electrical conductivity and located with its center on the neutral sphere 24, Figs. 1 and 3, or 24′ in Fig. 4, produces no coupling between the inductors 15, 16 and the inductor 18 of the Fig. 1 arrangement, or between the inductors 15′, 16′ and the inductor 18′ of Fig. 4, whereas any other position of the body in the vicinity of the inductor system does produce such coupling. Thus, when the arrangement of Fig. 1 is used to locate a buried body of this nature, the general position of the object is determined by the condition of maximum coupling between the pair of inductors 15, 16 and the inductor 18. When this has been accomplished, the depth of the buried object is determined by moving the inductor system 14 vertically relative to the ground surface until the center of the object lies on the surface of the neutral sphere at which time it produces no coupling between the inductors 15, 16 and the inductor 18 as previously explained. The diameter of the neutral sphere being known for any given inductor system, the depth of the buried object is then readily ascertained. An important application of this nature is in surgery where the system is used to detect the depth of a metallic object embedded in the body.

If only the position of a metallic body is to be determined, it is preferable so to proportion the parameters of the inductor system 14 or 14′ that the diameter of the neutral sphere is fairly small. On the other hand, where the inductor system 14 is to be used to locate the position and depth of a buried object, the arrangement of Fig. 4 is particularly suitable in that the neutral sphere 24′ of this arrangement is larger than the individual inductors of the inductor system 14′. In using this arrangement, the inductor system 14′ is held with the inductor 15′ nearest the buried object in order to determine the general position of the object. Then the inductor system 14′ is reversed and held with the inductors 16′ and 18′ nearest the object and in such manner that the center of the object is approximately on the axis of the inductor system. The inductor system is then moved axially relative to the body until a sharp indication of zero coupling between the inductors 15′, 16′ and the inductor 18′ is discovered. When this occurs, the buried object is then at a distance from the inductor system 14′ corresponding to the point x on the neutral sphere 24′. It has been found in practice that this indication of the distance of the object from the inductor system 14 or 14′ is quite critical and, hence, the indicated depth of the buried object is highly accurate.

Due to the geometric relationship between the inductors of the inductor system 14′ in Fig. 4, there are only certain diameters and spacings of the inductors which have commensurate dimensions. Further, there are certain preferred parameters for the structure of this inductor system by which the numbers of turns of the inductors 15′ and 16′ have a commensurate ratio which can be satisfied exactly by integral numbers of turns. The following tabulation gives a series of proportions for the preferred parameters in which the inductors 15′ and 18′ have a diameter greater than their separation:

Relative Diameters		Separation b	Turns n_1/n_3
$d_2=d_3$	d_1		
4	1	3	2/1
12	16/3	5	3/2
24	27/2	7	4/3
40	128/5	9	5/4

The following tabulation gives another series of preferred parameters of the inductor system 14′ in which the inductors 15′ and 18′ have a diameter less than their separation:

Relative Diameters		Separation b	Turns n_1/n_3
$d_2=d_3$	d_1		
3	1/3	4	3
5	1/5	12	5
7	1/7	24	7
9	1/9	40	9

Fig. 5 represents a modified form of the invention which is essentially similar to the balanced-inductor system 14 of Fig. 1, elements in Fig. 5 corresponding to similar elements in Fig. 1 being designated by similar reference numerals double primed, except that the inductors 15″, 16″ and 18″ have a square shape. The inductors of the present arrangement are fixedly positioned in coplanar coaxial relationship and have numbers of turns and diameters proportioned according to the relationships given by Equation 4. The "diameter" in this instance is measured along a side of an inductor as indicated in Fig. 5. The locus of zero normal component of intensity of the magnetic field produced by the inductors 15'' and 16'' is a geometric surface in space. The inductor 18'' need not be of square shape as shown, but may have other shapes so long as it lies approximately in the surface of zero normal component of magnetic-field intensity. Moreover, the inductors 15'' and 16'' need not be coplanar but, as in the arrangement of Fig. 4, may lie in parallel spaced planes, the plane of the inductor 18'' forming any desired angle with the planes of the inductors 15'' and 16''.

Fig. 6 represents a modified form of the invention essentially similar to the arrangements of Figs. 1 and 3, similar circuit elements being designated by similar reference numerals, except that the inductors of the inductor system 14''' have certain specific angular relationships relative to each other which render the inductor system particularly suited for use in proximity to a mass of material having a substantially flat surface and exhibiting an electrical characteristic, for example magnetic permeability or electrical conductivity.

Specifically and by way of example, such a system may be used to locate a metallic object A exhibiting electrical conductivity which is buried in the ground G, the latter exhibiting magnetic permeability and having a relatively flat ground surface S. A flat ground surface of uniform permeability produces an effect on the inductors of the inductor system 14''' just as if mirror images 15_m, 16_m and $18'_m$ of the inductors were formed below the ground surface. The strength of these images depends on the permeability of the ground G, but their position below the ground surface S depends only on the surface and homogeneity of the ground. In order that the mirror images 15_m, 16_m of the inductors 15 and 16, respectively, shall not be coupled to the inductor 18' or, conversely, in order that the mirror image $18'_m$ of the inductor 18' shall not be coupled to the inductors 15 and 16, the inductors 15 and 16 are fixedly positioned at a predetermined angle relative to the inductor 18'. The particular angular relationships required are disclosed and taught in United States Letters Patent No. 1,577,421, granted to Louis A. Hazeltine on March 16, 1926.

Specifically, inductor system 14''' of the Fig. 6 modification includes the pair of coplanar coaxial inductors 15, 16 positioned in fixed relation and having the same shape, for example a circular shape, but substantially different sizes and adapted to be operated with their axis *b—b* orientated at a first predetermined angle ϕ_1 relative to a line *a—a* passing through the center of the inductors normal to the plane S of the ground. The axis *b—b* of the inductors 15, 16 and the line *a—a* are included in or define a reference plane. As in the previous modification of the invention, the alternating currents flowing through the inductors 15 and 16 are adjusted in relative magnitudes and phases to produce a magnetic field of which the locus of zero normal component of magnetic intensity is a spherical surface 24 in space. The inductor system 14''' includes the third inductor 18' which is positioned in fixed relation to the inductors 15 and 16 and lies substantially in the surface 24 with the center of the inductor 18' on the line *a—a*. The latter inductor is so oriented that the projection of its axis *c—c* on the aforementioned reference plane forms a predetermined angle ϕ_2 with the line *a—a*. The angles ϕ_1 and ϕ_2 are so proportioned that the product of the tangents thereof equals 2. For example these angles may each be 54.8 degrees in a preferred embodiment. With this arrangement of inductors, the inductor 18' has substantially zero inductive coupling not only to both of the inductors 15 and 16 but also to their respective mirror images 15_m, 16_m in the ground G. Similarly, both the inductors 15 and 16 not only have zero inductive coupling to the inductor 18 but also to its mirror image $18'_m$. It may be noted that this nullification of ground coupling between the inductors of the inductor system 14''' is independent of the height of the inductor system above the ground surface S. As previously explained, when a metallic object A of concentrated dimensions and exhibiting electrical conductivity or magnetic permeability is brought into the vicinity of the inductor system 14''', it disturbs the magnetic field existing around the latter and produces coupling between the inductors 15, 16 and the inductor 18'. The particular symmetrical angular relationship of the inductors with respect to the line *a—a*, as shown in Fig. 6, has the advantage that it provides by symmetry maximum response to the object A when the latter is directly below the inductor system 14'''. Additionally, there is the advantage that the orientation of the inductors 15, 16 and 18' with relation to the ground surface S is not unduly critical because the residual ground coupling is proportional to the square of the angular displacement of the inductors, considered as a unit, from their normal position. In contrast to this, the prior art arrangement of crossed inductors has a ground coupling proportional to the first power of the angular displacement of its inductors relative to the surface of the ground.

From the foregoing description of the Fig. 6 inductor system, it will be apparent that the oblique angle between the axis *b—b* of the inductors 15 and 16 on the one hand and the axis *c—c* of the inductor 18' on the other, this angle being the sum of the angles ϕ_1 and ϕ_2, has a value proportioned to render the mutual inductance between the inductors 15, 16 and the inductor 18' substantially independent of the mass of material G as long as the inductors have a given predetermined orientation relative to the flat surface S of the mass of material.

This angular relationship between the several inductors of the inductor system 14''' may conveniently be considered from another aspect. In the particular arrangement shown, the windings of all of the inductors may be considered to be normal to a common plane which passes through the center of the inductor system. It will be apparent that the angle between the projections of the windings of the inductors on this plane has a value ϕ_3 equal to the difference between 180 degrees and the sum of ϕ_1 and ϕ_2. In accordance with the invention, the angle ϕ_3 lies within a range of substantially less than 90 degrees and slightly greater than 70 degrees, a preferred value being approximately 70 degrees.

The inductor system 14''' of Fig. 6 includes means for carrying the several inductors 15, 16 and 18', as a unitary structure, with relation to the mass of material G while maintaining them in a predetermined orientation relative to the surface S thereof. This means comprises a member 27 having one end secured to the several inductors 15, 16 and 18' and having its other end secured to a counterweight 28. By this arrangement a portable unitary structure is provided and the inductors may be carried with relation to a mass of material, such as ground, and maintained in a predetermined orientation with the surface of such mass of material. A carrying handle 29 is secured to the member 27 at an intermediate point. The counterweight 28 serves to maintain the inductor system 14''' suitably oriented with relation to the surface S of the mass of material G when the inductor system is carried by the handle 29.

The following table gives several values of the angles ϕ_1, ϕ_2 and ϕ_3 which are effective to avoid ground coupling between the inductors of the inductor system 14''':

ϕ_1	ϕ_2	ϕ_3
Degrees	*Degrees*	*Degrees*
15	82.4	82.6
30	74.5	75.5
54.8	54.8	70.4
40	67.2	72.8

It will be noted that the angular arrangement of the inductors shown in Fig. 6, in which ϕ_1 and ϕ_2 both are 54.8 degrees and ϕ_3 is 70.4 degrees, corresponds substantially to that specified in the above-mentioned Hazeltine patent.

As illustrative of specific embodiments of the invention, the following parameters are given for the embodiments of the invention of the types shown in Figs. 1 and 5:

Inductor 15:	
Diameter ----------foot--	1
Number of turns----------	50
Inductor 18:	
Diameter ----------foot--	5/8
Number of turns----------	80
Inductor 16:	
Diameter ----------foot--	25/64
Number of turns----------	80
Inductor 15'':	
Diameter ----------feet--	2
Number of turns ----------	1
Inductor 18'':	
Diameter ----------foot--	1
Number of turns ----------	1
Inductor 16'':	
Diameter ----------foot--	1/2
Number of turns----------	2

While there have been described what are at present considered to be the preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A unitary balanced-inductor system comprising, a first inductor having a predetermined shape and diameter d_1 and number of turns n_1, a second inductor having said predetermined shape but having a larger diameter d_3 and a number of turns n_3, said second inductor being positioned in fixed coaxial relation to said first inductor and said diameters and said numbers of turns of said first and second inductors being proportioned in accordance with the relation $n_1/n_3=\sqrt{d_3/d_1}$ so that alternating currents of equal magnitudes and opposite phases in said inductors produce a magnetic field which has zero normal component of intensity over a predetermined unbroken three-dimensional surface in space completely enclosing on all sides the smaller of said inductors but completely excluding the larger thereof, and a third inductor having any number of turns and being positioned in fixed relation to said first and second inductors and lying substantially in said surface, whereby said third inductor has substantially zero inductive coupling to said first and second inductors when carrying said alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to said first and second inductors in the presence of such bodies.

2. A unitary balanced-inductor system comprising, a first circular inductor having a predetermined shape and diameter d_1 and number of turns n_1, a second circular inductor having said predetermined shape but having a larger diameter d_3 and a number of turns n_3, said second inductor being positioned in fixed parallel concentric relation to said first inductor and said diameters and said numbers of turns of said first and second inductors being proportioned in accordance with the relation $n_1/n_3=\sqrt{d_3/d_1}$ so that alternating currents of equal magnitudes and opposite phases in said inductors produce a magnetic field which has zero normal component of intensity over a spherical surface in space completely enclosing on all sides the smaller of said inductors but completely excluding the larger thereof, and a third inductor having any number of turns and being positioned in fixed relation to said first and second inductors and lying substantially in said surface, whereby said third inductor has substantially zero inductive coupling to said first and second inductors when carrying said alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to said first and second inductors in the presence of such bodies.

3. A unitary balanced-inductor system comprising, a pair of relatively fixed inductors of the same shape but of substantially different diameters, said inductors being connected in series-opposing relation and having numbers of turns so proportioned in the inverse ratio of the square roots of their diameters that alternating currents of predetermined relative magnitudes and phases therein produce a magnetic field which has zero normal component of intensity over a predetermined surface in space, and a third inductor having the same shape as said pair of inductors and a diameter equal to the geometric mean diameter thereof, said third inductor being positioned in fixed relation to said pair of inductors and lying substantially in said surface, whereby said third inductor has substantially zero inductive coupling to said pair of inductors when carrying said alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to said pair in the presence of such bodies.

4. A unitary balanced-inductor system comprising, a first circular inductor having a diameter d_1 and number of turns n_1, a second circular inductor having a larger diameter d_3 and a number of turns n_3, said inductors being positioned in spaced coaxial relation to lie on the surface of a cone and said diameters and numbers of turns thereof being proportioned in accordance with the relation $n_1/n_3=\sqrt{d_3/d_1}$ so that alternating currents of equal magnitudes and opposite phases in said inductors produce a magnetic field which has zero normal component of intensity over a predetermined unbroken spherical surface in space

having its center at the apex of said cone, and a third inductor positioned in fixed relation to said first and second inductors and lying substantially in said surface, whereby said third inductor has substantially zero inductive coupling to said first and second inductors when carrying said alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to said first and second inductors in the presence of said bodies.

5. A unitary balanced-inductor system comprising, a first inductor having a predetermined shape and diameter d_1 and number of turns n_1, a second inductor having said predetermined shape but having a larger diameter d_3 and a number of turns n_3, said second inductor being so positioned in fixed parallel relation to said first inductor that alternating currents of equal magnitudes and opposite phases in said inductors produce a magnetic field which has zero normal component of intensity over a predetermined surface in space, and a third inductor having a diameter d_2 and any number of turns and being positioned in fixed relation to said first and second inductors and lying substantially in said surface, said diameters being proportioned in accordance with the relation

$$\frac{d_1}{d_2}=\frac{d_2}{d_3}$$

and said numbers of turns being proportioned in accordance with the relation

$$n_1=n_3\frac{d_2}{d_1}=n_3\frac{d_3}{d_2}=n_3\sqrt{\frac{d_3}{d_1}}$$

whereby said third inductor has substantially zero inductive coupling to said first and second inductors when carrying said alternating currents and in the absence of external concentrated bodies of magnetic or conductive materials but has substantial inductive coupling to said first and second inductors in the presence of such bodies.

6. A unitary balanced-inductor system adapted to be carried in a predetermined medium and in proximity to a mass of material, having a substantially flat surface and exhibiting an electrical characteristic different than said predetermined medium, comprising: a pair of relatively fixed coplanar coaxial inductors, included in a common electrical circuit, having substantially the same shape factor but substantially different size and having relative positions and numbers of turns effective when said inductors carry alternating currents of predetermined relative magnitude and opposite phase to produce a magnetic field which has zero normal component of intensity over a predetermined unbroken three-dimensional surface in space completely enclosing on all sides the smaller of said inductors but completely excluding the larger thereof; a third inductor fixedly positioned with relation to said pair of inductors and lying substantially in said surface, whereby said third inductor has substantially zero inductive coupling to said pair of inductors carrying said alternating currents; and means secured to said inductors by which said inductors may be carried as a unitary structure with relation to said mass of material and maintained in a predetermined orientation relative to the surface thereof, the angle between the axes of said pair of inductors and the axis of said third inductor having a value proportioned to render the mutual inductance between said pair of inductors and said third inductor substantially independent of said mass of material in the said predetermined orientation of said inductors.

HAROLD A. WHEELER.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
1,577,421	Hazeltine	Mar. 16, 1926
1,616,645	Wegner	Feb. 8, 1927
1,807,956	Apple	June 2, 1931
1,812,392	Zuschlag	June 30, 1931
1,865,840	Croft et al.	July 5, 1932
1,905,216	Capps	Apr. 25, 1933
1,992,100	Stein	Feb. 19, 1934
2,048,591	Berry	July 21, 1936
2,111,210	Ebel	Mar. 15, 1938
2,160,356	Fore et al.	May 30, 1939
2,167,490	Ryan	July 25, 1939
2,215,605	De Lanty	Sept. 24, 1940
2,220,070	Aiken	Nov. 5, 1940
2,220,788	Lohman	Nov. 5, 1940
2,376,659	Chireiz	May 22, 1945

FOREIGN PATENTS

Number	Country	Date
20,656	Australia	June 14, 1929

OTHER REFERENCES

"Geophysical Exploration," Heiland, pp. 819–823, published 1940 by Prentice Hall Inc., N. Y.