Oct. 29, 1957 C. L. HOGAN 2,811,697

MAGNETOELECTRIC INDUCTION DEVICES

Filed Sept. 16, 1953

FIG. 1

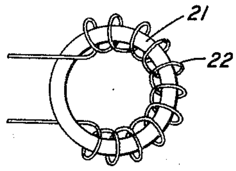


FIG. 2

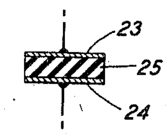


FIG. 3

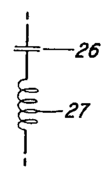


FIG. 4

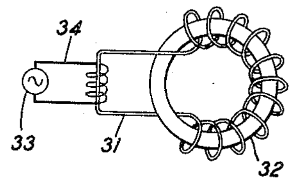


FIG. 5

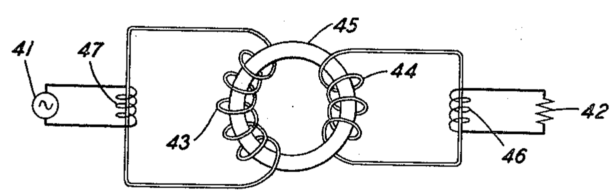


FIG. 6

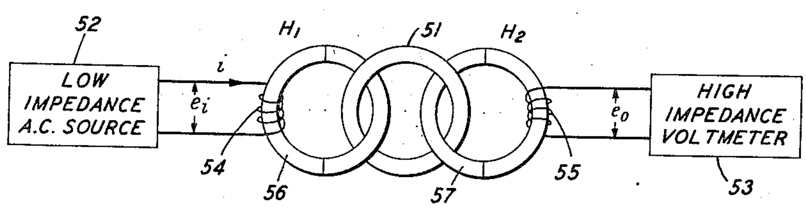


FIG. 7

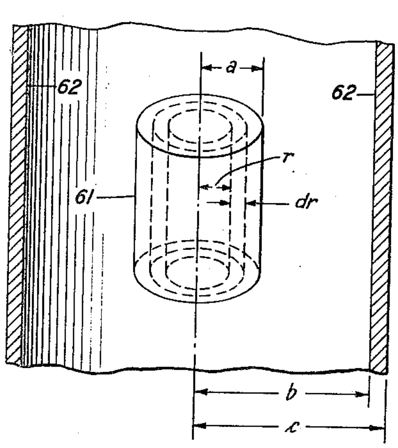
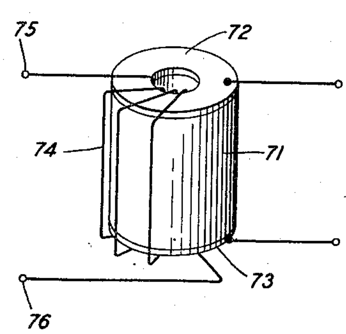


FIG. 8



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MAGNETOELECTRIC INDUCTION DEVICES

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2 Claims. (Cl. 333—32)

This invention relates to electrical reactive devices and to coupling structures utilizing the principles of magnetoelectric induction.

It is well known that an electric field is generated by a magnetic displacement current. This phenomenon has been designated electromagnetic induction and is employed in many practical devices such as transformers and generators. The analogous generation of a magnetic field by an electrical displacement field, which may be termed magnetoelectric induction, is not widely recognized and has only recently been verified experimentally. In this prior art experimental work in which conducting magnetic cores were used, the observed effects were exceedingly weak and very little coupling was obtained.

Accordingly, one object of the present invention is to make an improved electrical coupling structure utilizing the principles of magnetoelectric induction.

A more specific object is to increase the electrical coupling of magnetoelectric impedance transforming structures.

In accordance with the invention, it has been discovered that the use of magnetic cores having low conductivity greatly increases the effective coupling between the magnetic and the electrical displacement circuits in magnetoelectric devices. More specifically, and in accordance with one embodiment of the invention illustrated in the drawings, a polycrystalline ferrite cylinder having a coaxial hole therethrough is employed to obtain impedance transformation between a pair of electrodes secured to its ends and a coil threaded through the hole. Other specific embodiments of the invention involve the coupling of electric displacement currents in a circuit of high dielectric material, with a magnetic circuit having high permeability and low conductivity.

In the measurement of the dielectric constant of various samples by the conventional method in which electrodes are secured to the sample, considerable difficulty has been encountered at high frequencies with materials having high dielectric constants. Specifically, if the electrodes do not make intimate contact with the sample throughout the common surface areas, errors of large magnitude may appear, particularly when the dielectric constants involved are of the order of magnitude of 50,000 or 100,000 or higher.

An additional object of the present invention is, therefore, to improve and simplify the apparatus for measuring dielectric constants of materials having relatively high dielectric constants.

Other objects and certain features and advantages will be developed in the course of the detailed description of the drawings.

In the drawings:

Fig. 1 shows a core of high permeability material encircled by a "wire" of high dielectric constant material in accordance with the invention;

Fig. 2 illustrates a condenser having dielectric material between its plates;

Fig. 3 is an equivalent circuit diagram for the structure of Fig. 2 at high frequencies;

Fig. 4 depicts an inductance made up of an annular core of high dielectric material encircled by a wire of high permeability material;

Fig. 5 illustrates a transformer patterned after the inductance of Fig. 4;

Fig. 6 represents an arrangement for testing the dielectric constant of high dielectric constant materials at high frequencies;

Fig. 7 is a diagram employed in an analysis which is presented in the specification; and

Fig. 8 is an electromagnetic transducer constructed of a material having a high dielectric constant and a high permeability.

Referring more specifically to the drawings, Fig. 1 shows by way of example and for purposes of illustration, a closed loop of high permeability material 21 having a toroidal coil 22 of high dielectric constant "wire" wound thereon. Because of the historical emphasis on iron and copper inductances, it is contrary to expectations to find that the structure of Fig. 1, which is made up entirely of low conductivity material, exhibits substantial impedance. However, the symmetry of Maxwell's equations indicates that it makes no difference whether the current density in the coil 22 arises from conduction or displacement current. Therefore, assuming that the electric flux is entirely confined to the dielectric wire and does not leak between turns, the self-inductance of the coil can be defined as:

$$L=\frac{\mu N^2 A_c}{l_c} \tag{1}$$

where:

μ is the permeability of the toroid 21,
N is the number of turns of the coil 22,
A_c is the cross-sectional area of the toroidal core 21, and
l_c is the mean circumference of the core 21.

In addition, the apparent dielectric constant of the dielectric wire 22 of Fig. 1 is given by the expression:

$$\epsilon_{ap}=-\frac{l_c l_W}{\mu N^2 A_c A_W \omega^2} \tag{2}$$

where:

l_W is the length of the dielectric wire,
A_W is the cross-sectional area of the dielectric wire, and
ω is the angular frequency of the source of electromagnetic waves.

This is of course not the proper expression for the dielectric constant as the term is normally used, the fallacy being that the inductance of the structure is ignored. In other words the apparent dielectric constant as determined by the foregoing Expression (2) is not the true dielectric constant because it is measured in terms of the applied rather than the total field.

Having now established that dielectric samples can exhibit inductance in the same way that metallic samples can, it is important to investigate how important this might be in experiments designed to measure dielectric constant. In order to do this it is advantageous to treat the dielectric medium as an equivalent circuit. For the present purpose only lossless circuits will be considered. This implies that the dielectric constant is real and hence the equivalent circuit will contain no resistance. The loss in the dielectric material can easily be included by adding a resistance to the equivalent circuit, if desired.

Fig. 2 illustrates the apparatus which has usually been employed to measure the dielectric constant of a sample at frequencies below 100 megacycles. In this arrangement the electrodes 23 and 24 are connected across the cylindrical sample **25**. Since this dielectric sample has both inductance and capacitance, it can be represented by the equivalent circuit of Fig. 3, in which the capacitance **26** is equal to

$$\frac{\epsilon A}{l}$$

The inductance **27** of the sample can for the present be considered as the inductance of a single straight conductor, and is thus equal to

$$\frac{\mu l}{4\pi}$$

However, for reasons which will become apparent later it is assumed that the magnetic flux which is created by the displacement current is confined entirely within the dielectric material. This is a valid approximation if the dielectric is ferromagnetic. With these assumptions, the expression for the apparent dielectric constant is

$$\epsilon_{ap}=\frac{4\pi\epsilon}{4\pi-A\omega^2\mu\epsilon} \qquad (3)$$

where:

ϵ is the true dielectric constant of the material, and A is the cross-sectional area of the sample **25** taken perpendicular to the direction of the electric field. At low frequencies, the effective dielectric constant is the same as the true dielectric constant. However, at higher frequencies, approaching the resonance frequency at which the denominator terms are equal, the apparent dielectric constant is much different from the true dielectric constant. This indicates the danger of ignoring the inductance of a ferromagnetic dielectric in the megacycle range.

Proceeding now to a consideration of magnetic displacement currents rather than electric displacement currents, Fig. 4 shows a ferromagnetic wire **31** wound around a toroid **32** having a high dielectric constant. The source **33** and coil of conducting wire **34** establish the magnetic displacement current in the magnetic wire **31**. It will be assumed for simplicity that there is no magnetic flux leakage between turns of the coil of magnetic wire **31** but instead the magnetic flux is confined entirely to the wire. Due to the symmetry in Maxwell's equations it may be inferred that magnetic displacement currents encounter "inductance" and "capacity" in the same way that electric displacement currents do. Hence it should be expected that at the center of the magnetic coil in Fig. 4 an electric field will exist if a magnetic flux is changing in the ferromagnetic wire. In fact, treating the changing magnetic flux (magnetic displacement current) as a magnetic current an "inductance" for this coil may be readily derived. The expression for this inductance is

$$L_m=\frac{N^2A_T\epsilon}{l_T} \qquad (4)$$

where:

N is the number of turns of the wire **31**,
A_T and l_T are the area and length of the dielectric toroid **32**, and
ϵ is the dielectric constant of the toroid.

If the apparent permeability of the wire wound around a dielectric toroid is defined as the ratio between the flux density B and the magnetic field applied to the wire H_{ap}, the following expression may be derived:

$$\mu_{ap}=\frac{l_W}{A_W\omega\left[\frac{1}{\omega C_m}-\omega L_m\right]} \qquad (5)$$

where:

l_W is the length of the wire **31**,
A_W is the cross-sectional area of the wire, and
C_m and L_m are the effective capacitance and inductance of the structure.

At low frequencies the inductive reactance can be neglected and, under these conditions the ratio between the flux density B and the magnetic field H will give the true permeability of the ferromagnetic wire even though it is wound over a barium titanate toroid. The apparent permeability, however, shows a resonance phenomenon which will create large disparities between the apparent and the true permeabilities at higher frequencies.

In Fig. 5, a transformer structure is shown which is similar in construction to the inductance of Fig. 4. The impedance transformation between the source **41** and the load **42** is determined by the turns ratio of the magnet coils **43** and **44** on the dielectric core **45**, with the conducting coils **46** and **47** being identical.

Fig. 6 is a schematic showing of an arrangement for determining the dielectric constant of a sample **51** of a material having a high dielectric constant without the use of electrodes secured to the material. In this test circuit, the annular dielectric sample **51** is coupled to the low impedance high frequency source **52** and to the high impedance voltmeter **53** by means of the coils **54** and **55** and the annular cores **56** and **57** of high permeability material. The annular cores **56** and **57** must also be of relatively high resistivity or low conductivity materials so that eddy currents will not neutralize the magnetic field set up in these cores. By way of example, the new polycrystalline ferrites such as $Ni_{.3}Zn_{.7}Fe_2O_3$ are suitable materials for the cores **56** and **57**. These cores **56** and **57** are each made up of two separable portions for ease of insertion of the dielectric test samples such as **51**.

Now, assuming that the source **52** is a constant current source and thus that it has zero impedance, and that the voltmeter **53** has infinite impedance, the relationship between input and output voltages will be as follows:

$$\frac{e_o}{e_i}=\frac{1}{\frac{l_\mu l_\epsilon}{\omega^2\mu\epsilon A_\epsilon A_\mu}-1} \qquad (6)$$

where:

l_μ is the mean circumference of toroids **56** and **57**;
ω is the angular frequency of the exciting source;
ϵ is the dielectric constant of the sample **51**;
A_ϵ is the cross-sectional area of the dielectric toroid **51**;
l_ϵ is the mean circumference of the dielectric toroid **51**;
A_μ is the cross-sectional area of each of the toroids **56** and **57**;
e_i is the input voltage;
μ is the permeability of each of the elements **56**, **57**; and
e_o is the output voltage at the voltmeter **53**.

Further mathematical analysis discloses two well defined resonances, a series and a parallel resonance at very high frequencies. Below both of these resonances, however, the l in the denominator of Equation 6 may be neglected in comparison with the other term, and the equation becomes:

$$\frac{e_o}{e_i}=\frac{\omega^2\mu\epsilon A_\epsilon A_\mu}{l_\mu l_\epsilon} \qquad (7)$$

And, assuming that the dielectric test samples are cut to a standard shape, the output voltage e_o at the voltmeter **53** will be directly proportional to the dielectric constant ϵ of the test sample. Therefore, after an initial output voltage reading using a sample of known dielectric constant, the dielectric constant of any other sample may be quickly and easily determined. Thus, through the use of the arrangement of Fig. 6, the use of electrodes in dielectric measurement techniques is avoided and the principal source of error in such measurements (the lack of intimate contact of the electrode with the high dielectric constant material) is thereby eliminated.

Proceeding to a related matter, the problem of an infinitely long rod of ferromagnetic material that is being magnetized by an alternating magnetic field acting along the axis of the rod will now be considered. The magnetic current in the rod will set up circular lines of electric flux around the rod. As these electric flux lines alternately build up and collapse they will induce a back magnetomotive force in the rod. In other words this rod will also have inductance for the flow of magnetic current. In order to find the actual current distribution at high frequencies, it is necessary to know the geometry of the return circuit. For instance, if the geometry is such that the problem consists in finding the current distribution in two parallel cylindrical "wires" then the current distribution can be regarded as being made up of cylindrical sheets only if the distance between the axes of the "wires" is large compared with their radius. If this approximation is valid, then the current distribution is identical to that obtained by assuming that the return circuit is via a cylinder, coaxial with the dielectric sample and larger in radius. Since this geometry lends itself more readily to mathematical analysis, it is this model which will be used.

The problem is illustrated in Fig. 7 in which the central long rod **61** of ferromagnetic material is inclosed by the coaxial return path **62**. If a cylindrical tube of radius r and wall thickness dr is considered as the sample, then the equation giving the current in the tube is:

$$E=L\frac{\partial I_r}{\partial t}+\frac{Q_r}{C}=\frac{\partial \Phi_r}{\partial t}+\frac{Q_r}{C} \qquad (8)$$

where:

I_r is the total current in tube;

Φ_r is the number of lines of induction between two planes perpendicular to the axis of the cylinder and one meter apart which are linked by the current in this cylindrical tube;

E is the difference in applied potential between the two planes bounding the tube;

Q_r is the total charge on the two planes bounding the tube (i. e. $Q_r=\int_0^t I_r dt$); and

L and C are the effective inductance and capacity per unit length.

Solving the previous Equation 8 and neglecting the magnetic flux external to the cylinder (a valid approximation for ferromagnetic materials) the current density distribution is given by the following equation.

$$J_r=\frac{A\cdot J_0\left(\frac{2\pi r}{\lambda}\right)e^{i\omega t}}{J_0\left(\frac{2\pi a}{\lambda}\right)} \qquad (9)$$

where: A is an undetermined constant which depends on the amplitude of the applied field.

As a result of this current density distribution it may be determined that the apparent dielectric constant of the cylinder is:

$$\epsilon_{ap}=\frac{\epsilon\lambda}{\pi a}\,\frac{J_1\left(\frac{2\pi a}{\lambda}\right)}{J_0\left(\frac{2\pi a}{\lambda}\right)} \qquad (10)$$

where:

ϵ is the true dielectric constant of the material;

λ is the operating wavelength;

"a" is the radius of the cylinder as indicated in Fig. 7; and

J_0 and J_1 are Bessel functions of the zeroth and first orders respectively.

This expression has a resonance wherever the zeroth order Bessel function in the denominator has a zero. At lower frequencies the Bessel function of zero order can be adequately represented by the first two terms, and the function of first order can be represented by the first term only. Under these conditions Equation 10 may be reduced to an expression which is identical with Equation 3 which was derived by means of the approximation that the current density was uniform throughout the cylinder. Thus the approximate theory previously developed is even quantitatively valid up to the first resonance. Nevertheless, it

is important to realize that the exact theory does predict a different behavior above the first resonance than the approximate theory where the current density is assumed to be uniform.

For the case where loss occurs (i. e. μ and ϵ are complex), the above analysis is still correct except that the propagation constant cannot be written in terms of the wavelength in such a simple fashion. For lossy materials,

$$\epsilon_{ap}=\frac{2\epsilon}{\omega a\sqrt{\mu\epsilon}}\,\frac{J_1(\omega a\sqrt{\mu\epsilon})}{J_0(\omega a\sqrt{\mu\epsilon})} \qquad (11)$$

The same analysis can be carried out for the magnetic cylinder that is carrying a magnetic displacement current, (i. e. being magnetized and demagnetized in alternating cycles). The analysis is identical except that μ and ϵ exchange places. Hence, the apparent permeability without loss and with loss may be determined by interchanging μ and ϵ in Formulae 10 and 11, respectively.

Proceeding now to a consideration of Fig. 8, a hollow cylinder **71** of material having a high dielectric constant and a high permeability, such as one of the new nickel zinc ferrites, is provided with a pair of electrodes **72**, **73** at its two end surfaces and with a coil **74** threaded through its central aperture. When an alternating voltage is applied across electrodes **72**, **73** this establishes an electrostatic displacement current in the dielectric material **71** between the electrodes. This electric displacement current will be accompanied by a circumferential magnetic field which will be set up in the cylinder **72** by the electrostatic displacement current. This in turn will establish a current flow in the coil **74** which is coupled to the circumferential magnetic field. The structure of Fig. 8 will thus transform a high impedance input at electrodes **72**, **73** to a low impedance output at the output terminals **75**, **76** of the coil **74**.

In the present specification and claims, when the terms "high dielectric constant" or "high permeability" are employed it is understood that the relative dielectric constant or permeability will be greater than 1000. When the term "low conductivity" is employed, a conductivity less than 1 mho/centimeter will be understood. The necessity for employing materials having either a high dielectric constant or a high permeability or both of these properties is again stressed, inasmuch as it is these qualities which prevent undue dispersion of the electric or magnetic fields. In addition, the low conductivity of the high permeability material is important to prevent neutralization of the magnetic fields by circulating currents. Typical materials suitable for use as the high dielectric constant elements are barium titanate and potassium niobate. In addition to the nickel-zinc ferrite mentioned hereinbefore, other materials which have been reviewed in the literature may be employed as the high permeability-low conductivity elements discussed above.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In an impedance converter, a cylinder of polycrystalline ferrite material having a permeability greater than 1000, said cylinder having a substantially axial opening therethrough, a pair of apertured electrodes mounted on the opposite ends of said cylinder, a toroidal coil threaded through the axial opening in said cylinder and the apertures in said electrodes, said toroidal coil having its windings insulated from said electrodes, and separate electric circuits connected to said electrodes and said coil, respectively.

2. In an impedance converter, a cylinder of polycrystalline ferrite material having a chemical composition substantially that given by the formula $Ni_{.3}Zn_{.7}Fe_2O_3$, said cylinder having a substantially axial opening there-

through, a pair of apertured electrodes mounted on the opposite ends of said cylinder, a toroidal coil threaded through the axial opening in said cylinder and the apertures in said electrodes, said toroidal coil having its windings insulated from said electrodes, and separate electric circuits connected to said electrodes and said coil, respectively.

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