March 8, 1949. E. W. KELLOGG 2,463,778

MAGNETIC SHIELDING

Filed Dec. 15, 1943 2 Sheets-Sheet 1

Fig. 1.

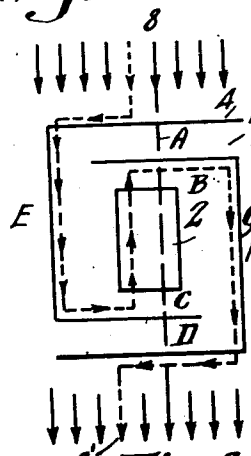


Fig. 2.

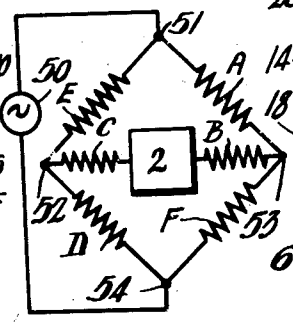


Fig. 3.

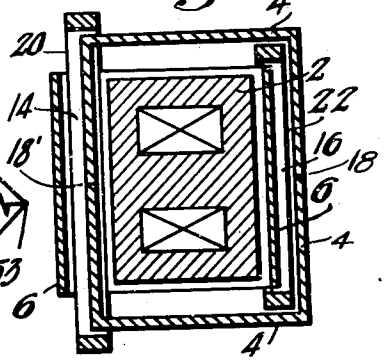


Fig. 7.

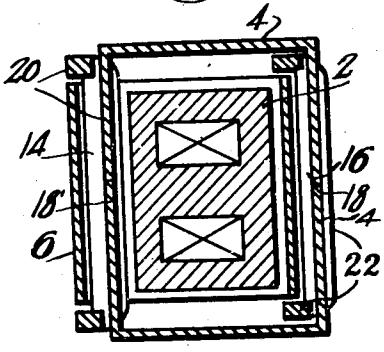


Fig. 8.

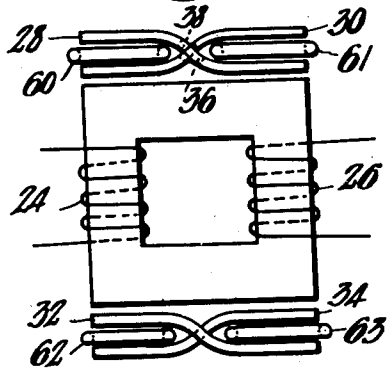


Fig. 9.

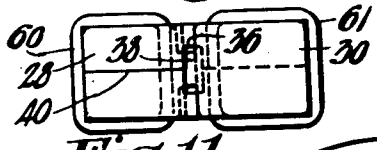


Fig. 10.

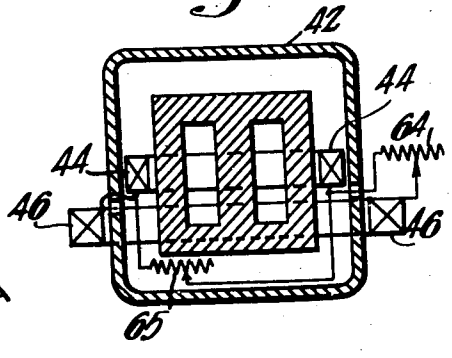
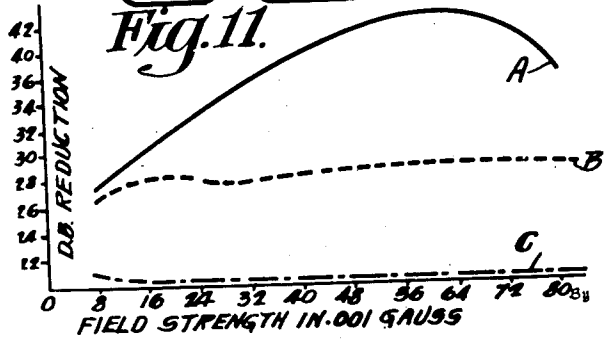


Fig. 11.



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MAGNETIC SHIELDING

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Fig. 4.

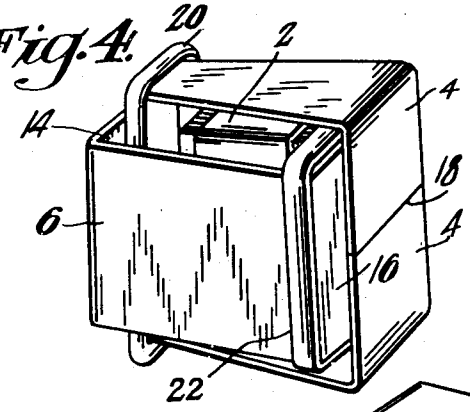


Fig. 5.

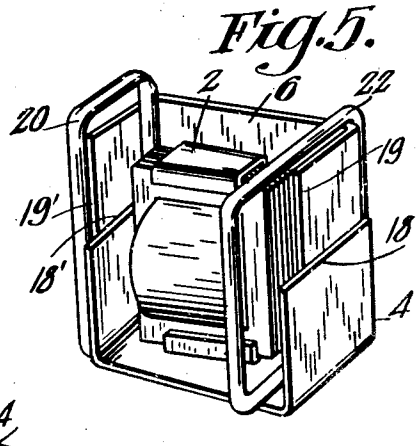
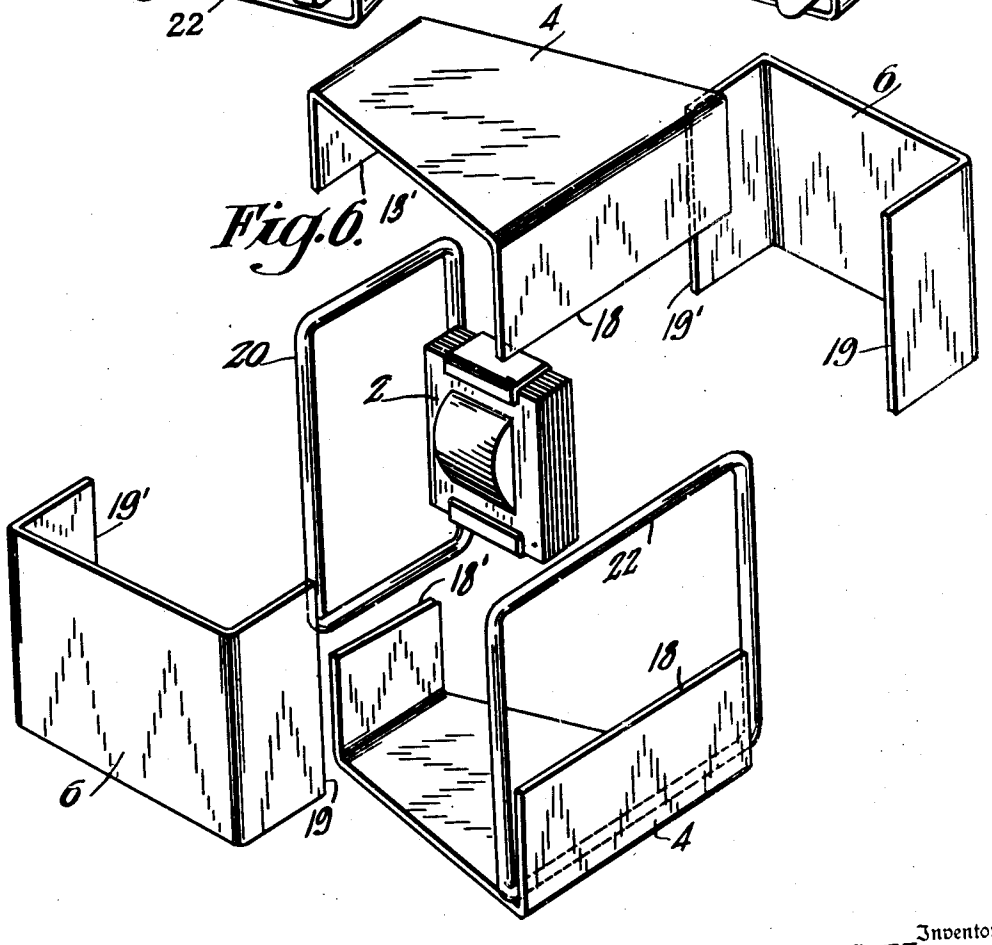


Fig. 6.



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UNITED STATES PATENT OFFICE

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MAGNETIC SHIELDING

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Application December 15, 1943, Serial No. 514,389

13 Claims. (Cl. 174—35)

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This invention relates to the magnetic shielding of transformers, reactors, and electromagnetic devices.

High quality magnetic shields for transformers or other electromagnetic devices are frequently made of special alloys possessing high permeability, and typical shielding may include from one to as many as three complete boxes, one enclosing the other, of high permeability material. Alloys of extra high permeability are comparatively expensive and they can be obtained only from a limited number of sources. Moreover, they may contain admixtures of elements such as nickel, cobalt, molybdenum and chrome, which cannot be obtained as easily as iron or steel, and some of which are mined outside of the United States. Their supply is, therefore, uncertain and untrustworthy, particularly in time of war.

Accordingly, it is an object of the invention to provide improved shielding means whereby adequate shielding may be obtained with more readily available magnetic materials.

Transformers are in general of two types, known as core type and shell type. Core type transformers have two coils so connected that the magnetism produced by one coil is in the opposite direction to that produced in the other coil. Such transformers produce much less stray fields than transformers of the shell type. Conversely, a magnetic flux which passes in the same direction through both coils as, for example, the field produced by some nearby transformer or coil, produces voltages in opposite directions, thus tending largely to neutralize disturbances from external fields.

Transformers of the shell type ordinarily have a single coil, or a group of concentric coils comprising a primary and one or more secondary windings. This coil surrounds a central leg of the core, the return path for the magnetic flux being through two outer legs. There is no balancing effect in the case of a shell type transformer. In the absence of a load on the winding, any flux which enters the coil in a direction parallel to the axis of the coil tends to divide in proportion to the cross-sectional areas of the center and side legs. Thus, if the cross-section of the center leg is equal to the sum of the cross-sectional areas of the outer legs, about half the flux will go through the coil and induce a voltage.

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The first embodiment of my invention is applicable to transformers of the shell type, for which it is important to reduce to a minimum the total flux from external alternating current sources having its direction parallel to the axis of the coil. The components of disturbing flux perpendicular to the axis of the coil have no effect.

The usual method of shielding transformers consists in by-passing the space occupied by the transformer core with a shield which surrounds said core but is spaced slightly away from it. Magnetic fields from surrounding space thus reach the shield before they can reach the transformer. The flux entering the shield then divides into two parts, one jumping across the air gaps into the core, while another portion is carried by the walls of the shield and issues from the opposite end without affecting the transformer. The shield thus cuts down the flux through the transformer in proportion as its reluctance is low compared with that of the air gaps between the ends of the transformer core and the adjacent portions of the shield. There is no balancing, and the effectiveness of the shield depends on its having very low reluctance.

It is an additional object of my invention to provide a system of magnetic shielding wherein a substantial balance is obtained when the reluctance of the shield becomes equal to that of the air gap between two portions of the shield. Under ideal conditions this would make it possible to produce complete extinction of the undesired magnetic flux within the device, with a ferromagnetic shield of such proportions and material as would, if employed in the ordinary manner, produce only about 50 per cent reduction in the magnetism entering the magnetic core of the device.

In another embodiment of my invention, I employ the same principle to provide improved shielding for certain unbalanced components of flux in core type transformers.

It is a further object of the invention to provide improved means for neutralizing external flux which penetrates a magnetic shield.

It is a further object of the invention to provide an improved transformer in which the amount of hum due to an external magnetic field is greatly reduced.

These objects are achieved in a preferred em-

bodiment of the invention by providing a pair of shields of magnetic material which enclose the transformer and which are so spaced from each other that the reluctance of the shields is substantially equal to the reluctance of the space between the shields. This has the effect of splitting the external flux into two substantially equal components, one of which flows in the shields and the other in the space between the shields. The two components are deflected through the core of the transformer so that they flow therein in opposite directions and tend to cancel each other out.

The principle of my invention and its method of execution can best be understood by reference to the accompanying drawing, in which:

Figure 1 is a schematic illustration for the purpose of explaining the balancing principle as applied to a shell type transformer,

Figure 2 is a circuit diagram of an electrical bridge analogous to the magnetic balancing system of Figure 1,

Figure 3 is a cross-sectional view through the shielding system and through the transformer,

Figure 4 is a perspective view of the complete transformer and shield, with spacing or positioning elements omitted to avoid confusion,

Figure 5 is a view also in perspective corresponding to Figure 4, but in which parts of the shields have been removed to show the spatial relationship of the various components of the apparatus,

Figure 6 is an exploded view of the various components of tlhe apparatus,

Figure 7 is a cross-sectional view of an alternative arrangement of the electrically conductive members for producing phase shift, resulting in a more compact design,

Figure 8 is a view in elevation of an embodiment for use with core type transformers where the disturbing field is of varying strength at the different windings,

Figure 9 is a plan view of the same embodiment,

Figure 10 is a perspective view partly in section of a further embodiment of the invention, using only one shield, and

Figure 11 exhibits curves showing the response of the apparatus illustrated in Figures 1 to 7 at 60 cycles and varying field strength, as compared with the response of conventional shielding means.

Referring to Fig. 1, a shell type transformer is represented by the rectangle 2, the axis of its coil being assumed to be vertical, and an external magnetic field is indicated by the arrows 8, 8'. The shielding is to divert the flux entering the shield 6 at the top side, and leaving through the bottom side of shield 6, so that none will pass through the transformer 2. It will be noted that there are two possible paths by which flux can travel through the transformer: (1) It may go directly through the upper side of shield 4 across air gap A, directly through the upper side of shield 6, through air gab B, then through the transformer and through gap C, through the lower side of the shield 4 and then through gap D, and through the lower side of shield 6; (2) On the other hand, as shown by the dash lines with arrowheads, flux may enter the upper side of shield 4 and follow throughout the length of shield 4 to the bottom side of the shield where it will divide, part going downward through the air gap D and the other part upward across gap C through the transformer, continuing through gap B, thence lengthwise through shield 6 down ward and out at the bottom side.

These two possible flux paths (1) and (2) hav components which are opposite in directio through the transformer. If shields 4 and 6 ar of high reluctance, most of the flux will pas downward through gaps A, B, C, and D in succes sion. On the other hand, consider that the shield are of extremely low reluctance compared wit gaps A and D. In this case, most of the flu would go through the shields and upward through the transformer. It is evident that some intermediate value of reluctance of the shields, a balance point can be found at which the tendencies for the flux to pass downward and upward are equal, and this is the balance point for which the shielding system is to be adjusted, for the net flux through the transformer will then become zero. This assumes that the flux through the shields will be in phase with the magnetic potential of the flux through the air gaps. Provision is made to secure equality of phase angles, as will later be described.

The shielding system may be compared to an electrical bridge as shown in Fig. 2, wherein a source of alternating voltage is shown at 50 and a device is shown at 2 wherein it is desired to neutralize all effects of a disturbance produced by the source 50. The resistances of the branches A and D correspond to the magnetic reluctances of the gaps A and D in Fig. 1, while the resistances E and F correspond to the relcutances of the shields. An electrical balance will be reached when the resistances E and F are equal to those of A and D, and in that case there will be no electrical potential between junctions 52 and 53 and no current will flow through device 2.

It is evident in Fig. 2 that the presence of resistances C and B make the adjustment less critical; in other words, assuming that a perfect balance cannot practically be obtained, the resulting current through device 2 will be reduced by the presence of these two resistances. Correspondingly, in Fig. 1 the gaps B and C are not theoretically necessary for obtaining a balance, but practically they make the tolerance for unbalance much larger than it would otherwise be.

There are two ways of reasoning with regard to the action of any bridge or balancing device. One is to consider potentials as determined by currents and resistances and determine the conditions for which there will be zero difference of potential between the balanced terminals. The other way of looking at the problem is to take into account the resistances which tend to send current in one direction through the balanced circuit and then the effect of the resistances or circuit branches which tend to send current in the other direction, and to show that at balance these two opposite currents are equal and, therefore, the total current is zero. In describing the action of my magnetic balances, I have herein in some instances followed the former and in some the latter methods of describing the effects produced, but it is to be understood that the action referred to is the same whichever way it is described, and the two methods of reasoning have been retained because some readers will probably find one description and some the other description easier to understand.

Were the disturbing field strictly parallel to the axis of the transformer winding, or vertical as shown in Fig. 1, the shields might be built as there indicated, but the presence of shields of this type, while providing the balance for the strictly

vertical component of flux, will upset a previously existing balance or neutrality with respect to magnetic fields in the horizontal direction. Thus, a magnetic field from left to right in Fig. 1 would enter at E, traverse the transformer in the directions C, B, and thence issue through the surface F. This would largely defeat the purpose, since a practical shield must be so designed that it will protect the transformer from external fields of random direction. This difficulty is obviated by making each shield in the form of a complete link, the two rectangular shields being interlinked like the links of a chain with the transformer between; thus, shield **4** would be a complete rectangle of flat material surrounding the transformer, as shown at **4** in Fig. 3. At right angles to this shield is another rectangle likewise surrounding the transformer. In Fig. 3, this other link is shown in cross-section at **6**, **6**. To facilitate assembly these links may be split, as indicated at **18—18'** in Fig. 3. Fig. 3 has been drawn showing the transformer turned over 90° as compared with Fig. 1, and it is here the field in a horizontal direction which is neutralized by the balancing effect. The symmetry of the system is such that components of magnetic field perpendicular to the axis of the transformer coil would pass through the structure without producing any components parallel to the coil axis. Such components of flux would pass partly through the transformer space and partly through the shields, but at all points remaining in planes normal to the coil axis. The linked rectangle construction has thus eliminated the introduction of unbalances for magnetic flux in directions for which the transformer was previously balanced, while the provision for obtaining balance for fields parallel to the coil axis is taken care of in accordance with the principles explained in connection with Fig. 1.

Shields **4** and **6**, in Figures 3 to 6 inclusive, may be made of any suitable magnetic material. In a practical embodiment, they were of $\frac{1}{16}$'' thick hydrogen-annealed Armco iron. As shown in Figure 4, they may be of generally rectangular shape and formed as two chain links, so that one side of each shield is inside the other shield. It will be seen that the transformer is protected by two shielding walls on the left and right-hand sides, but by only one wall at the front and back, and at the top and bottom. The shields are spaced from the transformer and from each other after adjustment by non-magnetic shims or spacers.

Two gaps **14** and **16** separate the shields, and the transformer is placed inside the shields with its axis of sensitivity pointing toward these two gaps. The shields are symmetrical about a vertical plane drawn through the axis of sensitivity of the transformer. For convenience of assembly, each shield is made in two parts joined at edges **18—18'** and **19—19'**. While it is not essential that the shields be of generally rectangular shape, this arrangement takes up minimum space and provides low leakage.

After the transformer has been placed inside the shields in the manner shown in Figures 3, 4 and 5, the shields should be balanced to make their reluctance equal to that of the gaps **14** and **16**. Any suitable method may be used for this purpose. One method is to place the device within a disturbing magnetic field, and then to attach a meter or hum measuring device to the secondary winding of the transformer and adjust the gaps until the meter gives a minimum reading.

Another satisfactory method is simply to connect a pair of earphones to the terminals of one of the windings, and adjust for minimum audible hum. By using spacing plates to position the shields and core in the direction of gravitation, the adjustable gaps can be changed by sliding the elements until the hum is a minimum. Best results are obtained by balancing the shields at the maximum anticipated strength of the disturbing field, for assuming that the balance is not equally good at all field strengths it is better that the less perfect balance should be experienced when the field is weak and the disturbance inherently low.

Shield **4** is tapered as shown in Figures 4 and 6, so that its face inside the other shield is narrower than the opposing face of shield **6**. This increases the space between the side of shield **4** and the legs of shield **6**, and reduces leakage between the two shields. The narrow face of shield **4** is still wide enough to cover the whole of the end of the transformer core, which is in the shape of an elongated rectangle.

The flux component which flows in the shields sets up eddy currents therein and this induces a phase shift in the flux. For better balance, an equivalent phase shift must be produced in the flux component flowing in the space between the shields, and this is accomplished by placing an electrically conductive member of proper resistance in such space.

In the prefered embodiment, the electrically conductive members for adjustment of phase shift are constituted by copper bands **20**, **22**. Their purpose is to produce a phase lag in the air gap flux, equal to the lag of the flux in the shields, due to hysteresis and eddy currents in the iron. They surround the gap but do not enclose any flux which passes through the shields. This is best seen in Figure 4. To conserve room and make the assembly take a more nearly cubical form, the copper bands may alternatively be shaped so that their two sides fit the steps formed outside the gap of the two shields, as shown in Figure 7. The proper resistance of the bands is related to the reluctance of the gaps which they surround, and since the requirement is to match the phase angle of the flux in the iron shields, the band resistance depends on the thickness and permeability of the shields, and in some degree on the frequency and on the strength of the field.

Arriving at a balance when two factors must be controlled, and adjustments are not independent of each other, requires that the final balance be reached by successive approximations. An analogous situation in the circuit of Fig. 2 would be that the arms E and F have a certain amount of inductance and, therefore, adjustable inductances have to be introduced into the arms A and D. First the resistance and then the inductance is adjusted, and with each readjustment a better aproximation to balance is attained.

In determining the design of the phase adjusting bands, one method of procedure is to make a preliminary coil of the desired shape, and enclosing the required area but having somewhat more copper than it is anticipated will be needed. This can be a multi-turn coil which facilitates using an external adjustable resistance. By using such a preliminary coil, a value of total resistance will finally be determined which, in conjunction with the optimum air gap length, will give the best cancellation of hum. With the total resistance and number of turns thus deter-

mined, a single turn coil or ring can then be designed with the same effective resistance, the proper resistance for the single turn being R/n^2 in which R is the resistance of the multi-turn coil, and n the number of turns.

When rings or bands of the correct resistance have been made, they are placed between the shields in positions to surround substantially the flux in the entire area of the air gaps between the shields. Shims or spacing blocks are made of correct thickness to fix the length of these air gaps at the experimentally determined value. The shields may then be bound by twine, or wedged into an outer case to hold them in position. The final assembly may be filled with wax or some other suitable insulating solid compound.

The advantages of the shielding means described are best seen from the graphs of Figure 11, in which the cancellation ratio of hum in decibels is plotted against the strength of an external disturbing magnetic field. Curve A for the apparatus so far described may be compared with curve B for a round drawn can of .02" "Mu-Metal" (the name by which one of the more commonly used high permeability alloys is known) and also with curve C for a $\frac{1}{16}$" thick box of hydrogen-annealed Armco iron. The field strength scale was chosen so that its mid-point was equal to the field strength generated by an RCA type RT-425A power transformer, placed twelve inches away from the shielded transformer. This power transformer is typical of those widely used for furnishing plate and cathode power to the tubes of audio amplifiers and receiving sets. The slope of curve A is due to the fact that the permeability of iron increases with the field strength, but that of an air gap is constant. A balance is thus possible only at one field strength. The shields should, in general, be balanced at the maximum anticipated strength of the disturbing field, for it is in the presence of strong fields that the need of a high degree of cancellation is most important.

A preferred arrangement of the shields for core type transformers is illustrated in Figures 8 and 9. Core type transformers, as has hereinbefore been stated, are inherently balanced for uniform magnetic fields, regardless of the directions of the fields. However, unbalance exists if one winding, for example winding 24 of the transformer shown in Fig. 8, is more closely coupled to the disturbing field than the other winding 26, so that the field is stronger at the former than at the latter. The shields 28, 30 adjacent to the top of the transformer, and the shields 32, 34 adjacent to the bottom of the ransformer are made to cross each other so that sufficient of the flux at winding 24 is diverted to winding 26 to cause both windings to be at equal magnetic potential.

In order to provide symmetry about the plane drawn through the longitudinal axes of the windings, the arrangement more clearly shown in Figure 9 is adopted. Shield 28 has a mortise-like opening 36 therein, which may be of any configuration, but should preferably be rectangular. Shield 30 is notched, so that the tenon-like portion 38 remaining can pass through the opening 36 with clearance all around, so as to minimize magnetic leakage from one shield to the other. Shields 32 and 34 adjacent to the bottom of the transformer have a similar opening and notch, respectively, like a mortise and tenon joint, at their crossing point; and shields 28 and 32 are split throughout their entire length at line 40

into two equal portions, so that they may be fitted around the other two shields. When this has been done, the space between the shields may be adjusted to make its reluctance balance that of the shields as in the previously described embodiment.

In order to balance the air gap reluctance against that of the shields, with respect to phase angle as well as magnitude, short circuited rings 60, 61, 62, 63 may be employed in the air gaps. The method of balancing the resistance of the rings and the length of the gaps is similar to that applicable to the shields for shell type transformers.

A further embodiment of the invention is illustrated by Figure 10. In this embodiment, only one shield 42 of magnetic material is used. The principle, however, is the same. The external field is used to create at the transformer a magnetomotive force opposite in direction and of proper magnitude to neutralize flux which succeeds in penetrating the shield. To achieve this, two coils 44, and 46, connected in series, are employed. Shield 42 surrounds the transformer and is spaced therefrom, while coil 44 is placed within the space between the shield and the transformer, so that it is in the path of any flux operative in that space. Coil 46 is outside the shield, so that the external field induces a voltage therein. This sends current through coils 46 and 44, which by proper adjustment can be made to neutralize the magnetic flux which comes through the upper and lower walls of shield 42. The number of ampere turns developed in coil 44 for a given field strength, depends largely on the resistance and inductance of the coils.

In putting this invention into effect, start with larger coils than would normally be necessary; make the total impedance of the coils 44 and 46, when in their respective places, substantially equal; and use a large enough conductor to give a low ratio of resistance to inductance. By this means, the flux through the transformer will be over-compensated. Adjustable series and shunt resistances 64 and 65, respectively, may then be employed; either or both of which will reduce the current through the inner coil 44. The series resistance will advance the phase of the circulating current, while the shunt resistance will retard the phase of that portion of the current which flows through coil 44. These resistances thus provide the necessary adjustments for balancing with respect to both magnitude and phase angle. Having obtained a balance with multi-turn coils, suitable coils having smaller numbers of turns can be designed, and a fixed shunt resistor, if one is required, using design principles well known to those skilled in the art.

I have thus described improved means for shielding transformers from external magnetic disturbance, in which high permeability alloys need not be used, and by the use of which penetrating flux may be substantially neutralized. A transformer so shielded will be more nearly free from hum than transformers shielded by means known to the prior art. While the invention has been described with particular reference to the shielding of transformers, it may also be employed in shielding any reactor or other electrical device employing coils. The invention may also be applied to an electromagnetic device to confine the leakage field and thereby to prevent

the device from adversely affecting neighboring devices.

I claim as my invention:

1. The method of minimizing the effects of a disturbing magnetic field in the region of a reactor by the aid of at least two spaced shields of magnetic material substantially enclosing said reactor, which consists in so placing said shields as to make the reluctance of said shields substantially equal to the reluctance of the spaces between said shields.

2. The method of neutralizing the effects of disturbing magnetic flux on an electromagnetic device by the aid of at least two spaced shields of magnetic material substantially enclosing said device, which consists in so placing said shields as to divide said flux into two substantially equal components, one of said components flowing in said shields and the other of said components in the spaces between said shields.

3. The method set forth in claim 2, characterized by the additional step of producing a phase shift in the component flowing in said spaces substantially equal to the phase shift of the component flowing in said shields.

4. In the method of shielding a reactor with respect to an undesired magnetic field, said reactor being enclosed by a pair of linked, spaced shields of magnetic material, the steps which comprise adjusting said shields spatially in relation to each other until the undesired effects of said field are substantially at a minimum, and then securing said shields at such adjustment.

5. The method of minimizing the effects of external magnetic flux within a predetermined region by the aid of two inter-linked, spaced shields of magnetic material substantially enclosing said region, which comprises providing a direct and an indirect path for said flux, said paths being of substantially equal reluctance, said direct path being through said region in substantially the original direction of said flux and said indirect path being through one of said shields, through region in a direction opposite to the original direction of said flux, through the other of said shields, and away from said region in substantially the original direction of said flux, and then making the phase of flux in said direct path substantially equal to the phase of flux in said indirect path.

6. In the method of minimizing the effects of disturbing magnetic flux on an electromagnetic device, including a first winding and a second winding, said first winding being more closely coupled to said flux then said second winding, by the aid of at least two spaced shields of magnetic material adjacent to said device, the steps which comprise so arranging said shields in relation to each other and to said device as to divert sufficient of the flux at said first winding through said shields to said second winding, to make said flux of substantially equal density at each of said windings.

7. In combination, an electromagnetic device and a pair of linked, spaced shields of magnetic material for shielding said device with respect to an undesired magnetic field, said shields being constituted by open-ended members substantially enclosing said device and having axes substantially normal to each other, said shields further being symmetrical about planes drawn through the axis of sensitivity of said device and so spaced from each other that the reluctance of said shields is substantially equal to the reluctance of the space between said shields.

8. In combination, a reactor and a pair of linked, spaced shields of magnetic material for minimizing the effects of external magnetic flux on said reactor, said shields being constituted by open-ended members substantially enclosing said reactor and having axes substantially normal to each other, said shields further being symmetrical about planes drawn through the axis of sensitivity of said reactor and so placed as to divide the flux impinging on said shields into two substantially equal components and to cause one of said components to flow in said shields and the other of said components to flow in the space between said shields.

9. Apparatus according to claim 8, characterized by the addition thereto, and in combination therewith, of means for producing a phase shift in the flux component flowing in said space substantially equal to the phase shift of the flux component flowing in said shields.

10. Means for shielding an electromagnetic device with respect to an undesired magnetic field, comprising in combination a first shield of magnetic material constituted by four walls in vertical planes adapted substantially to enclose said device whereby to shield it from the flux of said field, and a second shield of magnetic material linked with said first shield and spaced therefrom, said second shield being constituted by four walls adapted substantially to enclose respectively the top, the bottom and two of the sides of said device, the walls of said second shield adjacent to the top and bottom of said device being tapered towards one end thereof, the wall of said second shield at said end being narrower than the opposing wall of said first shield, said shields being symmetrical about planes drawn through the axis of sensitivity of said device, and so spaced from each other that the reluctance of said shields is substantially equal to the reluctance of the space between said shields.

11. Means for minimizing the effects of external magnetic flux within a predetermined region, comprising in combination two interlinked, spaced shields of magnetic material substantially enclosing said region and symmetrical about a plane drawn in the same direction as said flux, said shields being so positioned as to provide a direct and an indirect path for said flux, said paths being of substantially equal reluctance, said direct path being through said region in substantially the original direction of said flux and said indirect path being through one of said shields, through said region in a direction opposite to the original direction of said flux, through the one of said shields, and away from said region in substantially the original direction of said flux.

12. The method of minimizing the effects of disturbing magnetic flux upon an electromagnetic device within a plurality of shields of magnetically permeable material each having an intermediate value of reluctance, which consists in positioning one of said shields in spaced relation from said device to permit a given amount of said flux to traverse a first path through a portion of said device in one direction, positioning a second of said shields in spaced relation from said device and said one of said shields for diverting some of said flux into a second path and through said portion in the opposite direction, and adjusting the spacings to determine the reluctance of said paths so that the flux in said first path through said portion is substantially equal to that in said second path through said portion.

13. In combination, an electromagnetic device

exposed to disturbing magnetic flux, a pair of magnetic shields of a given intermediate value of reluctance and having sides extending in spaced overlapping relation over opposite ends, respectively, of said device to permit a certain amount of said flux to flow in a first path, coinciding with an axis of sensitivity to said flux, through a portion of said device in one direction, said sides being spaced from each other and from said ends to divert a certain amount of said flux into a second path and through said portion of said device in the opposite direction, the opposed fluxes in said paths through said portion being

equal whereby the effects of said flux upon said device are minimized.

EDWARD W. KELLOGG.

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

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