SATURABLE CORE TRANSFORMER

Filed Oct. 16, 1956 2 Sheets-Sheet 1

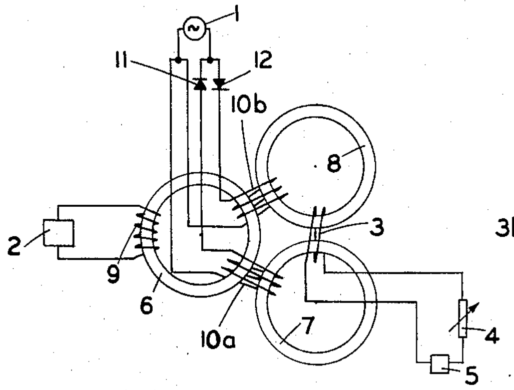

Fig.1

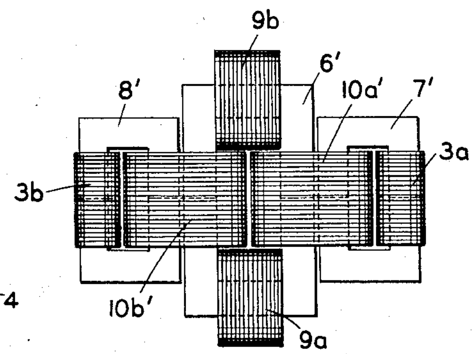

Fig.2

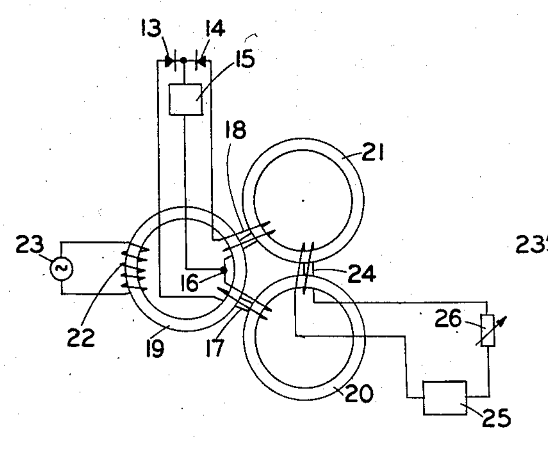

Fig.3

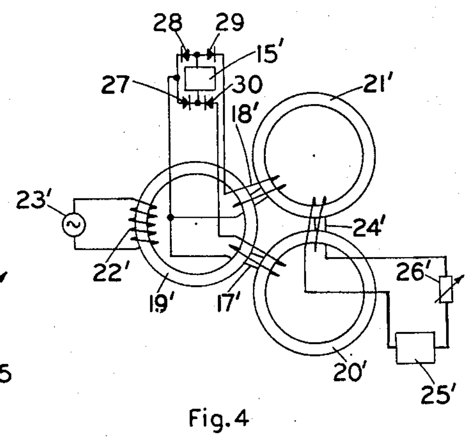

Fig.4

Inventor:
Fred W. Kelley Jr.
by Richard E. Hosley
His Attorney

SATURABLE CORE TRANSFORMER

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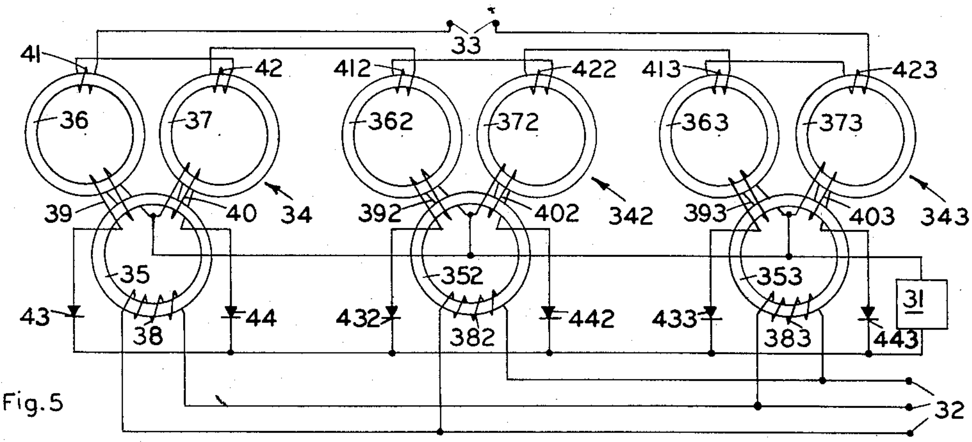

Fig.5

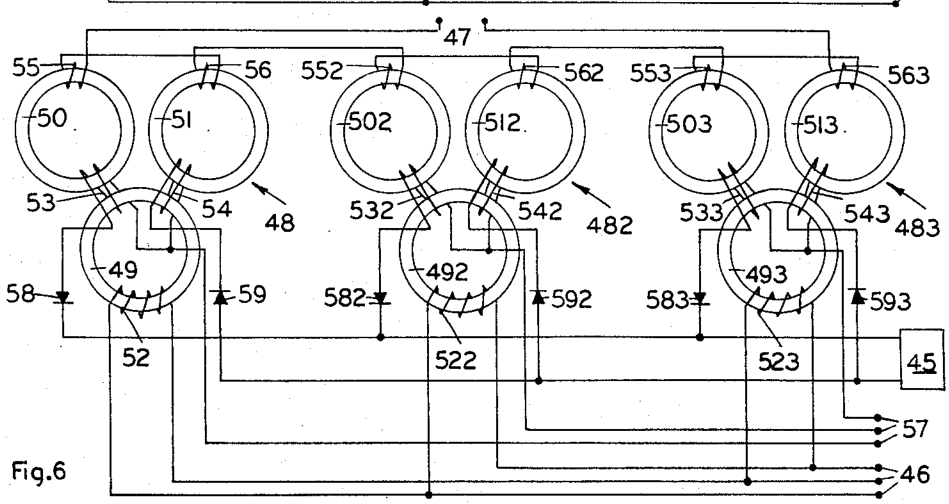

Fig.6

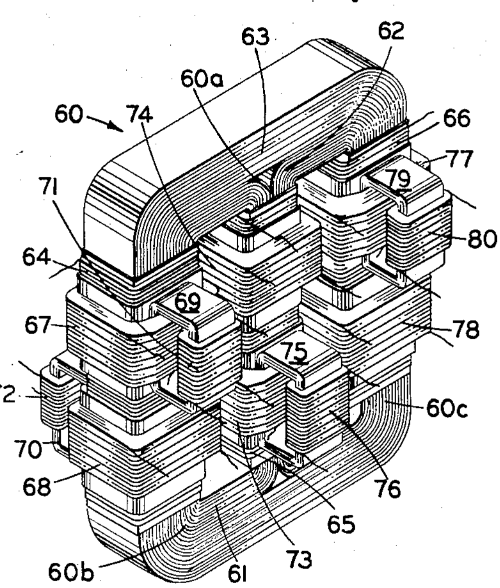

Fig. 7

Inventor:
Fred W. Kelley Jr.
by Richard E. Hosley
His Attorney

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SATURABLE CORE TRANSFORMER

Fred W. Kelley, Jr., Melrose, Mass., assignor to General Electric Company, a corporation of New York

Application October 16, 1956, Serial No. 616,311

9 Claims. (Cl. 323—56)

The present invention relates to improved saturable core apparatus and, more particularly, to magnetic-core control equipment wherein the functions of a transformer and amplistat are present in a unitary construction affording high gain.

Saturable core reactance devices of the type including A.-C. output windings and D.-C. saturating or control windings wound about the same core have gained widespread use in supplementing or replacing electronic amplifiers and rotating regulators, especially where the magnetic amplifier incorporating such devices also include rectifiers in certain circuit relationships which yield increased gain. Magnetic amplifiers of this construction have become identified by the term "amplistat," and commonly it is required that the amplistat be excited by or in unique circuit cooperation with a transformer.

Among the cardinal advantages of magnetic amplifiers are their relatively light weight, sturdiness, long life expectancy, wholly static operation, and adaptability to good impedance matching in most applications. Transformers share many like advantages, and since the two are frequently utilized in conjunction with one another, their combination into unitary structures wherein flux paths are common appears attractive. Prior efforts in this direction have resulted in the design of simple saturable reactance elements combined with transformers, although such combinations do not provide sufficiently high gain for many purposes and the resulting winding and core structures are complex. In combination units, a further important consideration is that control circuit impedances in the saturable reactor circuitry should preferably be of low value, such that these impedances need not be of excessive bulk and weight and such that matching with low impedance control components may be readily achieved; yet this requirement further militates against high gain and leads to undesired power losses.

Accordingly, it is one of the objects of the present invention to provide an improved and simplified magnetic device wherein operating characteristics of a transformer and a high gain magnetic amplifier are realized.

A further object is to provide a transformer and cooperating amplistat assembly of minimum size and weight and having a low impedance control circuit.

Another object is to provide unique core and winding arrangements which occasion heightened gain and curtail power losses in transformer-saturable reactance circuitry.

By way of a summary account of this invention in one of its aspects, I provide three closed magnetic cores each providing a closed magnetic flux path. Single phase A.-C. excitation is applied to a transformer primary winding about one of these cores, which is not saturated, the transformer secondary being in two halves each surrounding the same core and each also surrounding a different one of the other two cores. A D.-C. control signal winding surrounds both of these other two cores and controls their saturation. Output is delivered to a load coupled to a center tap intermediate the two secondary halves and to each of the secondary ends through a dry plate rectifier, each half of the secondary thereby delivering alternate pulses of unidirectional current to the load. Load current is responsive to the magnitudes of direct current caused to flow through the control signal winding.

Although the features of this invention which are believed to be novel are set forth in the appended claims, further details of the invention and the objects and advantages thereof may be readily comprehended through reference to the following description taken in connection with the accompanying drawing, wherein:

Figure 1 is a schematic diagram of a single phase transformer-amplistat embodying the present teachings and arranged to provide A.-C. outputs;

Figure 2 illustrates pictorially one core and winding assembly corresponding to that employed in the arrangement of Figure 1;

Figures 3 and 4 are schematic portrayals of bi-phase and bridge type circuits, respectively, which embody this invention in providing D.-C. output signals;

Figures 5 and 6 depict schematically two circuit arrangements for energizing D.-C. loads responsive to three-phase excitations; and

Figure 7 provides a pictorial view, in perspective, of one preferred three-phase transformer-amplistat core and winding assembly.

The arrangement presented in Figure 1 derives excitation from an A.-C. source **1** and delivers controlled A.-C. output to a suitable load **2**, with both a transformer action and high-gain saturable reactance control action occurring. Control is achieved through the usual type of adjustment of direct currents in a control signal winding **3**, as by manual or automatic variation of the effective values of an impedance **4** serially coupled with a direct current source **5** and control winding **3**. Three closed flux paths are created by three closed cores: a controlled core **6**; and two auxiliary or control cores **7** and **8**. Turns of the aforementioned signal winding **3** encircle both of the control cores **7** and **8**, while the output or secondary winding **9** surrounds only the controlled core **6**. A primary winding which also functions as a form of reactor winding appears in two independent halves, **10***a* and **10***b*, the turns of each encircling both the controlled core **6** and a different one of the control cores **7** and **8**. Winding half **10***a* is coupled across the A.-C. source through a dry contact rectifier **11**, which may be a selenium or germanium rectifier, for example, and the other primary winding half **10***b* is also coupled across the same source through a serially-connected dry contact rectifier **12** which is of a polarization opposite to that of rectifier **11**.

In the aforesaid electrical and magnetic circuit arrangement, the primary winding halves **10***a* and **10***b* are each excited by different alternate half cycles of the alternating current supply **1**, due to the selective blocking effects of rectifiers **11** and **12**. As each of these winding halves is excited in this periodic manner, it tends to drive magnetic flux through the controlled core **6** in a direction opposite to that occasioned by the other winding half and, thereby, to induce A.-C. output signals in the load output winding **9**. However, the inductive reactances exhibited by winding halves **10***a* and **10***b* in conjunction with their cores remain very high unless one of the cores associated therewith is saturated, and thus negligible power is absorbed from the source and delivered to the load without occurrence of certain saturations. These saturations do not appear in the controlled core **6**, because the windings **10***a* and **10***b*, core **6**, and source **1** are designed in known manner to preclude such occurrences. Instead, the control cores **7** and **8** are saturated periodically under influence of the pulsating fluxes produced therein by windings **10***a* and **10***b* and superimposed upon the unidirectional fluxes produced therein by the D.-C. control winding **3**.

Assuming for the moment that the instantaneous values of A.-C. voltage delivered by source **1** are rising from a zero level in a sense to cause current flow through primary winding **10***a*, and that a certain value of D.-C. flux insufficient to saturate control core **7** appears therein, it will be found that the self-induced voltage developed in winding **10***a* is large and opposes the flow of any substantial current therethrough. Accordingly, no appreciable current can be caused to flow to load **2** from the secondary output winding **9** during such times. Ultimately, during the same half cycle of voltage, the increase in source voltage results in increased flux density almost exclusively in the control core **7**, this core becoming saturated because of the additional unidirectional flux circulated therein by the control winding **3**. With this saturation, the flux in core **7** is unchanging, such that winding **10***a* no longer acts as a high impedance opposing current flow from source **1**. The impedance of winding half **10***a* then possesses a relatively low value, whereby the full supply voltage impressed across it occasions a large current flow through winding half **10***a* and yields a high output to the load **2**, this effect continuing during the remainder of the half cycle under consideration. During the next half cycle of source voltage, which is of course of opposite instantaneous polarity, the primary winding half **10***b* conducts current and occasions delivery of output to the load in the same manner. Adjustment of the amount of D.-C. control current flowing in the control signal winding **3**, as by adjustment of the control circuit impedance **4**, alters the time during each half cycle of applied A.-C. when the control cores **7** and **8** "fire" or saturate, and, hence, this adjustment results in greater or lesser current being delivered to load **2**.

One important aspect of the aforesaid operation is best appreciated by assuming that one of the two control cores **7** and **8** is absent from the circuit of Figure 1. If core **8** is omitted, for example, and if only the usual low impedances are present in the control circuit, then control winding **3** functions as a low-resistance or shorted winding about core **7** and would draw relatively large power from the source, in the manner of a transformer secondary, before the "firing" or saturating times in core **7**. Correspondingly large load currents would then be drawn through the secondary load winding **9** during such intervals, because of the large fluxes traversing the controlled core **6**. Net effects are loss of gain and undesired dissipation of power in the control circuit. While high impedances in the control circuit might offset these particular defects somewhat, then matching of the control circuit elements would be difficult and the required high impedances would be of undesired size and weight. With the other control core, **8**, in position, however, and with core **8** remaining essentially passive during firing cycles of core **7** because of the blocking actions of rectifier **12**, it is found that control winding **3** cannot act as a shorted winding and cause the mentioned difficulties. This is explained by the fact that the added control core **8** effectively increases the inductive impedance of winding **3** to a high value during the critical intervals. Thus, no additional impedance is required in the control circuit and only the usual low impedance control circuit elements are required. Gain and loss characteristics remain outstanding. Core **7** of course interchanges functions with core **8** when the primary winding **10***b* about the latter is excited.

A further important feature is found in the operation whereby the closed control cores each convey magnetic flux periodically from their respective primary windings in accordance with unidirectional exciting current. This results from the blocking actions of the rectifiers **11** and **12**. It has been found that cores which carry fluxes in accordance with an alternating current, as distinguished from pulsating unidirectional current, tend to become demagnetized such that greater control M. M. F. is needed to produce saturations. Accordingly, the fluxes (associated with the unidirectional exciting currents) in control cores **7** and **8** by primary halves **10***a* and **10***b* enable lesser control ampere-turns to regulate the core saturations, and the system gain is most advantageously heightened.

One configuration which may be assumed by cores and windings related in the manner of those schematically portrayed in Figure 1 is presented in Figure 2, the components which are full counterparts of those in Figure 1 being identified by the same reference characters with prime accents. The rectangular windowed cores **6′**, **7′**, and **8′** are of the usual laminated construction, and are each preferably fabricated from two U-shaped halves which may be fitted about the pre-wound cooperating windings. The two control cores **7′** and **8′** are disposed one each on outermost sides of parallel legs of the controlled core **6′**, and may be somewhat smaller than the controlled core. In this construction the control signal winding arrangement is divided into two equal serially-coupled halves **3***a* and **3***b*, each of which encircles a different one of the control cores **6′** and **7′**. Operational characteristics are not altered by this division. The secondary or load winding is likewise conveniently divided into two serially-coupled aiding halves, **9***a* and **9***b*, on the controlled cores **6′**.

Direct current output to a load may be provided without further rectification through circuitry such as that of Figure 3 or Figure 4. The bi-phase arrangement in Figure 3 employs a pair of rectifiers, **13** and **14**, which feed a D.-C. load **15** coupled between their junction and a center tap **16** between secondary winding halves **17** and **18**. It should be noted, in this instance, that these secondary winding halves each encircle the controlled core **19** and a different one of the control cores **20** and **21**, and that the primary winding **22** excited by A.-C. source **23** surrounds only the controlled core **19**. The primary and secondary windings are thus interchanged in relation to the orientations of corresponding windings of the circuit in Figure 1. Control signal winding **24** encircles both of the control cores **20** and **21**, or, as in the case of structure of Figure 2, may take the form of two serially-coupled halves each surrounding a different one of these control cores.

The A.-C. signals developed by primary winding **22** are insufficient to cause saturation of the controlled core **19**, and during the first portion of each half cycle of primary excitation, no appreciable signals are generated in the secondary winding halves **17** and **18**. This is true because the control cores **20** and **21** are unsaturated during such intervals, whereby both of the secondary halves **17** and **18** act as very large inductive impedances. If it be considered that the instantaneous signals appearing in secondary winding half **17** are increasing from a zero level in a sense to cause current flow through it and rectifier **13** and load **15**, the aforesaid inductive impedance effects will preclude such current flow until, ultimately, the flux density in control core **20** causes saturation thereof. This saturation results in part from the fluxes occasioned by winding **17** and in part from the unidirectional flux circulated by control winding **24**. Upon occurrence of this saturation, the effective inductance of the surrounding winding half **17** is minute, and large currents immediately flow to the load and continue to flow until the polarity reverses. Rectifier **14** blocks current during this particular half cycle but conducts during the other alternate half cycles when its associated secondary winding half **18** functions in the aforesaid manner. The load **15** thus receives periodic unidirectional current pulses. Direct current from source **25**, as regulated by the variable low impedance 26, controls the saturation characteristics of control cores 20 and 21 and thereby controls the power delivered to load 15. As in the case of the Figure 1 equipment, gain is optimized, power losses in the control circuit are avoided, and impedances in the control circuit may be of low value.

Bridge circuitry of rectifiers in conjunction with a D.-C. load is commonly employed with amplistats because of certain attendant advantages, and the present invention is conveniently practiced with such circuitry also. Figure 4 illustrates four suitable bridge rectifiers 27, 28, 29, and 30 which accomplish this known form of output circuit interconnection, the remaining components of the system there portrayed being identified by the same reference characters appearing with like components in Figure 3, with distinguishing prime accents added. Operation otherwise corresponds to that of the arrangement of Figure 3.

Multiple phase systems may employ these teachings as well. In Figure 5, for example, controlled direct current is supplied to the load 31 responsive to three-phase excitation applied across supply terminals 32 and further responsive to the control exercised by the usual D.-C. control circuit coupled across the control terminals 33. It will be recognized that each of the transformer-amplistat units 34, 342, and 343 is of the center-tap type described in connection with the illustration in Figure 3. The unit for one phase includes controlled core 35 and control cores 36 and 37, the primary winding 38 being mounted about the controlled core 35, the secondary winding halves 39 and 40 each encircling the controlled core and a different one of the control cores 36 and 37, and the two serially-coupled halves 41 and 42 of the control signal winding each encircling a different one of the control cores 36 and 37. A pair of rectifiers, 43 and 44, completes the circuitry of this transformer-amplistat unit, a different one being coupled serially between the load 31 and each of the ends of secondary halves 39 and 40. The other two units, 342 and 343, are of like construction, and corresponding components are thus identified by reference characters having the same first two digits. Each unit operates in the manner earlier set forth with reference to the unit of Figure 3, except that each is separately energized by A.-C. signals of a different phase from the three-phase supply terminals 32.

The three-phase transformer-amplistat schematically depicted in Figure 6 likewise delivers D.-C. output to a suitable load 45 responsive to three-phase excitation from across terminals 46 and responsive to control exercised by the customary control circuit coupled across control terminals 47. Connections are those for three-phase full wave bridge operation, however, with either full or partial control depending upon certain couplings described later herein. Considering the arrangement of but one of the three cooperating units, 48, it is found that it comprises a controlled core 49, a pair of control cores 50 and 51, an A.-C. primary winding 52 about the controlled core, a pair of oppositely-wound secondaries 53 and 54 each encircling the controlled core and a different one of the two control cores 50 and 51, and a pair of serially-coupled primary winding halves 55 and 56 each surrounding a different one of the two control cores. Units 482 and 483 are of like construction, with corresponding components identified by reference characters having the same first two digits. The three sets of D.-C. control signal windings are serially connected in the D.-C. control circuit through terminals 47, and each of the primaries 52, 522, and 523 is connected across a different one of the three phases of excitation appearing at supply terminals 46.

Center tap connections between the oppositely-wound secondary halves of each unit are brought out to terminals 57, where they may be shorted or where additional three-phase excitation may be applied. Ends of the series-connected secondary halves are coupled across the load 45 through oppositely-polarized rectifiers, such as rectifiers 58 and 59 in the case of unit 48.

Operation with terminals 57 shorted is comparable to a three-phase full-wave bridge system, in that there is an ordered sequence of the times when the various control cores saturate and when the control core fluxes are reset, the sequence being determined by the phase rotation of the three-phase supply connected to terminals 46. Assuming, for example, that core 50 saturates, it will be found that previous to this event either core 512 or core 513 is saturated, which one being determined by the phase rotation of the supply as connected to terminals 46. Therefore, assuming that when core 50 saturates core 512 is saturated, coils 53 and 542 are connected serially by either shorted terminals 57 or by a three-phase supply connected to terminals 57. The induced instantaneous voltages in coils 53 and 542 and the instantaneous voltage of the polyphase supply as connected to coils 53 and 542 at terminals 57, if the three-phase supply is used instead of a short circuit at terminals 57, are all additive and of a polarity to cause current to flow through rectifier 58, through the load 45, through rectifier 592, through coil 542, through either a short circuit at terminals 57 or through a branch of a polyphase power supply connected to terminals 57, and through coil 53. Next, core 513 will saturate, and a path consisting of rectifier 593, coil 543, and a different branch of the polyphase supply connected to terminals 57, if used, will replace the path consisting of rectifier 592, coil 542, and the previously used branch connected between coil 53 and coil 542 at terminals 57 in the previously described loop supplying current through the load. This switching of paths supplying current to the load will occur simultaneously with the event of a control core flux being increased to saturation. Each of the six control cores 50, 51, 502, 512, 503, and 513 is normally saturated once per cycle of the supply frequency, such that the switching of paths supplying current to the load will consist of six different events as previously described, and the sequence will be repetitive each cycle of the supply frequency. Load current control is exercised by the D.-C. control signals impressed by way of terminals 57, these signals governing the saturation periods in the control cores.

In some applications, it is not essential that the fullest control be exercised by the control signal circuitry, and a saving in equipment size and weight may be effected by applying part of the three-phase excitation across the terminals 57. These signals are phased properly, such that they will be rectified and delivered to the load additively with the signals controlled by the transformer-amplistat units in the manner last described.

One preferred construction of cores and windings useful in the practice of three-phase transformer-amplistat circuitry appears pictorially in Figure 7. Although winding interconnections and couplings to other circuit components are not illustrated, it should be apparent that these may be made in accordance with the teachings set forth elsewhere herein. The controlled core 60 in this arrangement is a unitary element which, it will be shown, serves the functions of three separate closed controlled cores. This core is of a spiral-wound construction wherein the two spiral-wound inner portions 61 and 62 are placed in an abutting relationship to form a center leg 60*a* of a given thickness and wherein an outer portion 63 encompasses these inner portions to build up the thickness of the two outer legs 60*b* and 60*c* to substantially the thickness of center leg 60*a*. Following the core winding operations, the unitary core 60 is preferably cut into two E-shaped halves which may be fitted together through the associated electrical windings next described. Three electrical primary windings 64, 65, and 66 surround the core legs 60*b*, 60*a*, and 60*c*, respectively, over substantially their entire lengths. To secondary winding halves in turn encircle each of the primaries, and each secondary simultaneously encircles a different closed control core, which is of relatively small size. For example, secondaries 67 and 68 surround primary 64 and controlled core leg 60*b*, and at the same time the turns of these secondaries pass through the windows of closed control cores 69 and 70, respectively. These two control cores are conveniently disposed one on each side of the controlled core leg 60*b*. Control signal windings 71 and 72 also encircle the control cores 69 and 70, respectively. Similarly, secondaries 73 and 74 surround core legs 60*a* and thread separate control cores, only one of which, core 75, is visible in the drawing together with its associated control signal winding 76. Two secondaries 77 and 78 also appear about core leg 60*c* and likewise thread separate control cores, the control core 79 and its control signal winding 80 alone being visible in the view taken in Figure 7.

While particular embodiments of this invention have been shown and described, it will occur to those skilled in the art that various changes and modifications can be made without departure from the invention, and therefore, it is aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. Apparatus for effecting controlled electrical excitation of a load comprising a source of periodically varying voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a magnetic flux path, a source of control current, first winding means energized by said control current source and disposed to vary the saturation characteristics of both of said control core members simultaneously responsive to said control current, second winding means linking said controlled core member, rectifier means, third winding means having two portions each linking both said controlled core member and a different one of said control core members and each coupled with said rectifier means to conduct current in but one direction, means coupling said source of periodically varying voltage with one of said second and third winding means, and means coupling the other of said second and third winding means with said load.

2. Apparatus for effecting controlled electrical excitation of a load comprising a source of periodically varying voltage, a controlled magnetizable core and a pair of saturable control cores each defining a magnetic flux path, a source of adjustable control current, first winding means energized by said control current source and linking both of said control cores to vary the saturation characteristics of both of said control cores simultaneously responsive to adjustments of said control current, second winding means encircling only said controlled core, third winding means having two winding portions each encircling both said controlled core and a different one of said control cores, means coupling said source of periodically varying voltage with one of said second and third winding means, means coupling said load with the other of said second and third winding means, and rectifier means coupled in circuit with said winding portions of said third winding means to conduct current in a different direction through each of said winding portions.

3. Apparatus for effecting controlled electrical excitation of a load comprising a source of periodically varying voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a closed magnetic flux path, a source of adjustable unidirectional control current, first winding means energized by said control current source and linking said control core members to vary flux density in each of said control core members simultaneously below the levels of saturation in said control core members, second winding means encircling said controlled core member, third winding means having two portions each encircling both said controlled core member and a different one of said pair of control core members, said second and third windings being brought into the relation of cooperating transformer windings by encirclement of said controlled core member, means coupling said source of periodically varying voltage with one of said second and third winding means, said controlled core member and said one of said windings being proportioned such that said controlled core member is not saturated responsive to said periodically varying voltage, means coupling said load with the other of said second and third winding means, and rectifier means coupled in circuit with said winding portions of said third winding means to conduct current in a different direction through each of said winding portions whereby each of said pair of control core members is saturated independently by unidirectional fluxes and said first winding means possesses high impedance opposing induced A.-C. signals therein.

4. Apparatus for effecting controlled A.-C. electrical excitation of a load comprising a source of alternating voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a magnetic flux path, a source of adjustable unidirectional control current, control winding means energized by said control current source and linking both of said control core members, primary winding means having two winding portions each encircling both said controlled core member and a different one of said control core members, secondary winding means encircling only said controlled core member and coupled with said load, means coupling said winding portions of said primary winding means with said source of alternating voltage for excitation thereby, and rectifier means in circuit with said primary winding means connected to conduct current from said alternating voltage source to each of said primary winding portions only during different alternate half cycles of said alternating voltage.

5. Apparatus for effecting controlled electrical excitation of a load, comprising a source of alternating voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a magnetic flux path, a source of adjustable unidirectional control current, control winding means energized by said control current source and linking both of said control core members, primary winding means encircling only said controlled core member and coupled with said source of alternating voltage for excitation thereby, secondary winding means having two winding portions each encircling both said controlled core member and a different one of said control core members, means coupling said winding portions of said secondary winding means with said load, and rectifier means in circuit with said secondary winding means connected to conduct current from each of said winding portions to said load only during intervals when signals of a predetermined polarity are induced therein.

6. Apparatus for effecting controlled electrical excitation of a load comprising a source of alternating voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a magnetic flux path, a source of adjustable unidirectional control current, control winding means energized by said control current source and linking both of said control core members to vary the flux density in each of said control core members simultaneously below the levels of saturation in said control core members, primary winding means encircling only said controlled core member and coupled with said source of alternating voltage for excitation thereby, said controlled core member and said primary winding means being proportioned such that said controlled core member is not saturated responsive to said alternating voltage, secondary winding means having two winding portions each encircling both said controlled core member and a different one of said control core members, said primary and secondary winding means

being brought into the relation of cooperating primary and secondary transformer windings by encirclement of said controlled core member, means coupling said load with said secondary winding means, and rectifier means coupled in circuit with said winding portions of said secondary winding means to conduct current through each of said winding portions to said load only during intervals when signals of predetermined polarity are induced therein whereby each of said pair of control core members is saturated independently by unidirectional fluxes and said control winding means possesses high impedance opposing induced A.-C. signals therein.

7. Apparatus for effecting controlled electrical excitation of a load comprising a source of three-phase alternating voltage, a source of adjustable unidirectional control current, three magnetic units each comprising a controlled core member and a pair of control core members, control winding means linking all of said control core members of said three units and excited by said source of control current to vary the flux density in each of said control core members simultaneously below the levels of saturation of said core members, three primary winding means each encircling a different one of said controlled core members of said units and each coupled with said three-phase source for excitation by voltage of a different phase, three secondary winding means each having two winding portions each encircling said controlled core member and a different one of said control core members of a different one of said units, means coupling said secondary winding means with said load, and rectifier means in circuit with said load and with each of said winding portions of said secondary winding means conducting current only in a predetermined direction through said winding portions.

8. Apparatus for effecting controlled electrical excitation of a load comprising a source of three-phase alternating voltage, a source of adjustable unidirectional control current, a three-legged closed magnetic core, three primary windings each encircling a different one of said core legs and each coupled with said three-phase source for excitation by voltage of a different phase source for excitation by voltage of a different phase, three pairs of closed magnetic control cores disposed one pair each alongside a different one of said core legs, three secondary winding means each having two winding portions both encircling a different one of said core legs and each also encircling a different one of said control cores alongside said one of said core legs, control windings each encircling a different one of said control cores and coupled in series across said source of adjustable unidirectional control current, means coupling said secondary winding means with said load, and rectifier means in circuit with said load and with each of said winding portions of said secondary winding means conducting current only in a predetermined direction through said winding portions.

9. Apparatus for effecting controlled electrical excitation of a load comprising a source of periodically varying voltage, a controlled magnetizable core member and at least one pair of saturable control core members each defining a magnetic flux path, a source of adjustable unidirectional control current, first winding means energized by said control current source and linking both of said control core members to vary the flux density in said control core members below the levels of saturation thereof, second winding means encircling said controlled core member, third winding means having turns encircling said controlled core member and one of said control core members, said second and third winding means being brought into the relation of cooperating transformer windings by encirclement of said controlled core member, means coupling said source of periodically varying voltage with one of said second and third winding means, said controlled core member and said one of said winding means being proportioned such that said controlled core member is not saturated responsive to said periodically varying voltage, means coupling said load with the other of said second and third winding means, and rectifier means coupled in circuit with said third winding means to conduct current in but one direction through said turns whereby said one of said pair of control core members is saturated by unidirectional fluxes and said first winding means possesses high impedance opposing induced A.-C. signals therein.

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