Dec. 28, 1937. B. D. BEDFORD 2,103,996

CONSTANT CURRENT MAGNETIC BRIDGE

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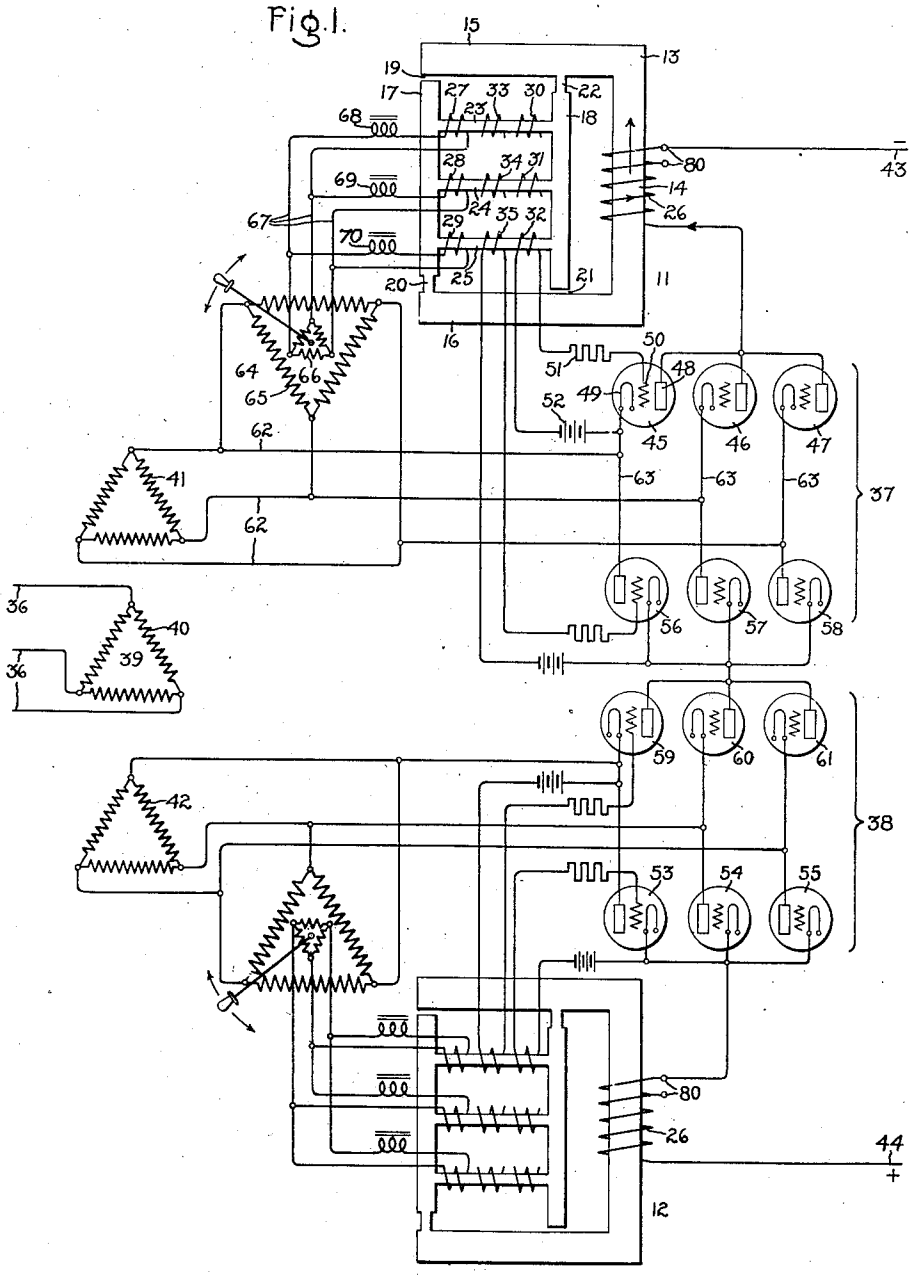
Fig. 1.



Inventor:
Burnice D. Bedford
by Harry E. Dunham
His Attorney

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Fig. 2.

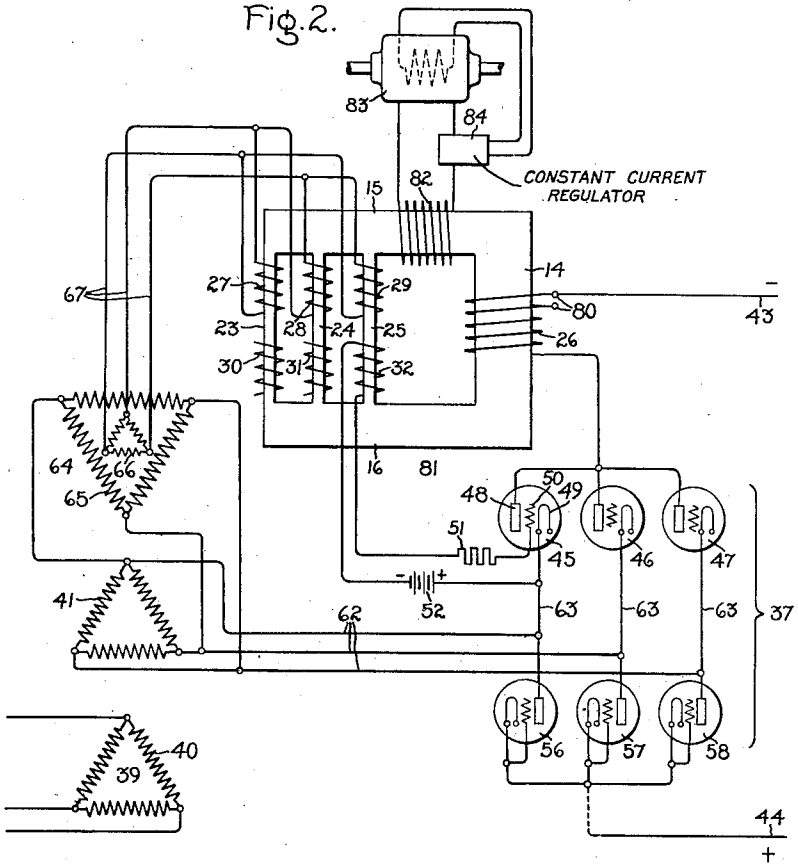


Fig. 6.

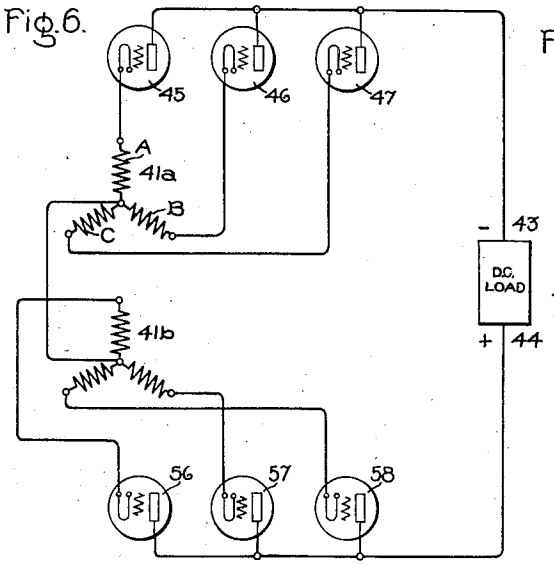


Fig. 7.

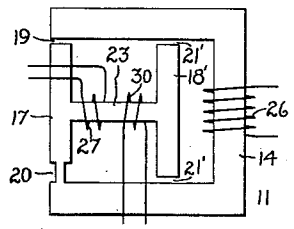
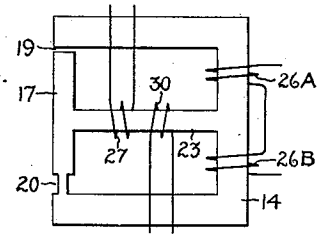


Fig. 8.



Inventor:
Burnice D. Bedford,
by Harry E. Dunham
His Attorney

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CONSTANT CURRENT MAGNETIC BRIDGE

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Fig. 3.

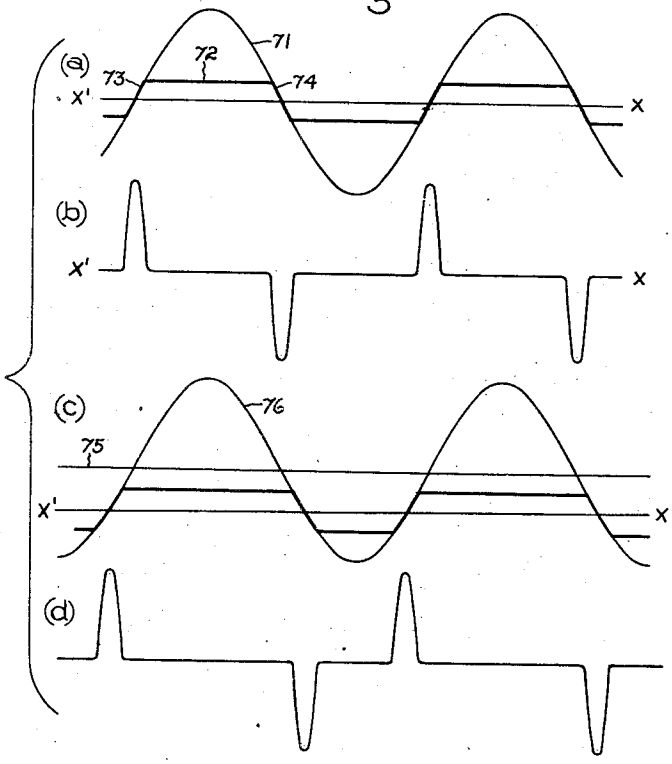


Fig. 4.

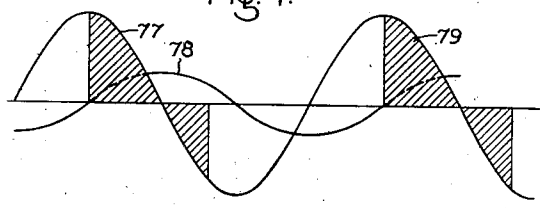
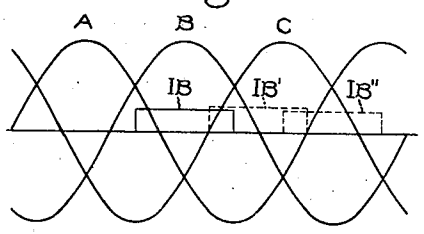


Fig. 5.



Inventor:
Burnice D. Bedford.
by Harry E. Dunham
His Attorney

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2,103,996

UNITED STATES PATENT OFFICE

2,103,996

CONSTANT-CURRENT MAGNETIC BRIDGE

Burnice D. Bedford, Schenectady, N. Y., assignor to General Electric Company, a corporation of New York

Application February 1, 1935, Serial No. 4,480

22 Claims. (Cl. 175—363)

My invention relates to current responsive and regulating apparatus having improved magnetic core constructions and concerns particularly the employment of such apparatus in grid-controlled discharge tube systems.

It is an object of my invention to provide a device which is sensitive to small per cent changes in current.

It is also an object of my invention to provide a constant-current device which responds very quickly to changes in current in order to protect other apparatus with which the device may be employed.

Still another object of my invention is to provide a magnetic bridge or normally balanced magnetic circuit having a detecting member which reverses in polarity when a magnetomotive force in a portion of the bridge exceeds a predetermined amount.

It is a further object of my invention to provide an improved arrangement for producing sharp voltage peaks which are adjustable in their phase position.

It is likewise an object of my invention to provide a transformer in which the secondary voltages may be varied in phase in response to variations in a magnetomotive force acting in the transformer.

An additional object is to provide a current-rectifying or inverting system of high power factor and good wave shape on the alternating-current side.

Other and further objects and advantages will become apparent as the description proceeds.

In accordance with my invention in its preferred form, I provide a magnetic bridge consisting of a magnetic core having parallel portions therein, at least one of which has a non-linear relationship between flux and magneto in force. The core is arranged so that the polarity of a member connecting the parallel portions is reversed as the magnetomotive force falls above or below a predetermined value. The magnetic bridge may be used as a current regulating device for maintaining a current constant if the magnetomotive force is supplied by a current-conducting winding in inductive relation with the magnetic core and electrically connected in series with the constant-current circuit. The magnetic bridge may be combined with a peak voltage producing transformer to produce variations in phase relationship of the sharp voltage peaks supplied by said transformer.

This arrangement may be employed, for example, in the control of rectifying and inverting systems employing vapor discharge valves having control electrodes by connecting the secondary windings of the peak voltage producing transformer to the control electrodes of the discharge valves so that current variations, by producing phase variations in the voltage peaks, will control the initiation of the discharge in the valves.

The features of my invention which I believe to be novel and patentable will be pointed out in the claims appended to this description and to the description in my copending continuation-in-part application Serial No. 114,998, filed December 9, 1936 entitled—Electric control circuits—and assigned to the assignee of the present application. A better understanding of my invention may be obtained from the following description taken in connection with the accompanying drawings in which Fig. 1 is a circuit diagram of a constant-current rectifier or inverter illustrating one embodiment of my invention; Fig. 2 is a circuit diagram of a rectifying system employing a modified form of magnetic bridge; Fig. 3 is a set of graphs illustrating the operation of the magnetic bridge in producing phase variations in peak voltages; Figs. 4 and 5 are graphs illustrating the operation of the discharge valves employed in the rectifying or inverting system; Fig. 6 is a simplified circuit diagram of a portion of the apparatus of Fig. 1; Fig. 7 represents a modification in the magnetic bridge of the embodiment of Fig. 1; and Fig. 8 represents still another modification in the magnetic bridge.

Referring now more in detail to the drawings in which like reference characters are used to designate like parts throughout, in Fig. 1, a pair of magnetic bridges 11 and 12 are represented as employed in connection with a rectifying or inverting system comprising two groups of discharge valves 37 and 38 and a transformer 39 for interchanging power between an alternating current circuit 36 and a direct-current circuit 43—44. Each of the magnetic bridges illustrated in Fig. 1 consists of a core 13 of magnetic material having a yoke portion 14 joining two arms 15 and 16 extending therefrom. The core 15 includes also bridging members 17 and 18 providing parallel magnetic paths between the arms 15 and 16 to close the magnetic circuit provided by the yoke 14 and arms 15 and 16. Each of the bridging members 17 and 18 contain substantially linear and non-linear portions in series, in other words a portion having substantially constant reluctance and a portion having variable reluctance, respectively. An air gap 19

is left between the upper end of bridging member 17 and the arm 15, and the lower end 20 of the bridging member 17 is reduced in cross section to form a saturating portion, which provided one form of non-linearity. In a similar manner, the bridging member 18 is provided with an air gap 21 and a saturating portion 22, reversed in relative position with respect to the air gap 19 and saturating portion 20 of the bridging member 17. Means responsive to magnetic polarity or responsive to both polarity and field strength are mounted between bridging members 17 and 18 in order that an indication or a response may be obtained dependent upon the magnetomotive force acting in the magnetic circuit.

The core 13 may include one or more connecting portions, such as portions 23, 24, and 25, joining the central portions of the bridging members 17 and 18, which will be referred to as the polar portions thereof. The connecting members 23, 24 and 25 are of such cross section that the flux therein tends to be small compared with the air flux between bridging members 17 and 18. The connecting members 23, 24, and 25, therefore, serve primarily as detectors of difference in magnetic potential between the polar portions of the bridging members 17 and 18 rather than as elements in the magnetic circuit through the yoke 14 and arms 15 and 16.

If the magnetic bridge 11 or 12 is designed to form a part of a current-responsive or regulating device, a current-conducting winding 26 is mounted on the yoke portion 14 of the core 13 and is connected to the electrical circuit in which the current is to be measured or regulated. The magnetic responsive means referred to in the previous paragraph may consist, for example, of means for producing sharp voltage peaks varying in phase with variations in the magnitude of the direct current in winding 26. To this end, the connecting portions 23, 24, and 25 of the core 13 may be provided with alternating-current windings, such as the windings 27 to 35. The primary windings 27, 28, and 29 are connected to one or more suitable sources of alternating current and the two groups of secondary windings 30, 31, 32, and 33, 34, 35 serve as the output windings producing voltage peaks.

The magnetic bridges 11 and 12 may be employed in connection with any type of apparatus which is designed to be responsive to variations in magnetomotive force or current. For example, the magnetic bridges 11 and 12 may be employed in connection with a converting system employing controlled discharge valves in order to maintain the direct current constant but it will be understood that magnetic bridges constructed in accordance with my invention are not limited to this application.

In the arrangement of Fig. 1, there is shown a constant-current rectifier supplied with alternating current by a three-phase power source 36. Rectifiers 37 and 38 consisting of groups of electric discharge valves are provided.

These electric discharge valves may comprise any of the valves well known in the art, although I prefer to utilize valves containing an ionizable medium among which are those of the vapor electric discharge type. Preferably, full-wave rectifiers are employed for the sake of greater operating efficiency and greater economy of apparatus, but the invention may also be carried out without full-wave rectifiers. By using two or more rectifiers in series, the permissible direct-current voltage is increased and certain other advantages are obtained which will be explained later. In order to transfer the three-phase power from the source 36 to the valve rectifiers 37 and 38, a three-phase transformer 39 or three single-phase transformers are provided. The windings are shown connected in delta for the sake of illustration. The transformer 39 consists of primary windings 40 and secondary windings 41 and 42 supplying power to the rectifiers 37 and 38, respectively.

In order to obtain full-wave rectification, i. e., to utilize both halves of the alternating-current wave, a pair of rectifying valves is provided for each phase. In the case of three-phase current supply, therefore, each of the rectifiers 37 and 38 consists of six discharge valves connected in series-multiple to form three multiple circuits with respect to a direct-current load circuit represented by its terminals 43, 44. The direct-current windings 26 of magnetic bridges 11 and 12 are connected in series with direct-current load circuit 43, 44 and the fullwave rectifiers 37 and 38.

The discharge valves 45, 46, and 47 of rectifier 37 and valves 53, 54, and 55 of rectifier 38 are provided with control electrodes which may be in the form of grids. The discharge valve 45, which may be taken as illustrative, consists of an anode, 48, a cathode 49, and a control electrode or grid 50. In order to regulate the instant of conductivity of the controlled discharge valves, the secondary peak voltage windings of the magnetic bridges 11 and 12 are connected to the control electrodes of the tubes. For example, the peak voltage winding 32 may be connected between the cathode 49 and the grid 50 of the discharge valve 45. Preferably, a current-limiting resistor 51 and a source of grid-biasing potential 52 are also included in the grid circuit. In a similar manner, the peak voltage windings 31 and 30 are connected in the grid circuits of valves 46 and 47. The connections, however, are omitted from the drawings to avoid confusion. The corresponding peak voltage windings of the magnetic bridge 12 are connected to the grids of discharge valves 53, 54, and 55.

Where the apparatus is to act only as a rectifier, the discharge tubes 56 to 61 may be of the two-element type, not having control electrodes or grids, or, if control grids are present, they may be left unconnected or may be tied to the cathodes as illustrated by tube 56 in Fig. 2. Where the apparatus is to be capable of acting as an inverter, however, additional secondary windings 35, 34, and 33 are provided in the magnetic bridges 11 and 12 and these windings are connected to the control electrodes or grids of the corresponding valves 56, 57, and 58 in a manner similar to the connections of windings 32, 31, and 30.

The three three-phase conductors 62 brought out from the secondary windings 41 of transformer 39 are connected to the three conductors 63 joining the cathodes 49 of discharge valves 45, 46, and 47, respectively, to the anodes of discharge valves 56, 57, and 58. This connection of the valves to form a full-wave polyphase rectifying system is one that is well known in the art and does not form a part of my invention.

In order to make use of the range of phase advancement and retardation of the peak voltages that may be obtained from magnetic bridge 11, it may be desirable to provide means for making the grid voltages lag in phase behind the anode voltages of the valves when the magnetic bridge is in balance. For this purpose, a phase-shifting transformer 64 may be provided having

primary windings 66 connected to the secondary windings 41 of the power transformer 39 and having secondary windings 68 from which conductors 67 are brought out. For maximum flexibility of control, the phase-shifting transformer 64 has its primary and secondary windings relatively movable, permitting changes in the angle of phase shift. The input alternating-current windings 27, 28, and 29 of the magnetic bridge 11 are connected to the conductors 67 either in wye or in delta, as desired, the delta connection being shown for the sake of illustration. The secondary winding 66 of the phase-shifting transformer 65 may be set in such a position that the instant when the grid of any valve reaches the critical value is at the middle of the half cycle of anode voltage for the valve. This setting permits the magnetic bridge to shift the grid voltages through the full range in either direction and still cause the grid excitation to be initiated during the conducting half cycle of the anode voltage. In practice, the voltage-shifting range of the magnetic bridge cannot be a full 180 degrees, and, therefore, it may be desirable under varying conditions of operation to be able to shift the operating range forward or back with respect to the anode voltage by moving the secondary winding 66 of the phase-shifting transformer.

If desired, nonsaturating series reactors 68, 69, and 70 may be connected in series with windings 27, 28, and 29 to limit the current upon saturation of the members 23, 24, and 25.

It will be apparent that the apparatus energized by the winding 42 of the transformer 39 is substantially the counterpart of the apparatus energized by the winding 41.

In order that the operation of the apparatus of Fig. 1 as a whole may more readily be perceived, the operating characteristics of the several elements thereof will first be explained. When the core 13 of the magnetic bridge 11 is subjected to a magnetomotive force as by passing a direct current through the winding 26, there will be a tendency for magnetic poles to appear on the bridging members 17 and 18. In the arrangement shown, the direct current flows around the yoke portion 14 in a counterclockwise direction viewed from above so that the lines of flux tend to flow upward in the yoke portion as indicated by the arrow. When the magnetization of the core is low, the reluctances of the air gaps 19 and 21 will be high compared with the reluctances of the neck portions 20 and 22 of the bridging members 17 and 18. Consequently, magnetic flux will flow from the bridging member 18 to the bridging member 17 or the bridging member 18 will tend to have a north polarity with respect to south polarity on the member 17.

On the other hand, when the magnetization of the core 13 is high, the neck portions 20 and 22 of reduced cross section will become saturated, reducing their permeability and, owing to the appreciable length of the neck portions 20 and 22, their reluctances will be high compared with the reluctances of the air gaps 19 and 21. As a result, magnetic flux will now flow from the bridging member 17 to the bridging member 18, thus reversing the relative polarities of these members from the previous condition. Necessarily, there is an intermediate degree of magnetization at which the magnetic bridge 11 is balanced and one bridging member has neither north nor south polarity with respect to the other. Magnetic responsive means, mounted between the bridging members 17 and 18, may, therefore, be arranged to operate current-controlling apparatus for maintaining a current in the winding 26 at the value corresponding to bridge balance. By making the ampere turns of the winding 26 relatively high compared with the magnetomotive force between bridging members 17 and 18, slight changes in current may be made to cause unbalance of the magnetic bridge.

The connecting portions 23, 24, and 25 with their windings and series impedances 68, 69, 70 are, in effect, peak voltage producing transformers and variations in polarity and strength of the magnetic field between bridging members 17 and 18 produce variations in the phase relationship between the primary and secondary voltages of the transformers thus formed. The operation of a peak voltage producing transformer is explained by graphs (a) and (b) of Fig. 3. Since the voltage ordinarily obtained from a source of alternating current is substantially sinusoidal, the voltages impressed on the primary windings 27, 28, and 29 and series impedances 68, 69, 70 will probably be sinusoidal. The currents in these windings and their magnetomotive force will tend to follow the primary voltages in wave form. The reactors 68, 69, and 70 connected in series with windings 27, 28, and 29 tend to supplement the inherent leakage reactance to insure substantial conformity in wave shape between the primary voltages and the currents and magnetomotive forces. The curve 71 represents the magnetomotive force of one of the primary windings, e. g., the winding 29, and may be substantially sinusoidal. The flux curve 72, however, is much flattened, owing to saturation which limits the flux to nearly a constant value represented by the flat tops of curve 72. The curve 72 represents the flux produced by the primary winding 29 and threading a secondary winding 32. The flux curve 72 has appreciable slope only in the portions 73 and 74 adjacent the points where the magnetomotive force curve 71 passes through zero. Since the secondary voltage is induced by variations in the flux 72, the secondary voltage curve (Fig. 3b) is highly peaked and the peaks occur at the points where the magnetomotive force curve 71 passes through zero.

If the current in the direct-current winding 26 is increased from that at balance, an amount sufficient to produce a variation in magnetomotive force of an amount represented by the horizontal line 75 (X'X being the zero axis), the resultant magnetomotive force will be represented by the unsymmetrical curve 76, Fig. 3(c). As before, the secondary voltage peaks (Fig. 3d) will be induced when the magnetomotive force 76 passes through zero, i. e., when it reverses in polarity. As will be apparent from the diagram, however, the positive voltage peaks will be advanced in phase, and the negative peaks will be retarded. If the current in the winding 26 had decreased instead of having increased, the opposite shift in phase of the voltage peaks would have been produced. From the foregoing, it is manifest that the phase shift of the voltage peaks of a given polarity is indicative of the magnitude and direction of deviation of current in the circuit 43, 44 from a predetermined value. In connection with the control of the rectifiers or inverters shown, of course, only the positive voltage peaks are of consequence.

The part of the core 13 including the connecting portions 23, 24, and 25 may also be regarded

as a magnetic flux-conducting unit of a device responsive to variations in the magnetomotive force applied by the winding 26, or in the magnetomotive force represented by the magnetic potential difference between the bridging members 17 and 18. Such magnetomotive forces are susceptible of reversal but will be referred to in the claims as unidirectional magnetomotive force in contradistinction to the rapidly alternating magnetomotive forces produced by the alternating current in the windings 27, 28, and 29.

Phase shift of the control voltage with respect to the anode voltage is very useful for the control of vapor discharge valves. Such valves become conducting only when both anode and grid voltages are positive (or above certain potentials determined by the design of the valves). Generally, when the valves once become conductive they remain conductive regardless of grid voltage until the anode voltage reverses. If alternating voltages are impressed on both the grid and the anode of such a valve and the grid is positive when the anode becomes positive, the valve conducts current during positive half cycles of anode voltage. However, if the grid voltage lags the anode voltage, current flow starts later in the anode voltage cycle. This characteristic of such a valve in single-phase operation is illustrated in Fig. 4 where 77 represents the voltage applied in the anode-cathode circuit of a valve, 78 represents grid voltage, and the shaded areas 79 represent the portion of the voltage-cycle during which current is flowing and show the voltage which aids or retards current flow. The current carry-over during the negative voltage half-cycle is the result of voltage induced in the inductance of the direct-current circuit which overcomes for a time the negative impressed voltage.

The current flowing in the direct-current circuit 43, 44 is, of course, the resultant of the direct currents flowing in all the discharge valves. Phase shift of the control voltage of the grids of the valves serves to control the current in the direct-current circuit by controlling the instant in the cycle where conduction begins. The connections of the magnetic bridges 11 and 12 are such that an increase in current retards the phase of the peak voltages impressed on the grids of the valves by the magnetic bridge secondary windings in order to decrease the current to the normal value. Likewise a decrease in current advances the phase of the grid voltage and permits the current to rise to the normal value.

Inasmuch as, with respect to the direct-current circuit 43, 44, the discharge valves 45, 46, 47, 53, 54, and 55 are in series with the other valves, phase control is needed for only one of these valves in any series group when the apparatus is used as a rectifier. The remaining valves may then remain continuously conducting for direct current without effect on the direct-current output. When the apparatus is operated as an inverter, however, the timing of current flow to the different phases of the windings 41 and 42 depends upon the timing of the conductivities of all the valves. For example, if valves 57 and 58 were continuously conducting, equal currents would flow in two of the windings of the group 41 whenever valve 45 was conducting. This, however, is not the desired result if three-phase currents are to be produced in transformer 39. Obviously valves 57 and 58 must also be controlled in order to control properly the timing of the admission of currents to those windings from valve 45. Similarly, the remaining valves must be controlled for inverter operation.

Owing to the fact that the change in magnetomotive force of the magnetic bridges 11 and 12 and the change in phase of the grid potentials of the valves with respect to the anode voltages responds very quickly to changes in direct current in the circuit 43, 44, my arrangement is very useful for protecting apparatus from damage in the case of short circuits when the apparatus to be regulated is of a type that would be damaged before ordinary overload relays or circuit breakers could have time to act.

The current at which one of the magnetic bridge balances depends, of course, on its physical dimensions and the number of turns of the direct-current winding 26. If desired, to permit adjustment after the device has been constructed, portions of the magnetic core may be made movable or a plurality of taps 80 may be brought out from the winding 26. The operating range covered by the magnetic bridge may also be adjusted by changing the angular position of the movable winding 66 of the phase-shifting transformer 64 with respect to the stationary winding 65.

A minimum current flow is obtained in the transformers for the condition when the direct load voltage is at a minimum and the wave shape of the alternating current is improved if only three valves are controlled in each group of six constituting a full-wave rectifier. A still further reduction in transformer current or in the reactive component of volt amperes may be obtained by adjusting the magnetic bridges 11 and 12 to balance at slightly different currents. One rectifier would then be controlled through its range of operation before the other is varied while a large change in current would be quickly corrected by the operation of both regulators. The maximum reactive component of volt amperes of the whole system under any condition of direct-current voltage would then be only the volt amperes required to cause one group of three valves to operate at the minimum direct-current voltage condition.

The reasons for the conclusions of the foregoing paragraph will be understood from a consideration of the instantaneous voltage and current curves of Figs. 4 and 5 and the theoretical simplified equivalent circuit diagram of Fig. 6 representing only one full-wave rectifier of six valves. In Fig. 6, the Y-voltages of the transformer winding 41 are represented by two Y-connected winding groups 41*a* and 41*b* actually in parallel but shown separated to make the principle of operation more evident. The windings of the groups 41*a* and 41*b* are drawn in such positions in the diagram that these windings represent also the vector diagrams of the voltages therein. The instantaneous values of the Y-phase voltages A, B, and C are shown in the sine curves of Fig. 5.

The action of valves 45, 46, and 47 will first be considered. The voltages A, B, and C applied to the valves 45, 46 and 47, respectively, are displaced 120 degrees apart. It will first be assumed that the grid voltages are in phase with the anode-cathode voltages. Current will flow through the valve to which the greatest positive instantaneous anode voltage is applied and will continue to flow until transferred to the next valve by drop in the anode voltage of one valve and increase in anode voltage of the next. For example, current will be transferred from valve 46 to valve 47 when voltage B drops so far below

voltage C that discharge can no longer continue. For three-phase circuits, the current blocks illustrated by the current block I_B will necessarily be 120 degrees long. Owing to the fact that inductance is usually inherent or is inserted in rectifier circuits, the current block I_B is shown with a flat top to represent the smoothing effect of inductance.

If now the grid voltages are retarded 90 degrees in phase so that the valves do not become conducting until the anode voltage peaks are reached, the inductance in the circuit induces positive voltages which keep the valves conducting for a time even after the transformer voltages become negative. The current block $I_{B'}$ illustrates the current in the valve 46 when its grid is 90 degrees lagging. The current block $I_{B'}$ corresponds to the current block I_B except that it lags 90 degrees behind it. It will be observed, however, that during half the current block $I_{B'}$, the voltage B is positive and, during the other half, it is negative. The total power input, therefore, is zero and the average voltage is zero. This is the condition of zero power-factor on the alternating-current side and zero voltage and output on the direct-current side. I_B, however, represents the condition of maximum power and voltage. Since the direct-current circuit in question is a constant-current circuit, variations in power are represented by variations in voltage. With all valves grid controlled, therefore, the alternating-current power factor falls as the direct-current voltage falls.

If the direct-current circuit 43, 44 is capable of delivering power, power may be fed back into the transformers by retarding the grid voltages still further to cause the valves to act as inverters. The condition of maximum power as an inverter results when the grids are retarded 180 degrees. This condition is illustrated by the current block $I_{B''}$, which again represents 100% power factor on the alternating-current side, disregarding the slight reduction in power factor represented by the commutating angle.

If the valves 56, 57, and 58 are left without phase control, i. e., are permitted to become conducting as soon as the anode-cathode voltage is positive, these valves will deliver the full direct-current power and voltage that they are capable of delivering. In order to reduce the output when the load voltage is less than the maximum, the phase-shifting magnetic bridge 11 will continue shifting the grid voltages of valves 45, 46, and 47 until they act as inverters and they produce direct-current voltages opposing those produced by valves 56, 57, and 58 so that the net load voltage may be reduced to a minimum with both groups of valves carrying current at substantially unity power factor with respect to the transformers.

It is apparent that the terminal potentials of the winding groups 41*a* and 41*b* of Fig. 6 are identical and that, therefore, the same operation is obtained with all six valves connected to the transformer windings as in Fig. 1. The connection of Fig. 1, however, has the still further advantage that the inverter and rectifier currents flow in the same windings and, therefore, substantially cancel when the direct-current voltage and load are at a minimum.

When the two full-wave rectifiers 37 and 38 are connected in series as shown in Fig. 1 and the magnetic bridges 11 and 12 are adjusted for slightly different currents, minimum reactive volt-amperes flow in the transformer somewhat as explained in the foregoing paragraphs in connection with the operation of a full-wave rectifier with only half the valves grid controlled. Assuming that the direct-current load and voltage has been a maximum and begins to fall off, the rectifier adjusted for the higher current will continue to deliver full power at substantially unity power factor, but the rectifier adjusted for lower current will be controlled to reduce its output while retaining its power factor at a maximum. After the output of the first full-wave rectifier has been reduced to zero, the second magnetic bridge will come in operation to reduce the output of the second full-wave rectifier while retaining its power factor at a maximum. When the direct-current load increases, the same operations will, of course, take place in inverse order. It is evident that the greatest reactive volt ampere component drawn from the transformers under any condition of load is that corresponding to the current and voltage of one group of three valves instead of the sum of the volt amperes of each valve at maximum current and voltage.

If the system is intended to transfer full power either as a rectifier or as an inverter, it is necessary that all valves be grid controlled. However, an elimination of reactive volt amperes at low loads can still be obtained by adjusting the magnetic bridges 11 and 12 for slightly different currents. In this case, one group of six valves operates at full output and unity power factor either as rectifier or inverter as the case may be, while the second group is controlled by its magnetic bridge to vary the load. When the load falls below half the capacity of the system, the second group of valves acts in opposition to the first as inverter or rectifier until the power transfer is reduced to zero. When the direction of power transfer changes, control is transferred to the magnetic bridge controlling the first group of valves and the power is controlled in this group of valves until full power is transferred in the changed direction. While I have described rectifiers and combined rectifier-inverters employing two full-wave groups of valves in series and two current regulators, it will be understood that my invention is not limited thereto but may be carried out with any number of valve groups and their accompanying current regulators.

By constructing the magnetic bridge 11 in the manner shown in Fig. 1 with the two oppositely arranged nonlinear members or bridge portions 17 and 18, I am enabled to obtain a relatively great variation in the magnetomotive force acting upon the connecting members 23, 24, and 25 because, as the magnetic potential of the intermediate portion of one bridging member such as 17, increases, the magnetic potential of the intermediate portion of the other bridging member decreases and vice versa.

In magnetic bridges constructed as shown at 11 in Fig. 1, the connecting portions 23, 24, and 25 are subjected to reversals and variations in magnetomotive force for the reason that the ends of the connecting members are subjected to opposite variations in magnetic potential as the current in the winding 26 varies. The magnetic potential in the intermediate or polar portion of the bridging member 17 increases when the magnetic potential in the intermediate or polar portion of the bridging member 18 decreases and vice versa. The ends of the connecting members 23, 24, and 25 are, of course, at the same mag-

netic potential as the adjacent polar portions of the bridging members 17 and 18.

However, my invention is not limited to this precise arrangement. Qualitatively, the same effect may be obtained in the connecting members 23, 24, and 25 by means of any other suitable arrangement for varying the magnetic potentials at the ends or for maintaining the magnetic potential fixed at one end and varying the magnetic potential at the other end. For example, in Fig. 7 a modified construction is illustrated in which the bridging member 18' is magnetically symmetrical. That is, it has the same type and magnitude of reluctance, for example, constant reluctance air gaps 21' at either end so that the intermediate portion adjacent the right-hand end of connecting member 23 remains at substantially the same magnetic potential whether or not the current in the winding 26 varies. However, the distribution of reluctance in the bridge member 17 and, consequently, the magnetic potential of its intermediate portion adjacent the left-hand end of the connecting member 23 varies as explained in connection with Fig. 1 when the current in winding 26 varies. Consequently, as in the construction of Fig. 1, the connecting member 23 is subjected to reversals in magnetomotive force and the peak voltages in the secondary winding 30 are shifted in response to variations in current in the winding 26.

Another arrangement for maintaining the right-hand end of the connecting member 23 at substantially constant magnetic potential is shown in Fig. 8. In this case, the direct-current winding 26 is split into two portions 26A and 26B and the right-hand end of the connecting member 23 touches the midportion of the yoke 14. The left-hand end of the connecting member 23, however, is subjected to variations in magnetic potential causing reversals in the magnetomotive force acting upon the connecting member 23 in response to variations in current in the windings 26A and 26B as in the constructions of Fig. 1 and Fig. 7.

A modified rectifying system is illustrated in part in Fig. 2. In some cases where especially fine regulation or control of current is desired, this arrangement may be found to possess certain advantages over the arrangement of Fig. 1. It differs from the arrangement of Fig. 1 in that the magnetic bridges 11 and 12 are replaced by one or more magnetic bridges or balancing devices of the form illustrated at 81.

The magnetic-balancing device 81 also comprises a core of ferromagnetic material having a yoke portion 14 and arms 15 and 16 extending therefrom. The arms 15 and 16, however, are joined directly by the connecting portions 23, 24, and 25. As before, a direct-current winding 26 and alternating-current windings 27 to 32 are provided. For the sake of illustration, the discharge valves 56, 57, and 58 are shown with their control grids tied to their cathodes and the additional peak voltage secondary windings 33, 34, and 35 have been omitted from the magnetic-balancing device 81. This arrangement, therefore, illustrates a system to be used only for rectification. It will be understood, however, that the apparatus of Fig. 2 may also be provided with grid control of all the tubes, as shown in Fig. 1, in order that it may be used as an inverter as well as for rectification.

The magnetic-balancing device 81 carries an additional direct-current winding 82 linking the main magnetic circuit and bucking the winding 26. The winding 82 is fed by a direct-current generator 83 provided with a constant-current regulator 84 of any suitable type. Preferably, the winding 82 is provided with a relatively large number of turns so that a small current flowing therein will balance the ampere turns of the winding 26 connected in series with the load. A generator 83 having a relatively small current output will suffice and, consequently, a low-power generator may be employed. Neither the generator 83 nor the constant-current regulator 84 need be constructed to carry large currents or to withstand high voltages. Furthermore, there will be little tendency for rapid current changes to take place in the generator 83. For all of these reasons, the current in winding 82 may readily be held very closely to a constant value.

In case the current of the load circuit 43, 44 in the winding 26 increases above or falls below that balancing the current in winding 82, direct magnetomotive forces will be superimposed on the alternating magnetomotive forces produced in the connecting members 23, 24, and 25 by the alternating-current windings 27, 28, and 29. Consequently, as explained in connection with the magnetic bridges 11 and 12 of Fig. 1, current variations in the power circuit will produce variations in phase of the secondary voltages applied to the grids of the discharge valves 45, 46, and 47, thereby correcting the current variations substantially instantaneously. The direct-current circuit 43, 44 may be one of a large current capacity or may be a high-tension circuit in which a low-voltage device of the type used at 84 would be unsuitable.

It is apparent, therefore, that the arrangement of Fig. 2 permits a high-voltage high-power direct-current circuit to be controlled with the same accuracy as a low-voltage low-power circuit. Furthermore, the arrangement provides an exceedingly prompt response to variations in direct current. The speed of response is independent of the speed of response of the low-voltage constant-current regulator 84 and, therefore, not limited to the speed of response usually obtainable from such devices.

I have herein shown and particularly described certain embodiments of my invention and certain methods of operation embraced therein for the purpose of explaining its principle and showing its application but it will be obvious to those skilled in the art that many modifications and variations are possible and I aim, therefore, to cover all such modifications and variations as fall within the scope of my invention which is defined in the appended claims.

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

1. A magnetic bridge sensitive to variations in magnetomotive force comprising a core of magnetic material having a pair of arms spaced apart from each other, a yoke portion joining said arms at one end and adapted to be subjected to a magnetomotive force, a pair of bridging members between said arms forming parallel magnetic paths therebetween, each including an air gap and a saturating portion of reduced cross section on either side of a polar portion, and means responsive to a reversal of polarity of the magnetic field between the polar portions of said bridging members, the relative positions of the air gap and the saturating portion in one bridging member being reversed with respect to the relative positions of the corresponding parts in the other bridging member.

2. A magnetic bridge comprising a core of magnetic material providing a magnetic circuit, said core including a portion comprising members providing parallel magnetic circuits in series with the main magnetic circuit, and means responsive to the polarity of the cross magneto-motive force between said parallel core members, each of said parallel core members including a portion of variable reluctance and a portion of substantially constant reluctance, the relative positions of which are reversed in the two parallel core members, whereby variations in magneto-motive force in the main magnetic circuit above or below a predetermined value result in reversals in polarity of said cross magnetomotive force and actuation of said magnetic polarity responsive device.

3. A current-responsive device comprising a core of magnetic material carrying current-conducting windings and having a pair of arms spaced apart from each other, a yoke portion joining said arms at one end, a pair of bridging members between said arms forming parallel magnetic paths therebetween, each including an air gap and a saturating portion of reduced cross section on either side of a polar portion, and means responsive to a reversal in polarity of the magnetic field between the polar portions of said bridging members, the relative positions of the air gap and the saturating portion of one bridging member being reversed with respect to the relative positions of the corresponding parts in the other bridging member.

4. A magnetic bridge sensitive to variations in magnetomotive force comprising a core of magnetic material having a pair of arms spaced apart from each other and adapted to have a magnetomotive force impressed therebetween, a pair of yoke members joining said arms, one of said yoke members having a portion of variable reluctance nonsymmetrical with respect to the ends of said yoke member to form a nonlinear magnetic circuit element, a connecting member between intermediate portions of said yoke members, whereby said connecting member is subjected to reversals in polarity by variations in the magnetic potential of the intermediate portion of the nonlinear yoke member in response to variations in the magnetomotive force acting between said arms, and means responsive to reversal in polarity of said connecting member.

5. A magnetic bridge sensitive to variations in magnetomotive force comprising a core of magnetic material having a pair of arms spaced apart from each other and adapted to have a magnetomotive force impressed therebetween, a yoke member joining said arms having an intermediate portion and being magnetically substantially symmetrical from end to end with respect to said intermediate portion whereby the magnetic potential of said intermediate portion remains substantially unchanged as variations take place in the magnetomotive force between said arms and between the ends of said yoke member, a second yoke member also joining said arms and having an intermediate portion but having a portion of variable reluctance between said intermediate portion and one of the ends of said second yoke member, whereby the magnetic potential of said intermediate portion tends to vary as variations take place in the magnetomotive force between said arms and between the ends of said latter yoke member, and means responsive to variations in magnetomotive force between the intermediate portions of said yoke members.

6. A magnetic bridge sensitive to variations in magnetomotive force comprising a core of magnetic material having a pair of arms spaced apart from each other and a yoke member joining said arms at one end and adapted to be subjected to a magnetomotive force, a bridging member between said arms having an intermediate portion and, between said intermediate portion and one of said arms, a portion of variable reluctance, whereby the magnetic potential of said intermediate portion varies in response to variations in the magnetomotive force acting upon said member, a detecting member composed of magnetic material having one end adjacent the intermediate portion of said bridging member, means for maintaining the other end of said detecting member at substantially constant magnetic potential, and means responsive to variations in magnetomotive force acting upon said detecting member.

7. In a magnetic bridge sensitive to variations in magnetomotive force, the combination of a nonlinear member having ends adapted to have a magnetomotive force act therebetween, having an intermediate portion, and having a portion of variable reluctance between one end and the intermediate portion, whereby the magnetic potential of said intermediate portion varies in response to variations in the magnetomotive force between the ends of said nonlinear member, the reluctances of the portions of said member being so chosen that the intermediate portion is normally at zero magnetic potential, a linear magnetic member having ends adapted to have said magnetomotive force act therebetween and having an intermediate portion remaining at zero potential independently of variations in magnitude of said magnetomotive force, a detecting member connecting the intermediate portions of said magnetic member, and means responsive to variations in polarity of the magnetization of said connecting member.

8. A magnetic bridge comprising a pair of parallel magnetic circuit members adapted to be subjected to the same magnetomotive force and having intermediate portions dividing the magnetic circuit members into two parts each, at least one of these parts being nonlinear in characteristic, whereby the difference in magnetic potential between said intermediate portions varies in response to variations in said magnetomotive force, and means responsive to variations in the difference in magnetic potential between said intermediate portions.

9. A magnetic bridge comprising four magnetic circuit elements in series-parallel, at least one of which is nonlinear in flux-magnetomotive force characteristic, and means for comparing the magnetic potential drops in a series pair of magnetic circuit elements.

10. A magnetic bridge sensitive to variations in magnetomotive force comprising a core of magnetic material providing a magnetic circuit and adapted to be subjected to a magnetomotive force, a portion of the magnetic circuit provided by said core comprising a pair of magnetic members in parallel, each including a portion of variable reluctance and a portion of substantially constant reluctance, the relative positions of which are reversed in the two parallel members so that the magnetomotive force between said parallel members reverses in polarity when the magnetomotive force acting in the main magnetic circuit varies above or below a predetermined value, a member transversely connecting said parallel members, primary and secondary current-conducting windings on said transversely

connecting member, and means for applying an alternating current to said primary winding of such magnitude as to saturate said transversely connecting member, whereby peak voltages are induced in said secondary winding varying in phase with the magnitude of the magnetomotive force acting in the main magnetic circuit.

11. A magnetic bridge sensitive to variations in magnetomotive force comprising in combination, a core of magnetic material composed of a plurality of magnetic circuit elements including a pair of elements in series, at least one of which is nonlinear in characteristic, whereby a variation in magnetomotive force applied in said core results in a variation in the magnetic potential at the junction of said series pair of magnetic circuit elements, a detecting member of nonlinear magnetic material connected between the junction of said series pair of elements and another portion of said core, whereby the detecting member is subjected to variations and reversals in magnetization in response to variations in magnetomotive force applied in said core, alternating-current primary and secondary windings on said core, and means for applying an alternating current to said primary winding, whereby secondary voltages are induced shifting in phase in response to variations in magnetomotive force supplied in said core.

12. A phase shifter responsive to deviations in a direct current comprising a magnetic core providing a magnetic circuit, a portion of which consists of parallel branches at least one of which comprises a member of variable permeability magnetic material, a direct-current winding thereon carrying a current, to deviations in which the phase shifter is intended to respond, a second direct-current winding on said core, means for causing a constant current to flow therein of a value and polarity to balance the intended normal value of the deviating current, a primary alternating-current winding on one of said branch circuit members composed of variable permeability material, means for supplying sufficient current thereto to saturate said last mentioned branch circuit member, and a secondary winding on said branch circuit core member, whereby said branch circuit core member is subjected to reversals in polarity by direct-current deviations and peak voltages are induced in said secondary winding varying in phase with the direct-current deviations.

13. A phase shifter responsive to deviations in direct current comprising a magnetic core providing a magnetic circuit, a portion of which comprises a member of variable permeability magnetic material, a direct-current winding on said core carrying a current to the deviations in which the phase shifter is intended to respond, a second direct-current winding on said core, means for causing constant current to flow therein at a value and polarity to balance the intended normal value of the deviating current, a primary alternating-current winding on said variable permeability member, a secondary alternating current winding in inductive relation thereto and means for supplying sufficient current to said primary winding to saturate said variable permeability member whereby said latter member is subjected to reversals in polarity by direct-current deviations and peak voltages are induced in said secondary winding varying in phase with the direct-current deviations.

14. A magnetomotive force responsive device comprising a magnetic flux-conducting unit, a portion of which consists of parallel branches, at least one of which comprises a member of saturable magnetic material, means for applying to said unit a unidirectional magnetomotive force, a primary alternating-current winding on said last mentioned branch member, means for supplying alternating current to said winding to saturate said last mentioned branch member, and a secondary winding on said branch member, whereby peak voltages are induced in said secondary winding and the phase thereof is varied in response to variations in the magnetomotive force applied to said magnetic flux-conducting unit.

15. A magnetomotive force responsive device comprising a magnetic flux-conducting unit, a portion of which comprises saturable magnetic material, a primary alternating-current winding magnetically linking said saturable portion, means for applying to said unit a unidirectional magnetomotive force, means for supplying alternating current to said winding to saturate said saturable portion, and a secondary winding linking said saturable portion whereby peak voltages are induced in said secondary winding and the phase thereof is varied in response to variations in magnetomotive force applied to said unit.

16. A magnetic comparison device comprising in combination a magnetic core providing a magnetic circuit containing a portion comprising variable permeability magnetic material, means for producing a magnetomotive force of predetermined value in said core, means for producing an opposing magnetomotive force, a primary alternating-current winding on said variable permeability portion, means for supplying alternating current to said winding, and a secondary winding on said variable permeability portion, whereby peak voltages are induced in said secondary winding and the phase thereof is varied in response to variations in the resultant of the magnetomotive forces acting in said magnetic core.

17. A device for interconnecting direct current and alternating current circuits comprising a discharge valve having a control electrode, and a magnetic comparison device having a magnetic core with a saturable portion, a direct-current winding carried by said core and connected in series with said discharge valve, means for producing a magnetomotive force of predetermined value in said core, a primary alternating-current winding on said saturable portion, and a secondary winding also on said saturable core portion, said secondary winding being connected to said control electrode.

18. A device for interconnecting direct-current and polyphase alternating-current circuits comprising a plurality of pairs of discharge valves connected in series-multiple with respect to the direct-current circuit, the valves in each pair being in series and having their common terminal connected to one of the terminals of the polyphase circuit and the other terminals connected to the terminals of the direct-current circuit, and a phase-shifting direct-current responsive device having a direct-current winding in series with the direct-current circuit, alternating-current primary windings, each in inductive relation to one of the phases of the alternating-current circuit, and at least one secondary winding corresponding to each of said primary windings in which variable-phase alternating voltage is induced, at least one of the valves of each of said pairs hav-

ing a control electrode connected to one of said secondary windings.

19. A device for interconnecting a constant-current direct-current circuit and a polyphase alternating-current circuit comprising a plurality of pairs of discharge valves connected in series-multiple with respect to the direct-current circuit, the valves in each pair being in series and having their common terminal connected to one of the terminals of the polyphase circuit and the other terminals connected to the terminals of the direct-current circuit, and a phase-shifting direct-current regulator having a direct-current winding in series with the direct-current circuit, alternating-current primary windings, each in inductive relation to one of the phases of the alternating-current circuit, and at least one secondary winding corresponding to each of said primary windings in which variable phase alternating voltage is induced, at least one of the valves of each of said pairs having a control electrode connected to one of said secondary windings.

20. A device for interconnecting an alternating-current circuit and a direct-current circuit comprising at least one vapor discharge valve having an anode, a cathode, and a control electrode, a phase-shifting direct-current responsive device having a direct-current winding connected to the direct-current circuit in series with said discharge valve through its anode and cathode, said responsive device also having means for producing reversals in magnetic polarity in response to deviations from a predetermined value of current in said direct-current winding, a saturable core subjected to such reversals in polarity, an alternating-current primary winding on said core, and an alternating-current secondary winding on said core, said alternating-current circuit being connected to the anode and the cathode of said discharge tube and to the primary winding of said phase-shifting device and the secondary winding of said phase-shifting device being connected between the cathode and the control electrode of said discharge valve.

21. Apparatus for interconnecting alternating and direct-current circuits comprising, connected in series with respect to the direct-current circuit, a plurality of translating devices of the vapor discharge valve type having anodes connected to the alternating-current circuit and having control electrodes, for each translating device a phase-shifting direct-current regulator having a direct-current winding in series with said translating devices, at least one primary alternating-current winding and for each primary winding a secondary winding in which voltage is induced varying in phase with deviations from a predetermined value of current in said direct-current winding, each control electrode being connected to a secondary winding of the current regulator for the translating device including the control electrode, said regulators being adjusted for slightly different currents to cause said translating devices to be loaded progressively as the amount of power to be transferred between the alternating-current and direct-current circuits varies.

22. Apparatus for interconnecting alternating-current and direct-current circuits comprising, connected in series with respect to the direct-current circuit, a plurality of translating devices of the vapor-discharge valve type having anodes connected to the alternating-current circuit and having control electrodes, for each translating device a phase-shifting direct-current regulator having a direct-current winding in series with said translating devices and means for producing an alternating voltage shifting in phase in response to deviations from a predetermined value of current flowing in said direct-current winding, each control electrode being connected to the shifting phase voltage-producing means for the translating devices including the control electrode, said regulators being adjusted for supplying different currents to cause said translating devices to be loaded progressively as the amount of power to be transferred between the alternating-current and direct-current circuits varies.

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