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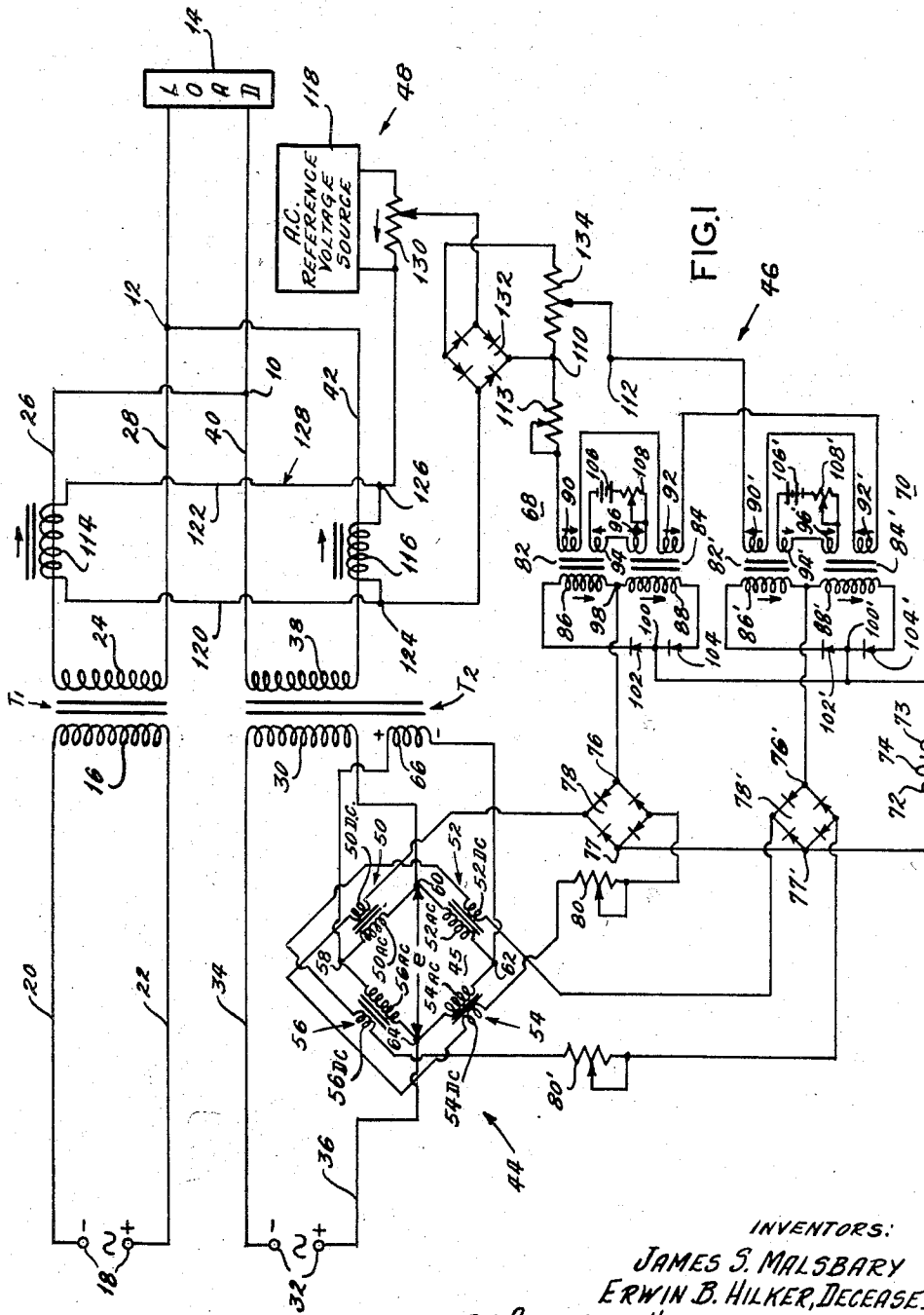
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CONTROL FOR PARALLEL CONNECTED A. C. SUPPLY CIRCUITS

Filed Dec. 11, 1957

2 Sheets-Sheet 1



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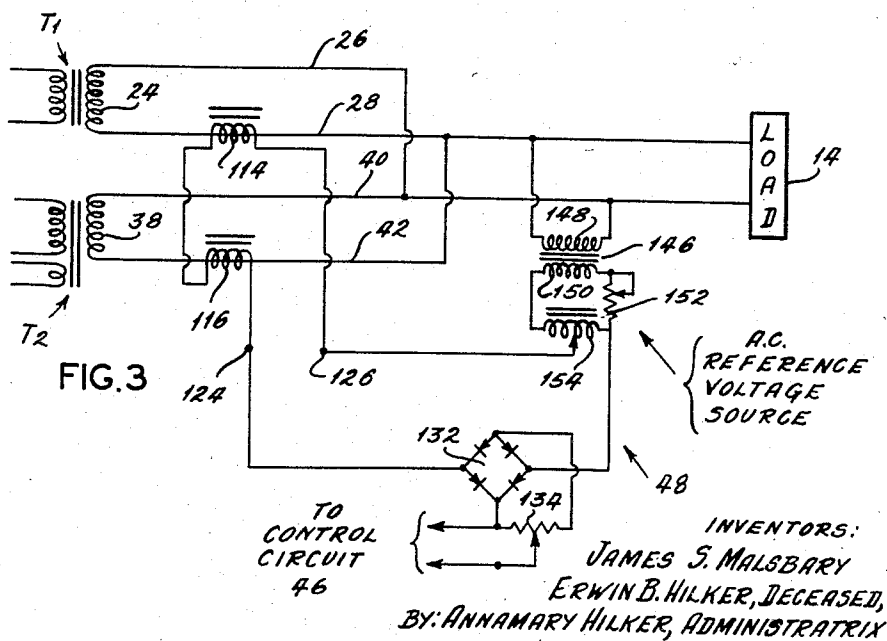
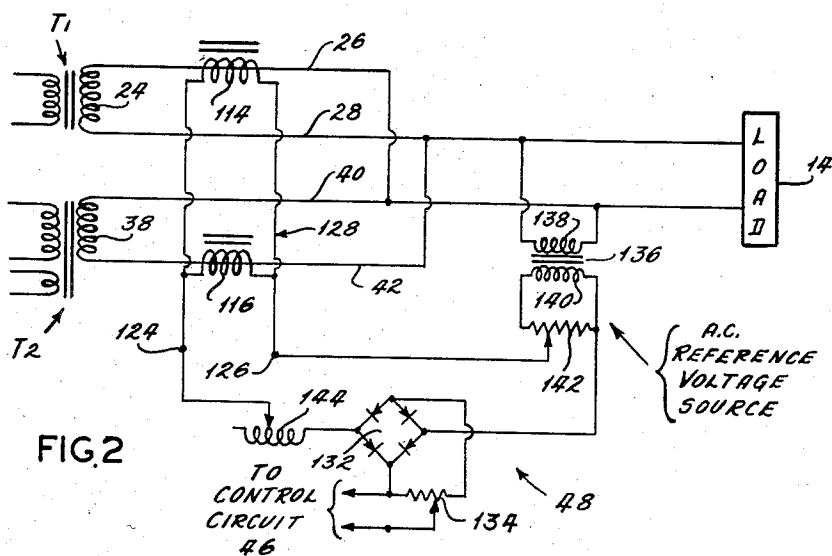
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CONTROL FOR PARALLEL CONNECTED A. C. SUPPLY CIRCUITS

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14 Claims. (Cl. 307—51)

This invention relates to control for parallel connected A. C. supply circuits and more particularly to means for automatically maintaining currents circulating between parallel operated supply circuits at a minimum.

When a plurality of A. C. supply circuits, such as power supply transformers are connected in parallel to supply power to a common power output circuit, circulating currents often flow in the parallel connection due to unequal output voltages of the transformers. These circulating currents often result in high losses in the system.

Transformers equipped with under-load tap changes have been connected in parallel with the switches of the tap changers synchronously operated by mechanical and electrical means in an attempt to maintain the output voltages of the transformers equal so as to obviate the flow of circulating currents. Such arrangements however have not been very satisfactory because they are based upon the assumption that both of the primary voltages of the transformers increase and decrease at a given time and by the same percentage. In many cases this assumption does not obtain.

Other arrangements have been suggested to overcome this difficulty but have been extremely complicated, expensive, or function unsatisfactorily.

It is therefore an object of the present invention to provide relatively simple and inexpensive means for automatically maintaining circulating currents between parallel connected A. C. supply circuits at a minimum.

Another object is to provide novel circuit means which automatically maintains circulating currents between parallel connected A. C. supply circuits at a minimum in a rapid and substantially noiseless manner.

Another object is to provide means for automatically maintaining the circulating currents between parallel operated A. C. supply circuits at a minimum and wherein the use of mechanical connections and switching or contacting devices are not required.

Still another object is to provide novel phase-sensitive voltage control means which automatically and continuously maintains the output voltages of parallel connected supply circuits substantially equal.

Briefly, in accordance with the present invention there is provided a phase-sensitive voltage control system in which the output voltage of one of a pair of parallel connected supply circuits is varied in accordance with the phase and magnitude of current circulating between the supply circuits and in a manner to reduce the circulating current or maintain it at a minimum.

Further objects and advantages of the present invention will be apparent from the detailed description, reference being had to the accompanying drawings wherein preferred embodiments of the present invention are shown.

In the drawings:

Fig. 1 is a schematic diagram of a preferred embodiment of the present invention, and

Figs. 2 and 3 are partial schematic circuit diagrams

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illustrating modifications of the current detecting apparatus shown in Fig. 1.

Referring to Fig. 1, there is shown for illustration two A. C. supply circuits including transformers T_1 and T_2 connected in parallel to supply power to a common power output circuit including terminals 10 and 12 to which is connected a load 14. The transformer T_1 has a primary winding 16 connected to an A. C. power input circuit 18 through a pair of conductors 20 and 22, and a secondary winding 24 connected to the power output terminals 10 and 12 by conductors 26 and 28, respectively. The transformer T_2 has a primary winding 30 connected to be energized from an A. C. power input circuit 32 through conductors 34 and 36 and a series connected network to be later described. A secondary winding 38 of transformer T_2 is connected in parallel with the secondary winding 24 and to the power output terminals 10 and 12 by conductors 40 and 42, respectively.

The power input circuits 18 and 32 may be supplied by a common A. C. supply source or may be connected to different sources of supply having voltages which are substantially cophasal and of the same frequency. Also, the transformer T_1 although shown as a standard transformer, may be provided with voltage control or regulation features if desired.

When the secondary voltages of the two transformers are equal no current circulates between the secondaries. However, if the secondary voltages tend to become unequal, for example, due to unequal voltages applied to the primaries or due to the transformers having unequal impedances, the transformer tending to have the higher secondary voltage will supply current to the secondary of the transformer having the lower secondary voltage. This current is referred to as circulating current and it flows in the parallel connection which includes the secondaries 24 and 38, and the conductors 26, 28, 40, and 42.

The present invention automatically reduces circulating currents flowing between parallel connected supply circuits and maintains them at low values. In the embodiments shown in the drawings the output voltage of transformer T_2 is varied in a manner which tends to maintain the output voltages of transformers T_1 and T_2 equal to thereby maintain the circulating currents at a minimum. This is accomplished by automatically controlling the output voltage of transformer T_2 in response to the magnitude and phase or direction of the current circulating between the parallel connected secondaries of the transformers.

As shown for illustration in Fig. 1, the output voltage of transformer T_2 is controlled or varied by means of a voltage control device indicated at 44. The voltage control device shown includes a Wheatstone type bridge circuit 45 for producing an adjusting or compensating voltage, indicated by the letter "e," which is combined with the supply voltage from circuit 32 for affecting the voltage applied to the primary winding 30. The magnitude and phase of the adjusting voltage "e" depend upon the balance conditions of bridge circuit as determined by a control circuit indicated at 46. The control circuit is in turn controlled in response to the output of a phase-sensitive current detector indicated at 48.

Referring now to the bridge circuit 45, it is shown including four saturable core reactors 50, 52, 54 and 56, each of which consists of an A. C. reactance winding and a D. C. control winding on a saturable magnetic core. In the drawing the reactance winding and control winding of each reactor are identified by like numbers with the letters D. C. or A. C. added thereto. The A. C. windings of the reactors are connected together and provide bridge corners 53, 60, 62, and 64.

If desired, each set of diametrically opposite reactors of the bridge circuit may be combined into a single reactor unit to form two reactor units, each unit having two A. C. reactance windings and a common D. C. control winding. For example, the diametrically opposite reactance windings of each set may be wound on the outer legs of a single three-legged core with a single D. C. control winding on the center leg.

The bridge corner 60 is connected to the lower end of primary winding 30 while the diametrically opposite bridge corner 64 is connected to one side of the input circuit 32 by the conductor 36. Across the other set of diametrically opposite bridge corners 58 and 62 is impressed an A. C. voltage. As shown for illustration, this voltage is supplied by means of an additional or auxiliary transformer winding 66 on the core of transformer T₂. Any suitable source of A. C. voltage may be used, for example, instead of the auxiliary winding 66, an additional transformer (not shown) may be employed. In such a case, the primary winding of the additional transformer may be connected, for example, across the power input circuit 32 while the secondary winding is connected across the bridge corners 58 and 62.

The magnitude of the A. C. voltage impressed across the bridge corners 58 and 62 determines the voltage control range of the device. For example, if it is desired to vary the output voltage within the range of $\pm 10\%$ of its normal value, the magnitude of voltage applied across these bridge corners by the auxiliary winding 66 would be approximately 10% of the supply voltage.

The D. C. control windings 50DC and 54DC of the bridge are shown connected in series with each other and the magnitude of the current flowing through them determines the impedance of the one set of A. C. reactance windings 50AC and 54AC. Similarly, the D. C. control windings 52DC and 56DC are shown connected in series with each other and the magnitude of the current flowing through them determines the impedance of the other set of A. C. reactance windings 52AC and 56AC. The balance conditions of the bridge are determined by the relative impedances of the two sets of opposed reactance windings. It will be assumed herein that when the currents flowing in the two sets of D. C. control windings are equal the impedances of all four A. C. reactance windings are equal and the bridge is balanced.

In accordance with the balance condition of the bridge circuit 45 the adjusting voltage "e," which appears across bridge corners 60 and 64, is substantially ineffectual, aiding the power supply voltage to increase the primary and secondary voltages of transformer T₂, or opposing the power supply voltage to decrease the primary and secondary voltages of transformer T₂. The bridge circuit permits the output voltage of transformer T₂ to be increased or decreased from its normal value in a stepless manner.

In Fig. 1 the bridge circuit 45 is conductively coupled into the primary side of transformer T₂, however, if desired, it may be coupled into either the primary or secondary side. Further, the bridge circuit may be coupled into the primary or secondary side by an additional transformer (not shown) instead of conductively connected as shown in Fig. 1. In such a case the primary winding of the additional transformer would be connected across the bridge corners 60 and 64 with the secondary winding connected in series with the primary or secondary winding of transformer T₂.

The control circuit 46 supplies the control currents to the two sets of D. C. control windings of the bridge. This control circuit includes a pair of amplifiers 68 and 70 which are shown in the drawing as magnetic amplifiers of the well-known self-saturating type. The parts of the amplifiers 68 and 70 are similar and like parts are identified by like numbers except that the numbers for the parts of amplifier 70 are primed. Also, where the amplifier circuits are similar, the detailed description will refer only to one of the circuits.

The amplifiers 68 and 70 are shown with a common power input circuit including a pair of input terminals 72 and 73 to which is connected an A. C. supply source indicated at 74 for supplying power to both amplifiers.

The amplifier 68 has an A. C. output circuit including a pair of terminals 76 and 77 which also form the A. C. input terminals of a full-wave rectifier 78. The D. C. output terminals of the rectifier 78 are connected to supply direct current to the one set of D. C. control windings 50DC and 54DC of the bridge circuit through an adjustable resistance 80. The amplifier 70 has an A. C. output circuit including a pair of terminals 76' and 77' which also form the A. C. input terminals of a full-wave rectifier 78'. The D. C. output terminals of rectifier 78' are connected to supply direct current to the other set of D. C. control windings 52DC and 56DC of the bridge circuit through an adjustable resistance 80'.

The amplifier 68 includes two saturable magnetic cores 82 and 84 having thereon reactance or power windings 86 and 88, respectively, D. C. control windings 90 and 92, respectively, and D. C. bias windings 94 and 96, respectively. The power windings 86 and 88 are each connected in a branch circuit with the branches connected in parallel between common junctions 98 and 100. The junction 98 is connected to the output terminal 76 and the junction 100 is connected to the A. C. input terminal 73. The other output terminal 77 is connected to the other A. C. input terminal 72. A one-way valve or half-wave rectifier 102 is connected in series with power winding 86 and a one-way valve or half-wave rectifier 104 is connected in series with the power winding 88. The half-wave rectifiers 102 and 104 are oppositely related or poled with respect to the supply voltage applied to the amplifier power input terminals 72 and 73 so that the rectifiers conduct current on opposite half cycles of the supply voltage and provide an A. C. output at the amplifier output terminals 76 and 77.

The bias windings 94 and 96 of amplifier 68 are connected to a source of bias current indicated in the drawing as a battery 106 and a series connected adjustable resistance 108. The bias current flowing in these windings flows in a direction to produce desaturating M. M. F.'s and the magnitude of the bias current is so adjusted that the output of amplifier 68 is low or at a minimum value for a predetermined low or minimum value of current flowing in the control windings 90 and 92.

Similarly, the bias windings of amplifier 70 are supplied with current from a bias source indicated as a battery 106' and a series adjustable resistance 108'. However, bias current flowing in the bias windings 94' and 96' flows in a direction to produce saturating M. M. F.'s and the magnitude of bias current is so adjusted that the output of amplifier 70 is high or at a maximum value for a predetermined low or minimum value of current flowing in the control windings 90' and 92'.

The control windings of both of the amplifiers 68 and 70 are shown connected in series with each other and are energized by the output of the detector 48. The output terminals of the detector are indicated at 110 and 112 with the terminal 110 connected to the upper end of winding 90 through an adjustable resistance 113 and with the terminal 112 connected to the upper end of winding 90'. The control windings 90 and 92 of amplifier 68 are wound and connected so that direct current from the detector output circuit flows in these windings in a direction to produce saturating M. M. F.'s which tend to increase the output of amplifier 68 when the direct current increases. The control windings 90' and 92' of amplifier 70, however, are wound and connected so that direct current from the detector output circuit flows in these windings in a direction to produce desaturating M. M. F.'s which tend to decrease the output of amplifier 70 when the direct current increases. If the current in the control windings decreases from some given value the output of amplifier 68 tends to decrease and the output of amplifier

70 tends to increase. Thus, the amplifiers are differentially or inversely controlled by the output of the detector 48, that is, the output of amplifier 68 is directly proportional to or varies in the same sense with respect to the output of the detector, while the output of amplifier 70 is inversely proportional to or varies in the opposite sense with respect to the output of the detector.

The direction of the M. M. F.'s resulting from current flow in each of the bias and control windings with respect to the direction of M. M. F.'s resulting from current flow in the power windings is indicated by the arrows adjacent the windings of the amplifiers.

The current detector 48 shown for illustration in Fig. 1 includes a pair of series or current transformers 114 and 116 arranged to produce a circulating current signal voltage which varies in magnitude and phase in accordance with the magnitude and phase or direction of currents circulating between the secondaries 24 and 38; and a reference voltage source, indicated at 118, for providing a properly phased substantially constant reference A. C. voltage. The phase of the reference voltage is chosen such that the signal voltage is substantially in-phase or 180° out of phase therewith depending upon the phase or direction of the circulating current. The signal voltage and reference voltage are compared or combined to produce a resultant control voltage at the detector output terminals 110 and 112.

As illustrated in Fig. 1, the current transformer 114 is connected in or coupled to the conductor 26 to obtain a voltage responsive to the flow of current in the secondary winding 24 while the current transformer 116 is connected in or coupled to the conductor 42 to obtain a voltage responsive to the flow of current in secondary winding 38. The secondaries of the two current transformers are connected in parallel with each other by a pair of conductors 120 and 122 which are connected to a pair of signal voltage terminals 124 and 126, respectively. The parallel circuit which includes the secondaries of the current transformers and conductors 120 and 122 is indicated generally by the numeral 128. The voltage source 118 is connected to supply an A. C. reference voltage across an adjustable resistance 130. The resistance 130 or a portion thereof is connected in series circuit relation with the parallel circuit 128 and the A. C. terminals of a full-wave rectifier 132. The D. C. terminals of the rectifier 132 are connected across an adjustable resistance 134. The movable arm of the resistance 134 is connected to terminal 112 while the left-hand end thereof is connected to the output terminal 110.

The current transformers 114 and 116 in Fig. 1 are so connected and arranged with respect to each other that when the output voltages of transformers T₁ and T₂ are equal and no current is circulating between the secondaries 24 and 38, the voltages induced in the secondary windings of the current transformers due to the load currents are substantially equal and in series aiding relation to cause induced current to flow in the parallel circuit 128. Because these induced voltages are equal and in series aiding relation, substantially no voltage appears across the signal voltage terminals 124 and 126.

In the example operation of the invention which follows, it will be assumed that when no circulating current flows between the secondary windings 24 and 38, the output voltages of the power supply transformers are equal with the bridge circuit 44 balanced. Thus, under these operating conditions the detector 48 is adjusted, for example by adjusting resistances 130 and 134, to provide a predetermined magnitude of output voltage with the amplifiers 68 and 70 being adjusted and related to produce equal output currents to thereby provide equal control currents to the D. C. control windings of the two sets of diametrically opposed bridge reactors and to thereby balance the bridge circuit.

In operation, if for any reason the secondary or output voltage of transformer T₂ tends to become greater than

the secondary or output voltage of transformer T₁, transformer T₂ supplies circulating current to transformer T₁. This circulating current component flows between the secondary windings 24 and 38 inducing voltages in the secondary windings of the current transformers 114 and 116. These induced voltages due to circulating current are in series opposing relation, that is, they oppose or buck one another tending to prevent induced current flow in the parallel circuit 128. Because these induced voltages are in opposing relation a voltage exists across the parallel circuit and the terminals 124 and 126. Since transformer T₂ is supplying the circulating current component, the phase or direction of the circulating current component is such that the induced voltages in the secondaries of the current transformers are in phase-opposition with respect to the reference voltage across resistance 130 (as indicated by arrows adjacent the secondaries of transformers 114 and 116 and the voltage source 118, Fig. 1). Thus, the signal voltage across terminals 124 and 126 is in phase-opposition with the reference voltage so that the resultant output voltage of the detector decreases in magnitude from its original predetermined value.

The decrease in output voltage of the detector decreases the current flowing in the control windings of the amplifiers 68 and 70 thus decreasing the output current of amplifier 68 and increasing the output current of amplifier 70. The decrease in output current of amplifier 68 reduces the D. C. current flowing in the control windings 50DC and 54DC of the bridge circuit 45 thereby increasing the impedance of reactance windings 50AC and 54AC. The increase in output current of amplifier 70 increases the D. C. current flowing in the control windings 52DC and 56DC thereby reducing the impedance of reactance windings 52AC and 56AC. Since the impedance of reactance windings 52AC and 56AC is lower than the impedance of windings 50AC and 54AC the bridge circuit 45 is unbalanced; and, from the instantaneous polarity signs shown adjacent the input circuit 32 and auxiliary winding 66, it is seen that the bridge corner 64 becomes positive with respect to the bridge corners 60 and that the adjusting voltage "e" across these corners opposes or is substantially in phase-opposition with the supply voltage for transformer T₂ to thereby reduce the voltage across primary 30. Thus, the secondary voltage of transformer T₂, which was higher than the secondary voltage of transformer T₁ is now reduced so that it substantially equals or approaches the secondary voltage of transformer T₁ thereby reducing or limiting to a low value the current circulating between the secondary windings 24 and 38.

On the other hand, if the output voltage of transformer T₁ becomes greater than the output voltage of transformer T₂, transformer T₁ supplies circulating current to the transformer T₂. This circulating current component flows between the secondary windings 24 and 38 inducing voltages in the secondary windings of the current transformers 114 and 116. The induced voltages are again in series opposing relation, that is, they oppose or buck one another tending to prevent induced current flow in the parallel circuit 128. Since these induced voltages are in opposing relation a voltage again exists across the parallel circuit and the signal voltage terminals 124 and 126. Because transformer T₁ is supplying the circulating current component, the phase or direction of the circulating current component is such that the induced voltages in the secondaries of the current transformers are in-phase with the reference voltage. Thus, in this case, the signal voltage across terminals 124 and 126 is substantially in-phase with the reference voltage so that the resultant output voltage of the detector increases in magnitude from its original predetermined value.

The increase in output voltage of the detector increases the current flowing in the control windings of the amplifiers 68 and 70 thus increasing the output current of amplifier 68 and decreasing the output current

of amplifier 70. The increase in output current of amplifier 68 increases the D. C. current flowing in the control windings 50DC and 54DC of the bridge circuit thereby decreasing the impedance of reactance windings 50AC and 54AC. The decrease in output current of amplifier 70 decreases the D. C. current flowing in the control windings 52DC and 56DC thereby increasing the impedance of reactance windings 52AC and 56AC. The bridge circuit is thus unbalanced and the adjusting voltage "e," due to these unbalanced bridge conditions, is in-phase with the power supply voltage for transformer T₂ and therefore increases the primary and secondary voltages. Thus, the secondary or output voltage of transformer T₂ is now increased so that it substantially equals or approaches the secondary voltage of transformer T₁ thereby reducing or limiting the currents circulating between the secondary windings 24 and 38 to low values.

Thus, when the output voltages of the supply transformers tend to become unequal, the output voltage of transformer T₂ is always automatically varied in a direction (increasing or decreasing) to reduce the difference in the output voltages and thereby reduce the circulating currents or maintain them at low values.

Where each of the parallel connected power supply transformers T₁ and T₂ in Fig. 1 has the same k. v. a. rating, each will supply the same magnitude of load current when the output voltages are equal. In such a case the current transformers 114 and 116 each have the same turns-ratio so that the equal load currents will induce equal voltages in their secondaries. On the other hand, where each of the parallel connected supply transformers has a different k. v. a. rating, each will supply a different magnitude of load current when the output voltages are equal. In the latter case, the current transformers 114 and 116 have different turns-ratios and are designed such that the induced voltages in their secondaries are equal although the load currents are normally unequal.

There is illustrated in Fig. 2 a partial schematic diagram of the circuit of Fig. 1 showing a modified form of the phase-sensitive current detector circuit 48. In this circuit the reference voltage is obtained by means of a transformer 136 having a primary winding 138 conveniently connected across the power output circuit and a secondary winding 140 connected across an adjustable resistance 142. A reactor 144, shown as an adjustable inductance and which will be discussed more fully hereinafter, is connected in the series circuit which includes the rectifier 132, resistance 142 and the parallel circuit 128.

The sensitivity of the detector circuit is best when the signal voltage, depending upon the phase or direction of the circulating current, is in-phase or 180° out of phase with the reference voltage. However, it has been found that the circulating current voltages appearing across terminals 124 and 126 are not generally in-phase or 180° out of phase with the power input or output voltages but at some intermediate phase angle therewith. Thus, in the circuit shown in Fig. 2 where the reference voltage is derived from the power output or load voltage the adjustable reactor 144 is employed to bring about proper phase relations in the detector circuit in order to obtain proper sensitivity of the detector. By properly proportioning the reactance and resistance in the detector circuit of Fig. 2 the current due to a signal voltage appearing across terminals 124 and 126 is shifted in phase so that the resultant voltage drop across that part of the resistance 142 which carries both the signal current and current from the reference voltage transformer 136 is substantially in-phase or 180° out of phase with the signal voltage.

Another modified form of the detector circuit is illustrated in Fig. 3. In this circuit arrangement the current transformer 114 is connected in or coupled to the conductor 28 and the current transformer 116 is connected

in or coupled to the conductor 42. The secondary windings of the two current transformers are connected in series with each other across the signal voltage terminals 124 and 126. The reference voltage is obtained by means of a transformer 146 having a primary winding 148 connected across the power output or load circuit and a secondary winding 150 connected across a phase shifting circuit which includes an adjustable resistance 152 and an adjustable reactance 154 connected in series with the resistance 152.

The phase shifting circuit in Fig. 3 provides means for obtaining a properly phased reference voltage. With suitable values of reactance and resistance, the reference voltage, which appears across the reactor 154 or a portion thereof, is substantially in-phase or 180° out of phase with a signal voltage appearing across terminals 124 and 126 due to the flow of circulating current in the secondaries of the supply transformers.

The current transformers in Fig. 3 are so connected and arranged with respect to each other that when no current circulates between the secondaries of the power supply transformers T₁ and T₂, the voltages induced in the series-connected secondary windings of the current transformers, due to the flow of load currents, are substantially equal and in opposing relation. Thus, when no circulating current is present substantially no voltage appears across the signal terminals 124 and 126 and the output voltage of the detector is then at its predetermined magnitude to thereby energize the amplifiers in control circuit 46 in a manner to balance the bridge circuit since no change in the voltage of transformer T₂ is required.

If circulating current begins to flow between the secondaries 24 and 38 due to unequal output voltages of the supply transformers, the circulating current component induces voltages in the series-connected secondaries of the current transformers which are in series aiding relation with respect to each other. Thus, a circulating current signal voltage appears across the terminals 124 and 126, the phase of the signal voltage, of course, being dependent upon the phase or direction of the current circulating between the secondaries 24 and 38. The signal voltage is combined with the reference voltage to energize the amplifiers in the control circuit 46 in such manner that the bridge circuit is unbalanced to provide a proper adjusting voltage "e" which changes the output voltage of transformer T₂ so that it equals or approaches the magnitude of the output voltage of transformer T₁ thus reducing the circulating current or maintaining it at low values.

It will be apparent that the operation of the apparatus shown and described is rapid and maintains the magnitude of the circulating currents at low values or within predetermined low limits when the output voltages of the power supply transformers tend to become unequal. Also, switching and contacting devices, such as tap changers, relays, etc., are not required, thus the apparatus operates rapidly, smoothly, and substantially noiselessly.

While parallel-connected single-phase supply circuits have been shown and described herein, this invention can equally well be used in conjunction with parallel-connected three-phase or other polyphase supply circuits.

It is to be understood that the foregoing description and the accompanying drawings have been given only by way of illustration and example, and that changes and alterations in the present disclosure, which will be readily apparent to one skilled in the art, are contemplated as within the scope of the present invention which is limited only by the claims which follow.

What is claimed is as follows:

1. In an A. C. supply system comprising a plurality of supply circuits interconnected to supply power to a common output circuit, the combination therewith of means for producing a signal responsive to the magnitude

and phase of current circulating between the supply circuits as a result of a difference in the voltages of the supply circuits, and phase sensitive voltage control means responsive to said signal for varying the voltage of one of said supply circuits in a direction to reduce the difference in the voltages of the supply circuits.

2. In an A. C. supply system comprising a plurality of supply circuits interconnected to supply power to a common output circuit, the combination therewith of first voltage producing means responsive to the flow of current in one of said supply circuits, second voltage producing means responsive to the flow of current in another of said supply circuits, means interconnecting said first and second voltage producing means to produce a signal voltage responsive to the magnitude and phase of current circulating between the supply circuits due to an inequality in the output voltages of the supply circuits, and phase sensitive voltage control means for varying the voltage of one of said supply circuits in response to said signal voltage and in a direction to reduce the flow of circulating current.

3. In an A. C. supply system comprising a pair of supply circuits connected in parallel to supply power to a common output circuit, the combination therewith of first transformer means for producing a voltage responsive to the flow of current from one of said supply circuits, second transformer means for producing a voltage responsive to the flow of current from the other of said supply circuits, means interconnecting said first and second transformer means to produce a signal voltage responsive to the magnitude and phase of current circulating between the supply circuits as a result of a difference in the voltages of the supply circuits, a reference voltage source, means for combining said reference voltage with said signal voltage to produce a resultant control voltage, and voltage control means for varying the output voltage of one of said supply circuits in response to said control voltage to reduce the difference in the voltages of the supply circuits.

4. In an A. C. supply system comprising a pair of supply transformers each having a secondary winding connected to supply power to a common output circuit, the combination therewith of first transformer means for producing a first voltage responsive to the flow of current from the secondary winding of one of said supply transformers, second transformer means for producing a second voltage responsive to the flow of current from the secondary winding of the other supply transformer, means interconnecting said first and second transformer means in a manner to produce a signal voltage which varies in magnitude and phase in accordance with the magnitude and phase of current circulating between said secondary windings, means for producing a reference voltage, means for combining the signal voltage with the reference voltage to produce a resultant control voltage, and voltage control means for varying the output voltage of one of said supply transformers in response to said control voltage, said control means including means for producing a variable phase compensating voltage.

5. In an A. C. supply system comprising a plurality of supply circuits connected in parallel to supply power to a common output circuit, the combination therewith of a set of terminals, first voltage producing means responsive to the flow of current from one of said supply circuits, second voltage producing means responsive to the flow of current from another of said supply circuits, means interconnecting said first and second voltage producing means to produce a signal voltage between said set of terminals which varies in magnitude and phase in accordance with the magnitude and phase of current circulating between the supply circuits, a reference voltage source, phase shifting means, means interconnecting said terminals, said voltage source and said phase shifting means to produce a resultant control voltage which varies in magnitude above and below a predetermined

value in accordance with the phase and magnitude of said signal voltage, and voltage control means for varying the output voltage of one of said supply circuits in response to said control voltage.

6. In an A. C. supply system comprising first and second supply circuits interconnected to supply power to a common output circuit and wherein circulating current flows in the supply circuits when an inequality in their voltages exists, the combination therewith of a pair of circuit terminals, means for producing a signal voltage across said terminals which varies in magnitude and phase in accordance with the magnitude and phase of said circulating current, said means comprising a first current transformer connected between the first supply circuit and the common output circuit, a second current transformer connected between the second supply circuit and the common output circuit, and means interconnecting the secondaries of said first and second current transformers in circuit between said terminals, said current transformers being so related with respect to each other that substantially no voltage exists across said terminals when the voltages of said supply circuits are equal, means for generating a reference voltage in circuit with said signal voltage to produce a resultant control voltage from the combination thereof, and voltage control means responsive to said control voltage and associated with one of the supply circuits for varying the voltage of said one supply circuit in a direction to reduce the flow of circulating current.

7. In an A. C. supply system comprising first and second supply circuits interconnected to supply power to a common output circuit and wherein circulating currents flow in the supply circuits when an inequality in the voltages of the supply circuits exists, the combination therewith of a pair of terminals, means for producing a signal voltage across said terminals which varies in magnitude and phase in accordance with the magnitude and phase of circulating current, said means comprising a first current transformer connected between the first supply circuit and the common output circuit, a second current transformer connected between the second supply circuit and the common output circuit, and means interconnecting the secondaries of said first and second current transformers in circuit between said terminals, said current transformers being so connected with respect to each other that substantially no voltage exists across said terminals when the voltages of said supply circuits are equal, means for generating a reference voltage in the circuit with said signal voltage to produce a resultant control voltage, and voltage control means including a Wheatstone type bridge circuit connected into one of said supply circuits for controlling the voltage of said supply circuit in response to said control voltage.

8. In an A. C. supply system comprising a pair of supply circuits connected in parallel to supply power to a common output circuit, the combination therewith of first transformer means for producing a voltage responsive to the flow of current from one of said supply circuits, second transformer means for producing a voltage responsive to the flow of current from the other of the supply circuits, means interconnecting said first and second transformer means to produce a signal voltage which varies in magnitude and phase with current circulating between the supply circuits due to an inequality in voltage of the supply circuits, means for producing a reference voltage in the circuit with said signal voltage to produce a resultant control voltage, means responsive to the control voltage connected to one of said supply circuits for producing a variable phase voltage that affects the voltage of said one supply circuit, said last named means comprising a Wheatstone type bridge circuit including two sets of opposed saturable reactors, each set having at least one D. C. control winding, a first source of current for supplying a first D. C. current to the D. C. control winding of one set of reactors, a

second source of current for supplying a second D. C. current to the D. C. control winding of the other set of reactors, and means for varying said first and second D. C. currents inversely in response to said control voltage.

9. In an A. C. supply system comprising a pair of power supply transformers each having a secondary winding connected to supply power to a common output circuit, the combination therewith of a first current transformer for producing a voltage responsive to the flow of current from the secondary winding of one of said supply transformers, a second current transformer for producing a voltage responsive to the flow of current from the secondary winding of the other of said supply transformers, means interconnecting said first and second current transformers in a manner to produce a signal voltage which varies in magnitude and phase with the magnitude and phase of current circulating between the supply circuits when an inequality in output voltage of the supply transformers exists, means for generating a reference voltage in the circuit with said signal voltage to produce a resultant control voltage from the combination thereof, means connected with one of said supply transformers for producing a variable phase voltage for affecting the output voltage thereof, said last named means comprising a Wheatstone type bridge circuit including two sets of opposed saturable reactors, each set of reactors having at least one D. C. control winding, a first amplifier having an output circuit connected to supply a first D. C. current to the D. C. control winding of one set of reactors, a second amplifier having an output circuit connected to supply a second D. C. current to the D. C. control winding of the other set of reactors, and amplifier control means for inversely varying said first and second D. C. currents in response to variations of said control voltage.

10. In combination with an A. C. supply system comprising a pair of power supply circuits connected in parallel to supply power to a common output circuit, means for maintaining circulating currents in said supply circuits at a minimum, said means comprising a first current transformer for producing a voltage responsive to the flow of current in one of said supply circuits, a second current transformer for producing a voltage responsive to the flow of current in the other of said supply circuits, means interconnecting the secondary windings of said first and second current transformers to produce a signal voltage which varies in magnitude and phase with current circulating between the supply circuits, means for generating a reference voltage in circuit with said signal voltage to produce a resultant control voltage from the combination thereof, means responsive to the control voltage for producing a variable phase voltage for affecting the output of one of said supply circuits, said last named means comprising a Wheatstone type bridge circuit including two sets of opposed saturable core reactors and two sets of opposed bridge corners, one set of opposed bridge corners being connected in series circuit relation with said controlled supply circuit, and means for impressing an A. C. voltage across the other set of corners, each set of reactors having at least one D. C. control winding; a first magnetic amplifier having an output circuit connected to supply a first current to the D. C. control winding of one set of reactors, a second magnetic amplifier having an output circuit connected to supply a second current to the D. C. control winding of the other set of reactors, and magnetic amplifier control means for inversely varying said first and second currents in response to variations of said control voltage.

11. In an A. C. supply system comprising a pair of supply transformers, a common power output circuit, a first set of conductors connecting the secondary winding of one of the supply transformers with the power output circuit, and a second set of conductors connecting the secondary winding of the other supply transformer with the power output circuit, the combination therewith of

means for maintaining circulating currents in the supply transformers at a minimum, said means comprising a first current transformer coupled to one of the conductors of said first set of conductors, a second current transformer coupled to one of the conductors of said second set of conductors, means interconnecting the secondary windings of said first and second current transformers to produce a signal voltage which varies in magnitude and phase in accordance with magnitude and phase of the circulating current, means producing a substantially constant voltage from said supply system, circuit means including phase shifting means in which said signal voltage is combined with said constant voltage to produce a resultant control voltage which varies in magnitude above and below a predetermined value in accordance with the phase and magnitude of said signal voltage, and voltage control means connected in circuit with one of said supply transformers for varying the output voltage of said supply transformer in response to changes in the magnitude of said control voltage in a direction to minimize the circulating current.

12. In an A. C. supply comprising a pair of supply circuits, a common power output circuit, a first set of conductors connecting one of the supply circuits with the power output circuit, and a second set of conductors connecting the other supply circuit with the power output circuit, the combination therewith of means for maintaining circulating currents in the supply circuits at a minimum, said means comprising a first current transformer coupled to one of the conductors of said first set of conductors, a second current transformer coupled to one of the conductors of said second set of conductors, a pair of terminals, means connecting the secondary windings of said current transformers in parallel to produce across said terminals a signal voltage varying in magnitude and phase with the magnitude and phase of said circulating current, a reference voltage source connected in circuit with said terminals to produce a control voltage variable in magnitude above and below a predetermined value in accordance with the magnitude and phase of said signal voltage, and voltage control means in circuit with one of said supply circuits for varying the output voltage of said one supply circuit in response to variations of said control voltage.

13. In an A. C. supply system comprising a pair of supply circuits, a common power output circuit, a first set of conductors connecting one of the supply circuits with the power output circuit, and a second set of conductors connecting the other supply circuit with the power output circuit, the combination therewith of means for maintaining circulating currents in the supply circuits at a minimum, said means comprising a first current transformer coupled to one of said first set of conductors, a second current transformer coupled to one of said second set of conductors, means connecting the secondary windings of said current transformers in series with each other to produce a signal voltage variable in magnitude and phase with the varying magnitude and phase of said circulating current, means for generating a reference voltage in the circuit with said signal voltage to produce a resultant control voltage variable in magnitude above and below a predetermined value in accordance with the magnitude and phase of said signal voltage, and voltage control means associated with one of said supply circuits for varying the output voltage of said supply circuit in response to variations of said control voltage.

14. An A. C. supply system comprising a plurality of power supply components connected in parallel for supplying power to a single source, one of said components having an auxiliary component associated therewith, a separate input and output for each component, first voltage responsive means coupled to the output of one of said components, second voltage responsive means coupled to the output of another of said components, said first and second voltage responsive means being connected together in a circuit to produce a resultant signal voltage

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which varies in response to the magnitude and polarity of the inequality in the outputs of said components, generator means producing a reference voltage connected to combine said reference voltage with the signal voltage to produce a control voltage therefrom, a reactance bridge circuit including two sets of opposed bridge corners, one set of said corners being connected in circuit with the input of one of said components and the other set of said

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bridge corners being connected across the auxiliary component associated therewith, and amplifier means connected to communicate the control voltage with said bridge circuit for varying the impedance of the bridge circuit in a direction to equalize the outputs from said components.

No references cited.