

April 19, 1966

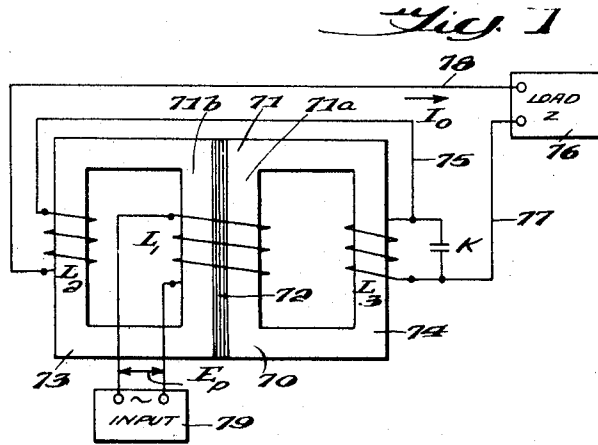
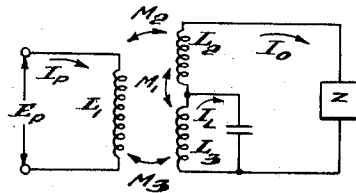
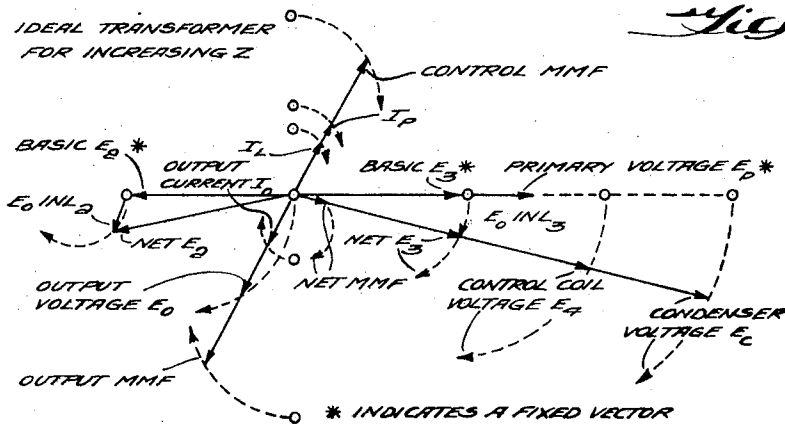
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3,247,450

TRANSFORMER APPARATUS

Original Filed March 15, 1957

3 Sheets-Sheet 1



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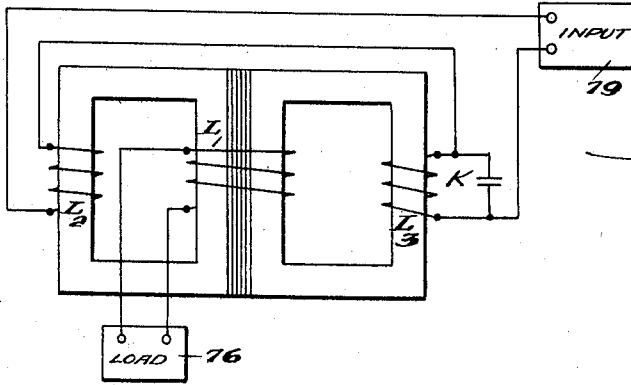


Fig. 4

Fig. 5

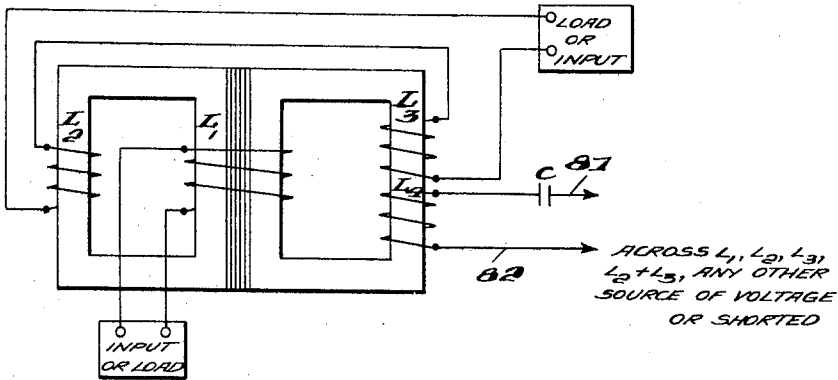
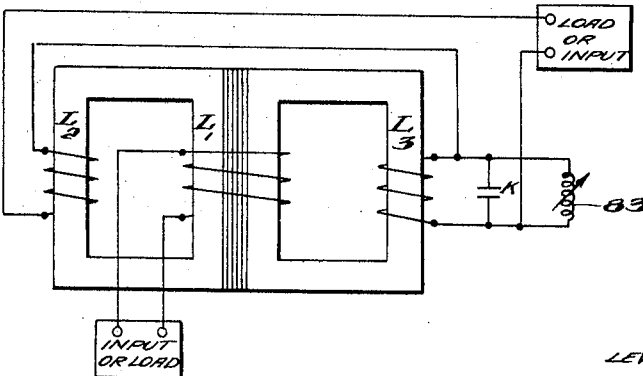


Fig. 6



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3 Sheets-Sheet 3

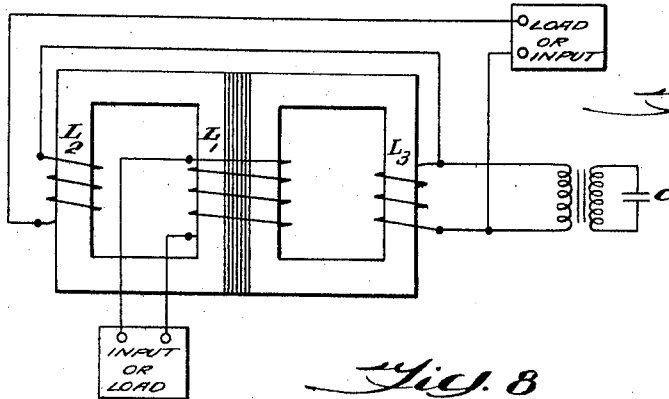


Fig. 7

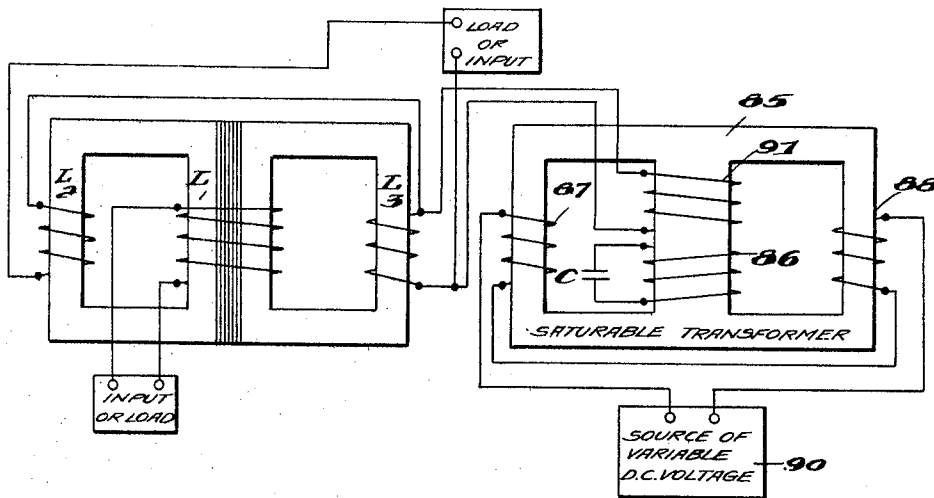
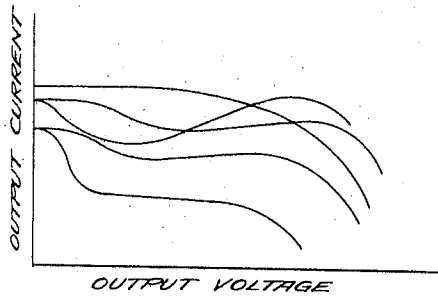


Fig. 9



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3,247,450

TRANSFORMER APPARATUS

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Original application Mar. 15, 1957, Ser. No. 646,429, now Patent No. 2,999,973, dated Sept. 12, 1961. Divided and this application Aug. 21, 1961, Ser. No. 132,846
10 Claims. (Cl. 323-60)

This invention relates to a transformer system for supplying power from an A.-C. input to a load, and, more particularly, to a transformer system for supplying a substantially constant current to a load subject to variations of impedance. This application is a division of my co-pending application Serial Number 646,429, filed March 15, 1957, and now U.S. Patent 2,999,973.

As will be understood after the following explanation, the transformer system of this invention is capable of supplying a large number of different characteristic outputs. Among such outputs are a characteristic rise of current output with increasing load, a characteristic drop of current output with increasing load, and a substantially constant current output with increasing load. The invention will be more fully described in conjunction with the last-mentioned characteristic, which is preferred, but it will be understood that the invention is not limited to this characteristic.

In the past, several different means of obtaining a substantially constant current output with changing load impedance have been evolved. Perhaps the earliest of these various systems is that using a movable coil, the coil being counter-balanced and automatically adjusted in accordance with changing load to vary the distance between the input and output sides of the transformer and thereby to vary the coupling. This system is still in use today for constant current lighting systems, but it is subject to several disadvantages, among which are poor speed of response, the substantial expense of the system, the bulkiness of the unit, and the use of moving parts subject to wear and eventual shutdown of the system.

Another past-suggested constant current apparatus uses a saturable core reactor. The reactor may be a relatively simple one or may be a complex system utilizing shunts, partial air gaps, etc. This type of system, however, is relatively expensive, as well as being complex. Moreover, it has a lagging power factor.

A third general type of known constant current system is one using a resonance phenomenon. This type of system has taken many forms, but the simplest form is the series resonant circuit, including an inductive reactance and a capacitive reactance connected in series, the two reactances being adjusted to be substantially equal, and the load being connected across one of the reactances. While this type of system provides quite good constancy of output current, it has been found necessary to provide auxiliary means to limit the voltages across the components on open circuit. Moreover, this type of system is not readily adjustable to change the level of output current which is to be maintained constant. In order to provide for such change, there must be a change in both the actual inductance and the actual capacity of the components.

Another adaptation of the resonant system is the so-called "monocyclic square." This system is subject to several of the disadvantages enumerated above for the simple series resonant system.

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In contrast to all of the above previously suggested systems, the transformer system of the present invention provides a substantially constant current output at high efficiency, with no moving parts, with no need for auxiliary units to limit component voltages on open circuit, with relatively easy adjustment of the parts to change the level of output current to be maintained constant, and for a substantially lower cost than many of the previous systems.

The transformer system of this invention is in the nature of a resonant phenomenon, but, as will be obvious from the theoretical analysis to follow, it is far from a simple resonant phenomenon. None of the various embodiments of the invention to be described uses a simple series resonant circuit, and all of the embodiments actually automatically adjust themselves to maintain a substantially resonant condition even with change of only one of the components, such as change in capacity. The system is not dependent for its operation upon leakage reactance or on saturation of the core or any of its components, and the system actually is *limited* and adversely affected in its operation by these ever-present effects.

One important advantage of the transformer system of this invention is the fact that it draws a leading power factor current from the input, rather than the lagging power factor usually obtained with a transformer system.

The apparatus of the present invention is capable of use wherever it is desired to draw a substantially constant current through a variable load, when a constant voltage input is provided. One instance of such use is in lighting systems.

The apparatus of the present invention, generally described, includes an input, an output, and a control electrical circuit, each of these circuits including at least one coil which may be wound on a transformer core. The coils of the input and output electrical circuits are so inductively related, wound and connected with respect to one another that two magnetic circuits, an input and an output, are formed. The magnetic circuits have two common portions, in one of which the magnetomotive forces generated by the input and output currents aid, and in the other of which the magnetomotive forces generated by these currents oppose. As a result, there is no direct coupling of power between the input circuit and the output circuit. The control electrical circuit includes a capacitor and is inductively coupled to one of the coils of the input and output circuits through one of the common portions of the magnetic circuits. Current through the control circuit generates a magnetomotive force which is opposite in phase and of greater magnitude than the output magnetomotive force in the common portion through which the coupling takes place. The control magnetomotive force in effect reverses the output magnetomotive force in said common portion of the magnetic circuit and hence couples power from the input to the output through the control electrical circuit.

The invention will now be described in conjunction with the accompanying drawings, showing preferred embodiments thereof.

In the drawings:

FIG. 1 is a schematic diagram of a transformer apparatus constructed in accordance with the invention;

FIG. 2 is an equivalent schematic circuit diagram of the apparatus of FIG. 1;

FIG. 3 is a vector diagram to be used in explaining the operation of the apparatus of the subject invention;

FIG. 4 is a schematic diagram of an apparatus similar to that of FIG. 1 but with the positions of the input and load reversed;

FIG. 5 is a schematic diagram illustrating the use of a control coil and the various possible connections thereof;

FIG. 6 is a schematic diagram of the apparatus of FIG. 1 with additional means for varying the effective capacity in the control circuit;

FIG. 7 is a schematic diagram of a transformer apparatus similar to that of FIG. 1 but embodying transformer coupling of the capacitor in the control circuit;

FIG. 8 is a schematic diagram of a transformer apparatus similar to that of FIG. 1 but embodying a saturable transformer to vary the effective capacitance in the control circuit; and

FIG. 9 is a graphical representation of the various types of characteristics that can be obtained with transformer apparatus constructed in accordance with the invention.

(1)

$$I_o = \frac{-E_p \left[p^2 K \frac{M_3 M_1 + M_2 L_3}{L_1 L_3 - M_3^2} - \frac{M_3 - M_2}{L_1 L_3 - M_3^2} \right]}{z \left[p^2 K + \frac{L_1}{L_1 L_3 - M_3^2} \right] + p^3 K \left[L_2 - M_2 \frac{L_3 M_2 + M_1 M_3}{L_1 L_3 - M_3^2} - M_1 \frac{L_1 M_1 + M_2 M_3}{L_1 L_3 - M_3^2} \right] + p \left[1 + 2 \frac{L_1 M_1 + M_2 M_3}{L_1 L_3 - M_3^2} + \frac{L_1 L_2 - M_2^2}{L_1 L_3 - M_3^2} \right]}$$

Referring now to the drawings in detail, FIGS. 1-8 illustrate embodiments of the invention each including a three-legged shell-type core having a separator of non-magnetic material splitting the center leg into two parallel sections, with the result that the two outer legs are separated by a non-magnetic gap. One coil is wound about the two separated center-leg sections, while the two other coils of the basic embodiments are wound around the two outer legs. The core is preferably of ferromagnetic material, and stamped laminations of standard transformer iron may make up the core.

It is not absolutely necessary that ferromagnetic material be used for the core, if the increased reluctance and leakage of non-ferromagnetic material is not too important or is compensated for by the proper selection of the other parameters of the systems. However, a ferromagnetic core, because of its high permeability, but not because of its saturation characteristics, is preferred.

Referring first to FIG. 1, that figure discloses a transformer system including a shell-type core 70 of ferromagnetic material having center leg 71 divided into two portions 71a and 71b by a strip of non-magnetic material 72. Any appropriate non-magnetic material may be used, or the separator may be an air gap. A coil L_1 is wound around both of parallel sections 71a and 71b of center leg 71. Outer legs 73 and 74 have coils L_2 and L_3 wound therearound.

It is not necessary that the legs of the core be coplanar, or parallel, as shown in the drawings. Moreover, it is not necessary that the non-magnetic gap formed by separator 72 be the only gap in the core. It is only necessary that magnetic paths be formed between the two outer legs and the adjacent portions of the center leg.

Coils L_2 and L_3 are connected in series by conductor 75, and the series combination of these coils is connected to a load 76 of impedance Z by leads 77 and 78. Coils L_2 and L_3 are so wound on the outer legs and connected with respect to the direction of primary flux that their voltages oppose in the output circuit.

Coil L_1 forms the input electrical circuit and is connected across a source of constant A.-C. voltage 79.

Coils L_2 and L_3 form the output electrical circuit, and the parallel combination of coil L_3 and capacitor K forms the control electrical circuit.

The apparatus of FIG. 1 is capable of providing several different types of output characteristics, but it is preferred that it be used to provide a substantially constant current output with variation in load impedance. For such use, the voltage of the input must be maintained substantially constant. If constant current output is not

desired, however, the voltage input may or may not be constant, depending upon the conditions and the characteristics to be obtained. Moreover, the impedance Z may be of any type. However, if a constant current output is desired, the load should be mainly resistive, and, for best constancy, loads of substantially unity power factor are preferred.

The equivalent electrical circuit of the apparatus of FIG. 1 is shown in FIG. 2, in which the voltage input is represented as E_p , the primary current by I_p , the output or load current by I_o and the control current as I_L . The mutual inductance or inductive coupling between coils L_1 and L_2 is represented by M_2 , between coils L_2 and L_3 by M_1 , and between coils L_1 and L_3 is represented by M_3 .

Using $p=j\omega$, setting up mesh equations for the input, output and control circuits, assuming one:one turns ratios, neglecting ohmic resistance of coils, leakage reactance and core loss, and solving for the load current, we obtain the following equation:

$$I_o = \frac{-E_p \left[p^2 K \frac{M_3 M_1 + M_2 L_3}{L_1 L_3 - M_3^2} - \frac{M_3 - M_2}{L_1 L_3 - M_3^2} \right]}{z \left[p^2 K + \frac{L_1}{L_1 L_3 - M_3^2} \right] + p^3 K \left[L_2 - M_2 \frac{L_3 M_2 + M_1 M_3}{L_1 L_3 - M_3^2} - M_1 \frac{L_1 M_1 + M_2 M_3}{L_1 L_3 - M_3^2} \right] + p \left[1 + 2 \frac{L_1 M_1 + M_2 M_3}{L_1 L_3 - M_3^2} + \frac{L_1 L_2 - M_2^2}{L_1 L_3 - M_3^2} \right]}$$

It is evident that the above equation is relatively complicated and not susceptible of easy analysis, but it will be noted that the impedance value Z appears in only one term, that being in the denominator of the equation. For the load current I_o to be independent of load, the multiplier of the impedance Z must be zero, so we obtain:

$$(2) \quad p^2 K + \frac{L_1}{L_1 L_3 - M_3^2} = 0$$

This obviously is the condition for pure constancy of the load, or output, current. Through simple arithmetical operations on the last equation, we obtain:

$$(3) \quad \omega \left[\frac{L_1 L_3 - M_3^2}{L_1} \right] = \frac{1}{\omega K}$$

This last equation is obviously for a resonant system, but it also is obviously not a simple resonance equation.

The apparatus of FIG. 1 forms two magnetic circuits, split into two separate closed loops by the non-magnetic separator, while the second magnetic circuit is identical with the first magnetic circuit. It will be evident that the two magnetic circuits have two common portions, the two separated closed magnetic paths being these two common portions.

The current flowing through the primary coil L_1 generates a magnetomotive force F_p . There is also an output magnetomotive force F_o which generates flux which follows the same path as the primary magnetomotive force. It will be noted that magnetomotive forces F_o and F_p aid in the righthand common portion of the two magnetic circuits, while they oppose in the other common portion. Consequently, there can be no coupling of power directly between the input and the load. However, the control electrical circuit causes a control magnetomotive force F_L to be generated in the righthand common portion of the two magnetic circuits, which magnetomotive force is much greater than the output magnetomotive force in this leg and opposes it, with the result that the resultant of the control and output magnetomotive forces in this leg is effectively reversed from the output magnetomotive force and causes coupling of power between the input and the load through the control electrical circuit.

In general, operation of the transformer apparatus above described is similar to that explained in detail in my copending application Serial Number 646,429, filed March 15, 1957, now U.S. Patent 2,999,973, of which the present application is a division, and said copending application sets out in detail a vector analysis and characteristic curves applicable to the apparatus here described.

FIG. 3, which was shown and described as FIG. 6 of

that depending application, is designed to give a complete picture of the action of the ideal transformer, showing all important component voltages and currents thereof, for increasing impedance. It will be noted that as the impedance increases continuously, the vector net E_3 will rotate clockwise, decreasing continuously. Since the control current I_L is driven by net E_3 (and the voltage across the control coil which is in phase with net E_3) the control coil current must rotate and decrease continuously with net E_3 . Likewise, the control m.m.f. will decrease continuously with net E_3 and, E_0 , being substantially 90° behind net E_3 , will rotate clockwise. The output current is directly dependent upon the control current, so that, as the control current decreases, the output current likewise decreases continuously, describing a semi-circle of diameter equal to the original output current at zero impedance.

It will also be noted that the primary current I_p is substantially in phase with the control coil current I_L , and so leads the primary voltage E_p . This results in a leading power factor ordinarily an advantageous condition.

It will be observed from the vector diagram of FIG. 3 that the ideal transformer tends toward a continuously decreasing output current with increasing load impedance, rather than a constant output current. However, an ideal transformer has been stipulated, in which negligible m.m.f. is required to drive the fluxes necessary to produce the voltages in the system, that is, the core material has zero reluctance. The inductances of the coils would be infinite but the mutual inductance between the coils, due to their physical separation, would be finite. Therefore the second term of Equation 2 would be zero so that it could never balance the first term. Hence the impedance would play a very large part in the operation of the system and the output current would vary inversely therewith.

In actual practice, however, the inductances of the coils are never infinite and it has been found that the coupling, as represented by M in Equation 2, automatically adjusts itself in correspondence with the value of capacity to make the equation substantially true.

To bring out this compensating feature of practical transformers in which the coupling is not perfect and in which the core has appreciable reluctance, consider next a different ideal core material having appreciably less than perfect coupling and constant reluctance, but not subject to saturation effects. With such a core material, the net m.m.f. must be appreciable to drive the circulating flux which links coils L_2 and L_3 . There must be relative rotation between the control and output m.m.f.'s toward Basic E_3 to produce this appreciable net m.m.f. In other words, the control and output m.m.f.'s are no longer substantially at 180° to each other, and the net m.m.f. must therefore rotate back toward Basic E_3 from the phase relationship in which it was substantially in phase with net E_3 .

For this new ideal core material, the relative rotation between the control and output m.m.f.'s required to produce the linearly increasing net m.m.f. with increasing output voltage will tend to maintain the output current constant. If the reluctance is of proper value, the net m.m.f. will stay midway between Basic E_3 and net E_3 despite increasing output voltage and clockwise rotation of net E_3 . The output current then would be perfectly constant over a range of output voltage limited only by leakage between the windings. If the reluctance was too high, of course, the required net m.m.f. would be so high that it would be closer to Basic E_3 than to net E_3 and the output current would rise with increasing voltage. If the reluctance was too low, the system would approach the first ideal core having negligible reluctance, and the current would drop off. However, it is the apparent reluctance, as represented by the coupling, rather than the physical reluctance, that is important. The value of this apparent reluctance relative to the other parameters of

the system, then, determines the characteristic of output current versus output voltage.

The apparatus of FIG. 1 was connected so that the input was shunted directly across coil L_1 , while the output was connected across the series combination of coils L_2 and L_3 . Referring now to FIG. 4, it is shown therein that the positions or connections of the input and load in the system may be reversed. In other words, input 79 may be connected across the series combination of coils L_2 and L_3 , while load 76 may be connected across L_1 . The operation of this form of the invention is substantially the same as the operation of the apparatus of FIG. 1.

In FIG. 5, it is shown that a separate control coil may be used for the control electrical circuit. This coil, L_4 , is wound on the same leg with coil L_3 , and is connected in series with capacitor C . The leads 81 and 82 of the control electrical circuit formed by the series combination of control coil L_4 and capacitor C may be connected across any appropriate source of voltage including coil L_1 , L_2 , L_3 , the series combination of L_2 and L_3 , any other source of voltage, or the two leads may be shorted together. For best range of constancy, however, the phase relationships should be such that the control current is substantially 90° out of phase with the primary voltage at zero load.

The increased number of turns of the control circuit obtained with a separate control coil increases the voltage available to drive the control current, thus increasing the magnitude of that current. Since the output current is directly related to the control current, an increase in control turns increases the level of output current. The use of the separate control coil may be interpreted into the above equations by substitution of the actual value of the capacity C in the equation for the effective capacity K , using the equivalency $K = \beta^2 C$, where $\beta = 1 + \alpha$ and α is the turns ratio between coils L_3 and L_4 .

It has been found that output current regulation, in transformer apparatus constructed in accordance with the invention, is substantially the same for each pre-selected value of capacitance in the control circuit, in contrast to the usual resonant circuit. Also, the mutual inductance apparently changes automatically to maintain the proper apparent reluctance of the system to provide constant current output.

For commercial applications, it is desirable that the level of output current to be maintained constant be selectable. In order to provide for such selection, the modification of FIG. 6 may be employed. This modification provides a variable inductor 83 shunted directly across capacitor K . Variation of the inductance of this inductor will vary the effective capacity in the control electrical circuit, thereby permitting variation of the output current.

It is also possible to couple the capacitor into the control electrical circuit indirectly, rather than by placing the capacitor directly in series with the control coil. This may be done, as in FIG. 7, by connecting a transformer T into the control electrical circuit. The secondary of that transformer is connected directly across capacitor C , and the primary is connected across the control coil L_3 . Moreover, the capacitor may be coupled into the control circuit through a variable transformer, or Variac, to permit adjustment of effective C through change in transformer turns ratio.

FIG. 8 shows a further embodiment of the invention which provides for transformer coupling of the capacitor into the control electrical circuit, as well as variation of the effective capacity in the circuit. This embodiment uses a saturable transformer core 85 having a secondary winding 86. Capacitor C is shunted across winding 86. Coils 87 and 88 are wound around the two outer legs of the saturable transformer core and are connected in series. The distal ends of these coils are connected to a source of variable D.-C. voltage 90, with the result that

variation in the voltage applied to coils 87 and 88 by source 90 changes the level of saturation of core 85, and hence the primary exciting current. Wound on the center leg with secondary winding 86 is a primary winding 91 which is connected directly across control coil L₃. The change in primary exciting current causes a change in the effective capacity in the control electrical circuit, thus changing the level of output current which may be maintained constant by this apparatus.

The invention has been described primarily for use in maintaining a constant current output with variation in load impedance from 0 upwardly. However, the various embodiments described are useful for providing other characteristics than constant current output. FIG. 9 illustrates some of the characteristics of output current versus output voltage which can be obtained in accordance with the invention, with variation of the control coil connections and of different parameters of the system. It will be evident that a rising current characteristic, a drooping current characteristic, and various combinations of these two general types of characteristics, as well as a constant current output, can be obtained. Accordingly, the invention is not to be considered limited to use of the apparatus to obtain a constant current load since, in its broadest aspects, the invention is usable to obtain many other different types of desirable characteristics.

As explained above, all of the embodiments of the invention have a substantially unlimited constancy action with variation in capacity of the control circuit capacitor. When leakage reactance is ignored, all embodiments described have unlimited constancy. This surprising result is achieved by automatic variation in the mutual inductance of coils on separate legs to compensate for changes in capacity, so that resonance is substantially maintained. As far as is known, the action of transformer systems in accordance with the invention in varying mutual inductance automatically, without adjustment of parts, is novel.

It will be obvious that many minor variations could be made in the elements of the various embodiments of this invention shown and described without departure from the spirit of the invention. For instance, the positions of the various coils on the respective legs of the transformer core could be changed about and the characteristics fundamental to the system still be maintained. From the description of the various embodiments, it will be evident that all of these embodiments have the following in common:

The embodiments include two magnetic circuits, which have two common portions, in one of which common portions the input and output magnetomotive forces aid, and in the other of these two common portions the input and output magnetomotive forces oppose, so that there is no direct coupling between the input and the load. The control magnetomotive force in effect reverses the total or resultant magnetomotive force in its common portion from the direction of the output m.m.f., so as to couple power from the input to the load through the control electrical circuit. From the above, it will be obvious that this invention is not to be considered limited to the various embodiments shown and described, but rather only by the scope of the appended claims.

I claim:

1. A transformer system for supplying power to a load from a constant voltage A.C. input comprising a core of a single type of ferromagnetic material having two outer legs and a center leg, said legs being of such configuration and so aligned with each other that substantially closed high permeability paths are formed between the outer legs and the center leg, said center leg being separated by non-magnetic material into two parallel portions also parallel to said portions of the outer legs, so that the reluctance of the path between said parallel portions of the center leg is extremely high in comparison with the reluctance of said substantially closed

paths; at least three coils wound on said core, a first and a second of said coils being wholly wound on different ones of said outer legs and connected in series, the third coil being wound with each turn surrounding both of and only said parallel portions of the center leg; an input, an output, and a control electrical circuit, all passing current, the input circuit including one of (a) said third coil and (b) the series combination of said first and second coils, the input circuit being connected across said constant voltage A.C. input, the output circuit including the other one of (a) said third coil and (b) the series combination of said first and second coils, the output circuit being connected across said load; said input and output electrical circuits forming with said core an input and an output magnetic circuit, both including one of said parallel portions of the center leg and the outer leg with which a substantially closed high permeability path is formed and the other of said parallel portions of the center leg and the other outer leg, said input and output electrical circuits being so inductively related to said outer legs that the input and output magnetomotive forces generated by the input and output currents aid in one and oppose in the other of said outer legs; and a capacitive reactance, said control electrical circuit including said capacitive reactance and being inductively coupled to the leg on which said first coil is wound; whereby no power is directly coupled between said input and output electrical circuits, but the control current producing a magnetomotive force in the leg on which said first coil is wound of phase and magnitude to produce a resultant of the control and output magnetomotive forces opposite to the output magnetomotive force in said last-mentioned leg and thereby to couple power from the input to the load through said control electrical circuit.

2. The apparatus of claim 1 in which said control electrical circuit includes said first coil and said capacitive reactance is shunted across said coil.

3. The apparatus of claim 1 in which said control electrical circuit includes a control coil wound on the leg on which said one of said first and second coils is wound.

4. The apparatus of claim 3 in which the series combination of said control coil and said capacitive reactance is connected across a source of voltage.

5. The apparatus of claim 4 in which the series combination of said control coil and said capacitive reactance is connected across said first coil.

6. The apparatus of claim 3 in which the series combination of said control coil and said capacitive reactance is connected across said first coil.

7. The apparatus of claim 3 in which the capacitive reactance is shunted across the control coil.

8. The apparatus of claim 1 in which said control electrical circuit includes a variable inductive reactance shunted across the capacitive reactance to permit variation of the effective capacity and hence of the output current.

9. The apparatus of claim 1 in which said control electrical circuit includes a saturable core transformer, at least one coil wound on the core of said transformer, a source of D.C. voltage connected to said last-mentioned coil and variable to change the saturation of the transformer core, a secondary coil wound on said transformer core and connected across said capacitive reactance, and a primary coil inductively coupled to said secondary coil.

10. The apparatus of claim 1 in which said control electrical circuit includes a transformer having a primary and a secondary coil, said capacitive reactance being connected across said secondary coil, and said primary coil being inductively coupled to said secondary coil.

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