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VOLTAGE REGULATORS CONNECTED IN PARALLEL

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2 Sheets-Sheet 1

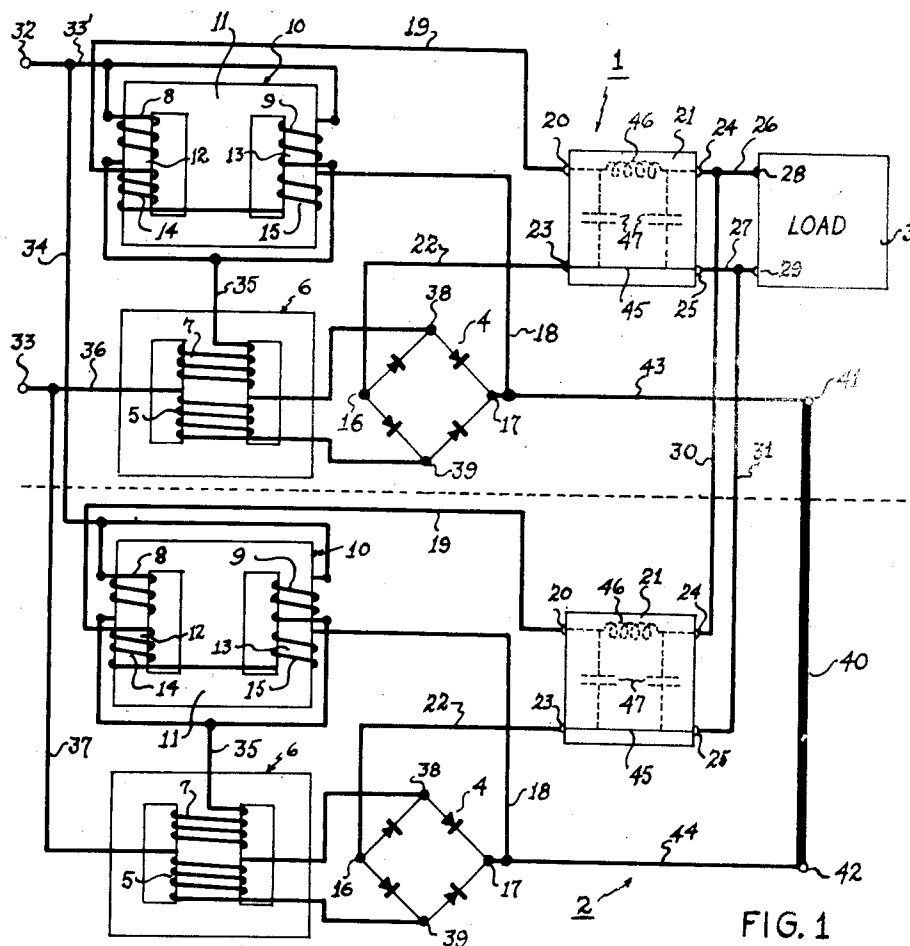


FIG. 1

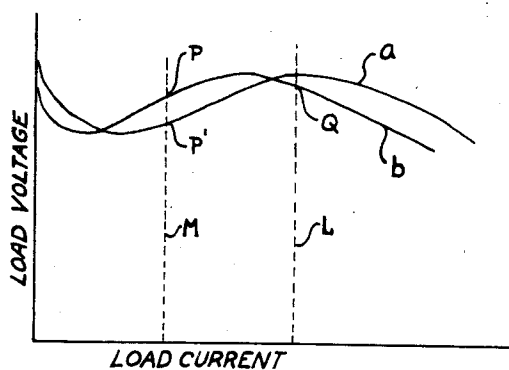


FIG. 2

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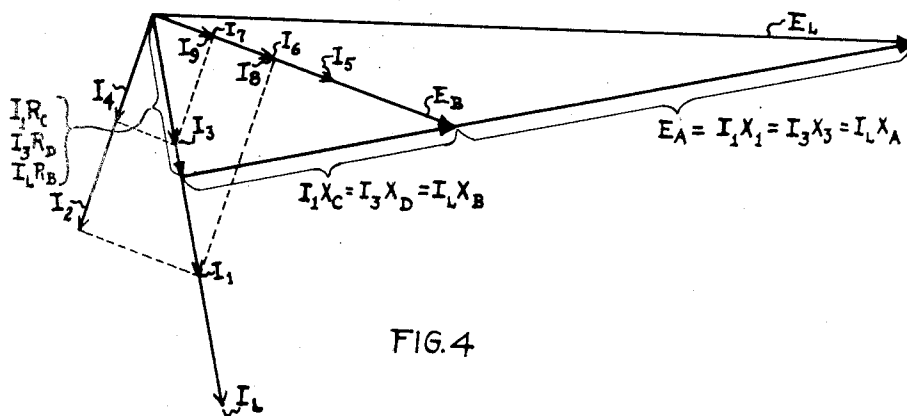
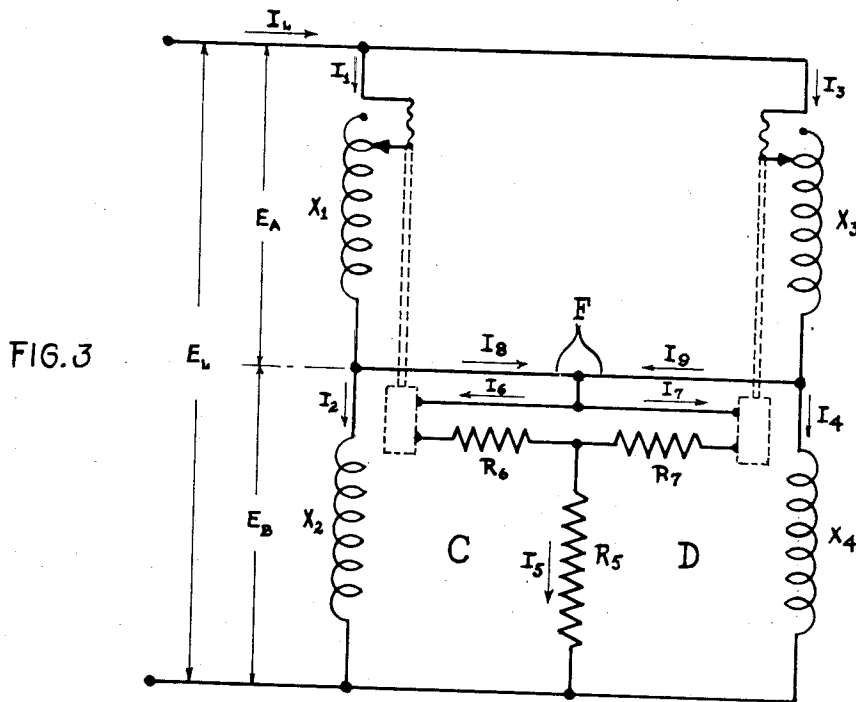
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VOLTAGE REGULATORS CONNECTED IN PARALLEL

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UNITED STATES PATENT OFFICE

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VOLTAGE REGULATORS CONNECTED IN
PARALLEL

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6 Claims. (Cl. 175-363)

This invention relates to voltage regulators connected in parallel, and more particularly to such a connection in which the regulators are of the type supplying a rising voltage characteristic to an apparatus such as a rectifier and associated filter, whereby the output voltage of said apparatus is substantially constant.

An object of my invention is to enable a plurality of voltage regulators of the type described to be connected in parallel from a common source of alternating voltage to supply a common load, and automatically cause the load to divide between them in accordance with their power rating.

Another object of my invention is to devise such a system in which the load division between the voltage regulators is maintained in a stable manner.

A still further object of my invention is to enable voltage regulators to be adapted to be connected into such a system with a minimum of additional apparatus.

The foregoing and other objects of my invention will be best understood from the following description of an exemplification thereof, reference being had to the accompanying drawings, wherein:

Fig. 1 is a diagrammatic representation of one form of my novel system;

Fig. 2 is a set of characteristic curves typical of such voltage regulators, as illustrated in Fig. 1;

Fig. 3 is an equivalent circuit diagram of the arrangement shown in Fig. 1; and

Fig. 4 is a vector diagram showing the relationships between the various vector components of the equivalent circuit illustrated in Fig. 3.

It is often desirable in supplying a relatively large load to supply that load from a plurality of voltage regulating devices. To do this it is further desirable to connect said voltage regulators in parallel across a common source of alternating current and to connect the output sides of said regulators in parallel across the common load. In the case of voltage regulators of the type in which the load current drawn from said regulators controls the operation thereof to maintain the output voltage of the system substantially constant, the load current output voltage characteristic thereof is usually rising through at least a part of said characteristic. Thus, for example, curves *a* and *b* of Fig. 2 might represent the characteristic curves respectively of two voltage regulators. In Fig. 2 the horizontal axis represents values of load current while the vertical axis represents values of load

voltage. If we assume that the two voltage regulators are substantially of equal power rating and said two voltage regulators were connected in parallel, it would be desirable to divide any load drawn from said voltage regulators substantially equal. Thus, for example, if it were desired to supply a value of load current such as that represented by *L*, each of the voltage regulators should furnish to the load a value of current represented by *M*. Under these conditions the regulator having the characteristic *b* would be operating at *P*, and the regulator having the characteristic *a* would be operating at *P'*. Since under these conditions the point *P* is at a higher voltage than point *P'*, the voltage regulator with the characteristic *b* would tend to force a larger amount of current through the load. As the current from said voltage regulator increased, the output voltage thereof would rise due to the rise of the characteristic curve *b*, and therefore the tendency for said regulator to supply an additional amount of current to the load would be increased. This condition would cause said voltage regulator to supply substantially all of the current to the load, and its operating point would move along to point *Q* on the characteristic curve *b* while the voltage regulator having the characteristic curve *a* would cease to supply current to the load and its output current would drop substantially to zero. In Fig. 2 I have represented the two voltage regulators as having slightly different characteristics. However, even in the case of identical characteristics, the same type of operation would almost inevitably occur. If two such identical regulators were operating on a rising portion of their characteristics, a slight disturbance in the system, causing one of said regulators to supply a slightly increased current to the load, would upset any conditions of equilibrium which might have existed and cause that regulator to supply an increasingly larger proportion of the load until its operation had shifted to such a point where it supplied substantially all of the current to the load, while the other voltage regulator would cease supplying any substantial amount of current to said load.

I have found that the above difficulty may be eliminated by connecting voltage regulators in parallel in accordance with my invention. In Fig. 1, which represents one form of said invention, I have illustrated two voltage regulators 1 and 2 adapted to be connected in parallel across a common supply of alternating current and supplying in parallel a common load 3. The dotted line through the central portion of Fig. 1 is used

to designate the separation between the two voltage regulators 1 and 2. Each of said voltage regulators consists of a rectifier 4 fed from a secondary winding 5 of a transformer 6 whose primary winding 7 has in series therewith inductance coils 8 and 9 of a control choke 10. The two inductance coils 8 and 9 are preferably connected in parallel to secure such operation as is more fully set forth in the co-pending application of Frederick S. Dellenbaugh, Jr., Serial No. 759,852, filed December 31, 1934. The rectifier 4 is illustrated diagrammatically as being a full-wave rectifying bridge. Any other rectifying arrangement could be used, such as for example a full-wave rectifying tube or tubes or even a single-wave rectifier. The choke 10 consists preferably of a three-legged core 11 having the coils 8 and 9 wound on the two outer legs 12 and 13 thereof. Two additional coils 14 and 15 are also wound on the legs 12 and 13, and connected in series with each other. The coils 8, 9, 14 and 15 are so related that any alternating current induced in coil 14 is neutralized by a substantially equal and opposite alternating voltage induced in coil 15. The rectifier 4 has two output terminals 16 and 17. One of the output terminals, for example 17, is connected by a conductor 18 through coils 15 and 14 and then by an additional conductor 19 to an input terminal 20 of a filter 21. The other output terminal 16 of the rectifier 4 is connected by a conductor 22 to the other input terminal 23 of the filter 21. The two output terminals 24 and 25 of filter 21 of the voltage regulator 1 are connected by conductors 26 and 27 to input terminals 28 and 29 of load 3. The two output terminals 24 and 25 of filter 21 of regulator 2 are likewise connected by conductors 30 and 31 to the conductors 26 and 27, respectively, whereby the output of regulator 2 is connected in parallel with the output of regulator 1 across the common load 3. The system may be provided with two input terminals 32 and 33 which are adapted to be connected to some suitable source of alternating current. One of the input terminals, for example terminal 32, is connected by means of a conductor 33' to the coils 8 and 9 of regulator 1. An additional conductor 34 connected to the conductor 33' is connected to the two coils 8 and 9 of the regulator 2, thus connecting said coils to the input terminal 32. The coils 8 and 9 of regulators 1 and 2 are each connected by means of an additional conductor 35 to one end of the primary winding 7 of transformer 6. The other end of the primary winding 7 of regulator 1 is connected by means of a conductor 36 to the other input terminal 33, and likewise the other end of primary winding 7 of regulator 2 is connected by a conductor 37 to said other input terminal 33. Instead of coils 8 and 9 being in parallel, it is sometimes desirable to connect these coils in series with each other. The terminals of the secondary winding 5 of each voltage regulator are connected to two input terminals 38 and 39 of the rectifier 4.

When an alternating voltage is applied to the input terminals 32 and 33 and a direct current load is drawn from the load terminals, the load current will divide between the two voltage regulators and current will flow through the various coils shown. The current so flowing will introduce voltage drops in these various coils, and will also introduce voltage drops in each rectifier 4 and in each filter 21 associated therewith. By passing the load current drawn from each recti-

fier through the coils 14 and 15, this load current will tend to saturate the core 11 and thus reduce the reactance of coils 8 and 9. This reduction in the reactance or inductance of these coils will decrease the voltage drop introduced by these coils, and will permit a larger portion of the impressed voltage to be impressed upon each primary 7. This causes the voltage across each secondary 5, which voltage is impressed upon the respective rectifiers 4, to increase with an increase in load. By properly designing the various constants of the system, this increase in voltage can be made to compensate for the additional voltage drops, due to the increase in current through the system, and produce for each voltage regulator such a substantially constant voltage current output curve as might be illustrated diagrammatically by characteristic curves *a* and *b* of Fig. 2.

As has been pointed out above, if such a system as I have described contained no additional means than those described above for preventing a non-desirable division of current between the two regulators, the current supplied to the load would not be supplied by each regulator in the desired manner, and the difficulties set forth would result. I have found that by providing an equalizing connection 40 substantially in the manner as shown in Fig. 1, these difficulties are avoided. This equalizing connection 40 is connected between the equalizer terminals 41 and 42 of the regulators 1 and 2, respectively. The equalizer terminal 41 is connected by a conductor 43 to the output terminal 17 of the rectifier 4 of regulator 1. The equalizer terminal 42 is connected by means of a conductor 44 to the output terminal 17 of rectifier 4 of regulator 2. I have also found that it is desirable for each filter 21 to be so constructed that between the input terminal 23 and the output terminal 25 be provided a connection 45 in which is interposed substantially no impedance. The various choke members of the filter 21 may be connected in the other side of the filter as illustrated diagrammatically by the dotted choke 46, while the various condenser elements, such as represented by dotted condensers 47, may be connected between the two sides of said filter. The dotted members 46 and 47 are merely intended to represent possibly a more complex arrangement of a plurality of such members. Due to this arrangement it will be seen that the output terminals of both rectifiers 4 are connected directly in parallel with each other on one side by the conductors 40, 43 and 44, and on the other side by the conductors 22, 45 and 31. Thus the voltage at the output terminals of each rectifier 4 must be the same as the voltage at the output terminals of the other rectifier at all times. In certain circumstances, such as where regulators of equal power rating are used, it might be useful to interconnect the input terminals of the rectifiers of like polarity. Such a mode of connection, while not as effective as the connection illustrated in Fig. 1, will prevent an excessive inequality of load division. In a broad sense, however, the connection 40 can be considered as being from a point intermediate the output terminals of the secondary winding 5 and the coils 14 and 15 on each regulator to a similar point on the other regulator.

In order to explain the principles of my invention and to illustrate why such an equalizer connection 40 connected in the manner illustrated accomplishes the desired results, I have schemat-

ically represented in Fig. 3 substantially the equivalent circuit of the arrangement as shown in Fig. 1. The reactance of coils 8 and 9 of regulator 1 is represented by X_1 . The effective reactance of the transformer 6 of regulator 1 referred to the primary circuit thereof is represented by X_2 . The reactance of coils 8 and 9 of regulator 2 is represented by X_3 . The effective reactance of the transformer 6 of regulator 2 referred to the primary circuit thereof is represented by X_4 . The effective resistance of the filter 21 of regulator 1 as referred to the primary of transformer 6 thereof is represented by R_6 . The effective resistance of the filter 21 of regulator 2 as referred to the primary 7 thereof is represented by R_7 . The effective resistance of the load referred to the primary system of the two voltage regulators is represented by R_8 . Since the current which flows through the respective filters likewise controls the reactance of the coils 8 and 9 of the respective regulators, I have represented this fact in Fig. 3 by the dotted lines connecting the circuits in which R_6 and R_7 are placed to the arrows representing adjustability of the two inductances X_1 and X_3 , respectively. The presence of the equalizer connection 40 in Fig. 1 effectively introduces into the equivalent circuit of Fig. 3 the connection F in the position as indicated therein, the symbols I_1 and I_2 to I_5 , inclusive, together with their associated arrows, represent the current flowing through the various parts of the system. Any other equivalent impedances of the circuit shown in Fig. 1 which might be represented in Fig. 3 are of such small value in a practical system that the effect upon the operation and analysis of that system may be neglected without substantially affecting that analysis.

The operation of the equivalent circuit as shown in Fig. 3 is analyzed vectorially in Fig. 4. In the analysis as illustrated in Fig. 4, I have assumed that regulator 1 is designed for twice the power rating for which the regulator 2 is designed. This analysis will indicate the manner in which the current supplied to each voltage regulator is in proportion to its power rating. In Fig. 4 I have represented a condition of equilibrium and will point out subsequently wherein my system tends to maintain that condition of equilibrium in a stable manner.

The vector E_L in Fig. 4 represents the line voltage applied to the system. If a load current is drawn through the load R_8 , a current I_L will be drawn from the line. Due to the presence of the relatively high inductance of the regulating system, this current I_L will lag behind the voltage E_L , as indicated in Fig. 4. The voltage E_L may be divided into two components E_A and E_B . Due to the fact that circuit A is substantially entirely inductive and circuit B has considerable resistance therein, there will be an angular displacement between the two voltages E_A and E_B . The current I_L flowing into the circuit A will subdivide into currents I_1 and I_3 . Since the same voltage E_A is impressed across the two inductances X_1 and X_3 , the currents I_1 and I_3 will be inversely proportional to the value of said inductances, respectively. In voltage regulators such as I have illustrated, the inductances X_1 and X_3 will be inversely proportional to the power rating of the respective regulators. Thus if a regulator is built with a higher power rating than another regulator, its inductance X_1 will be lower due to the presence of the larger amount of material which is used and the higher values of current

which it is designed to handle. Thus the currents I_1 and I_3 will be related to each other substantially in accordance with the power rating of the respective regulators. If regulator 1 has twice the power rating of regulator 2, I_1 will be twice I_3 , as shown in Fig. 4. The voltage drop through the inductances X_1 and X_3 is entirely inductive, and therefore this voltage which is equal to E_A occurs at right angles to the currents I_1 and I_3 . Also due to the fact that the two inductances X_1 and X_3 are substantially pure inductances, I_1 and I_3 will be substantially in phase with one another, and therefore will add directly to give the resultant line current I_L . As the current I_1 reaches the circuit C, it will divide into the two currents I_2 and I_4 , and likewise the current I_3 upon reaching the circuit D will divide into the currents I_4 and I_5 . The inductances X_2 and X_4 likewise are inversely proportional to the power rating of their respective regulators for substantially the same reasons as set forth with respect to the inductances X_1 and X_3 . Since the same voltage E_B is impressed across both of these inductances X_2 and X_4 , the relationship between the two currents flowing through said inductances, namely I_2 and I_4 , will be in inverse ratio to the values of said inductances X_2 and X_4 . Due to this condition, the currents I_2 and I_4 will be related to each other substantially in accordance with the respective power rating of their regulators. Therefore if regulator 1 has double the power rating of regulator 2, I_2 will be double I_4 as shown in Fig. 4. The two currents I_2 and I_4 will be at right angles to the voltage E_B because of the fact that these currents flow through a purely inductive circuit. In order to determine the magnitude of the currents I_5 and I_6 , it is merely necessary to subtract from the currents I_1 and I_3 the respective currents I_2 and I_4 . If this is done, it will be found that the resultant current I_5 will be double the resultant current I_6 . Since the network through which these two currents flow is entirely a resistance network, these currents will be in phase with the voltage E_B impressed across said network. Since I_5 and I_6 represent the load current supplied from the regulators 1 and 2, respectively, it will be seen that by the arrangement which I have illustrated, under a condition of equilibrium, the load current I_5 will subdivide between the two regulators substantially in accordance with their power rating. Since the circuits in which R_6 and R_7 are placed are in parallel with each other, the same voltage will be impressed across them, and therefore the current I_5 will divide between them inversely in accordance with the respective value of R_6 and R_7 . R_6 and R_7 likewise will be related to each other substantially inversely in accordance with the power rating of their respective systems for substantially the same reasons as set forth with respect to X_1 and X_3 . Therefore I_6 and I_7 will be related to each other substantially in accordance with the power rating of their respective systems. Under the conditions which I have assumed, I_6 will therefore be double I_7 . The vector sum of these two currents will likewise be I_5 . Under these conditions I_5 and I_7 will be substantially equal to I_6 and I_4 , respectively. Thus under a condition of equilibrium, the regulating current for each voltage regulator will be substantially equal to the load currents applied by that voltage regulator, and thus the proper output characteristic of each regulator will be secured so as to maintain at the load a substantially constant voltage.

If instead of such a condition of equilibrium as I have assumed with respect to Fig. 4, there exists a temporary unbalance of conditions, currents will flow through the various parts of the system tending to re-establish the condition of equilibrium. Thus if two voltage regulators having the characteristics a and b , as illustrated in Fig. 2, are connected in parallel and it is desired to operate these regulators so that each supplies the current of the value M , temporarily a condition might be created in which an equilibrium did not exist. If we assume that regulator 1 has the characteristic b and regulator 2 has the characteristic a in Fig. 3, the voltage across X_2 would tend to be higher than the voltage across X_4 , and thus I_8 would increase with respect to I_9 , thus resulting in a decrease of I_9 . The load current I_5 would, however, remain substantially constant. Since the division between I_6 and I_7 does not depend upon the voltage conditions which exist across X_2 and X_4 but only upon the value of I_5 and the relative values of R_6 and R_7 , I_6 and I_7 would still be related in accordance with the power rating of the respective regulators. Therefore these two currents I_6 and I_7 would remain substantially constant and there would not be any substantial change in the values of either X_1 or X_3 . The increase in I_8 and possibly an increase in I_2 would result in an increase of I_1 . Likewise a decrease in I_3 would be effected. Since X_1 would remain substantially constant, the increase in I_1 would produce an increased drop through X_1 , and therefore would tend to decrease the voltage across X_2 . Likewise the decrease in the current I_3 through the then constant reactance X_3 would cause a decrease in the voltage drop across X_3 , and therefore would tend to increase the voltage across X_4 . Under such a condition of unequilibrium, the characteristic b at the point P , instead of tending to have a rising characteristic, would temporarily have a falling characteristic, and therefore the tendency to supply all of the load current, which would exist without the equalizing connection 40 or F , no longer is present. Upon reaching a point of equilibrium with regulators having the characteristic shown in Fig. 2, it will be found that I_8 will have increased slightly over the desired ideal distribution of current and I_9 will have decreased slightly over such an ideal sufficiently to introduce an added voltage drop in X_1 and slightly decrease the voltage drop in X_3 sufficiently to make the voltages at points P and P_1 equal to each other. Upon referring to Fig. 4 it will be seen that the voltage E_A , which represents the inductive drop through the inductances X_1 and X_3 , is a fairly large proportion of the voltage E_L . Under these conditions, a very slight change in the currents I_1 and I_3 is necessary to effect the proper corrective voltage drop to reach a condition of equilibrium, even with such dissimilar characteristics as illustrated in Fig. 2. Thus upon reaching such a condition of equilibrium, the change in currents I_8 and I_9 will be so small that the relationship between them will still be substantially in accordance with the power rating of their respective regulators. Of course as the characteristic curves of the systems connected in parallel more closely approximate each other, the smaller will be the deviation of the division of the load currents from the theoretical ideal. With any two systems connected as I have illustrated, the operation thereof is extremely stable and the division of the load currents between the systems, often under conditions of

considerably different voltage characteristics, is substantially in accordance with the power rating of the respective regulators.

Of course it is to be understood that this invention is not limited to the particular details of the arrangement as described above as many equivalents will suggest themselves to those skilled in the art. For example, various circuit changes may be made which will produce substantially the same effect as the circuit arrangement shown in Fig. 1. Thus, if instead of using separate primary and secondary windings for the transformer, a single winding were used upon which primary and secondary circuit connections were made, the operation of the system would be substantially the same. Therefore, when using the term "connected across" any element in the claims, I intend that this expression shall designate either an inductive coupling of two elements, such as primary and secondary windings 1 and 5, or a direct electrical connection across such an element. Likewise when using the expression "connected in series" to designate the connection between two elements or circuits I intend that this expression shall be broad enough to include an inductive coupling as part of said series connection, such as, for example, the primary and secondary windings 1 and 5 or a direct electrical connection of the two elements or circuits. Various other changes will likewise suggest themselves. It is accordingly desired that the appended claims be given a broad interpretation commensurate with the scope of the invention within the art.

What is claimed is:

1. A voltage regulating system comprising a plurality of voltage regulators each comprising impedance means adapted to be connected in series with a source of alternating voltage, a separate output circuit connected in series with each of said impedance means, and current-responsive means in each of said output circuits for varying the associated impedance means inversely in response to the amount of current flowing through the respective current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current responsive means being connected in parallel with each other and in series with said common load.

2. A voltage regulating system comprising a plurality of voltage regulators each comprising two impedance means adapted to be connected in series with a source of alternating voltage, a separate output circuit connected across one of each of said pairs of impedance means, and current-responsive means in each of said output circuits for varying the other impedance means of the associated pair of impedance means inversely in response to the amount of current flowing through the respective current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current-responsive means being connected in parallel with each other and in series with said common load.

3. A voltage regulating system comprising a plurality of voltage regulators each comprising two inductance means adapted to be connected in series with a source of alternating voltage, a separate output circuit connected across one of each of said pairs of inductance means, and current-responsive means in each of said output

circuits for varying said other inductance means of the associated pair of inductance means inversely in response to the amount of current flowing through the respective current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current-responsive means being connected in parallel with each other and in series with said common load.

4. A voltage regulating system comprising a plurality of voltage regulators each comprising two impedance means adapted to be connected in series with a source of alternating voltage, rectifying means connected across one of said impedance means, said rectifying means having output terminals, an output circuit across said output terminals, and current-responsive means in said output circuit for varying said other impedance means inversely in response to the amount of current flowing through said current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current-responsive means being connected in parallel with each other and in series with said common load.

5. A voltage regulating system comprising a plurality of voltage regulators each comprising two inductance means adapted to be connected in series with a source of alternating voltage,

rectifying means connected across one of said inductance means, said rectifying means having output terminals, an output circuit across said output terminals, and current-responsive means in said output circuit for varying said other inductance means inversely in response to the amount of current flowing through said current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current-responsive means being connected in parallel with each other and in series with said common load.

6. A voltage regulating system comprising a plurality of voltage regulators each comprising inductance means in series with the primary circuit of a transformer, said transformer having a secondary circuit connected to rectifying means, said rectifying means having output terminals, an output circuit across said output terminals, and current-responsive means in said output circuit for varying said inductance means inversely in response to the amount of current flowing through said current-responsive means to produce a rising voltage output characteristic for its regulator, said output circuits being connected in parallel across a common load, said current-responsive means being connected in parallel with each other and in series with said common load.

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