

July 25, 1961

I. K. DORTORT

2,994,028

CURRENT BALANCING REACTORS FOR RECTIFIER ELEMENTS

Filed Dec. 14, 1956

4 Sheets-Sheet 1

FIG. 1

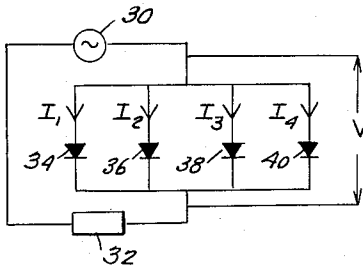


FIG. 2

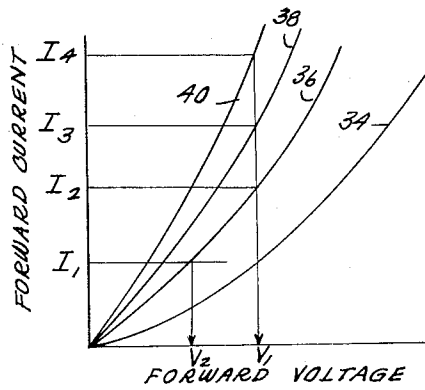


FIG. 3

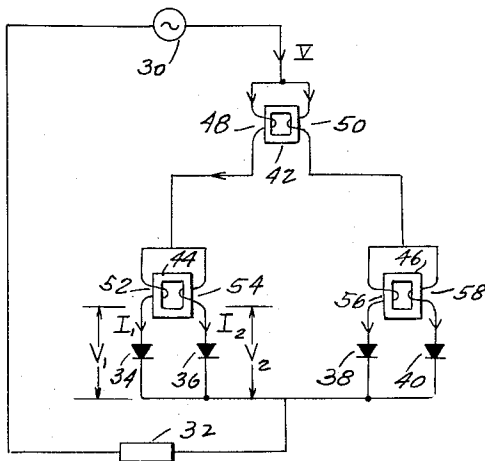


FIG. 4

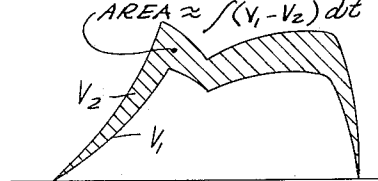


FIG. 5

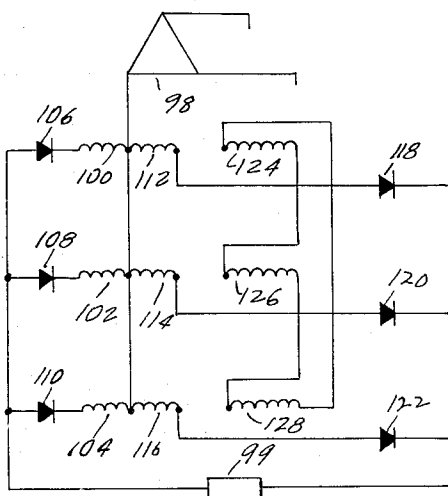
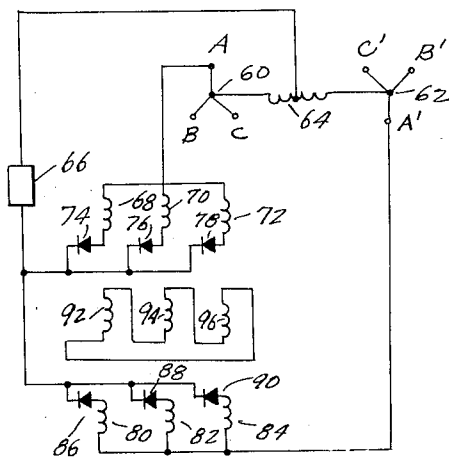


FIG. 6



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FIG. 8.

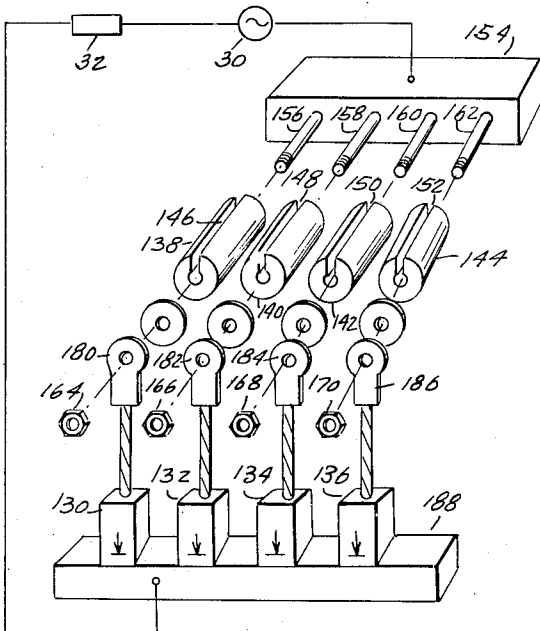


FIG. 7.

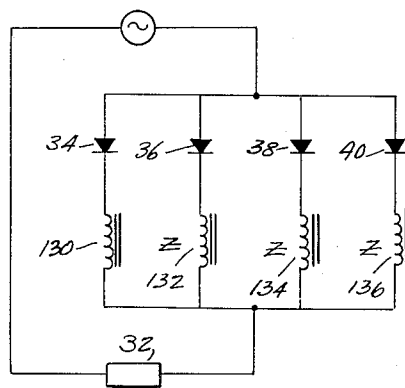


FIG. 9.

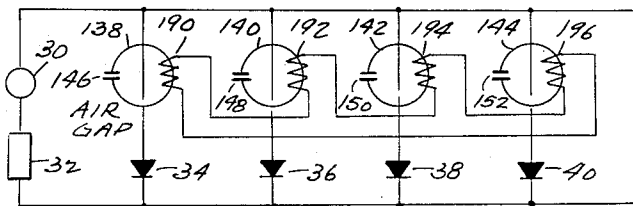


FIG. 10.

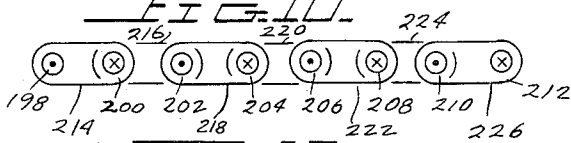


FIG. 11.

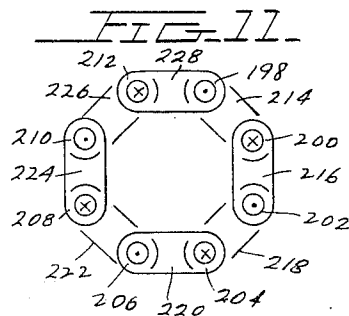


FIG. 12.

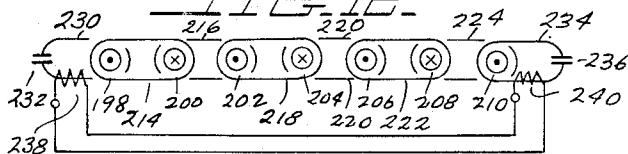
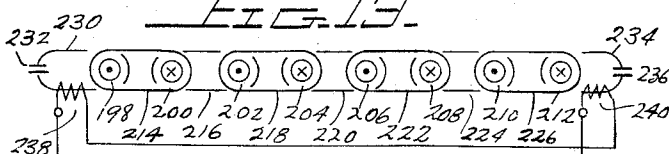


FIG. 13.



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FIG. 15

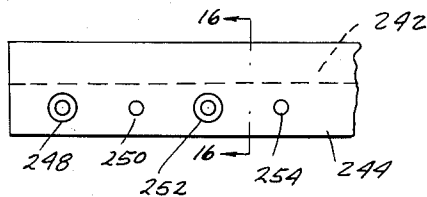


FIG. 16

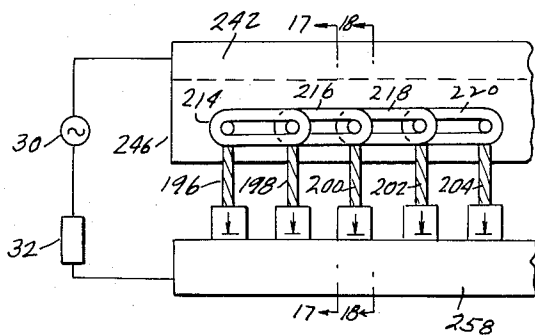
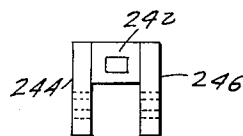


FIG. 14

FIG. 18

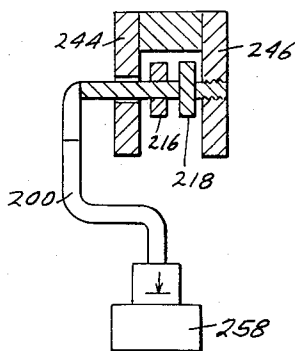


FIG. 17

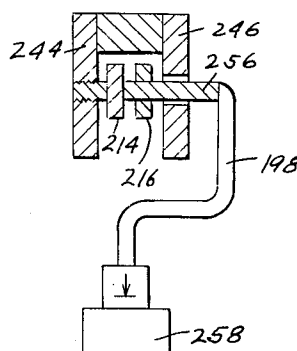


FIG. 18a

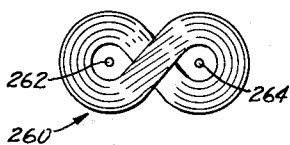


FIG. 18c

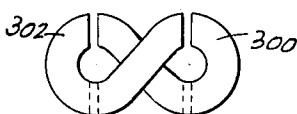


FIG. 18d

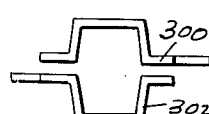
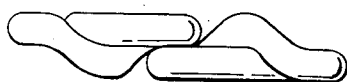


FIG. 18b



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FIG. 19.

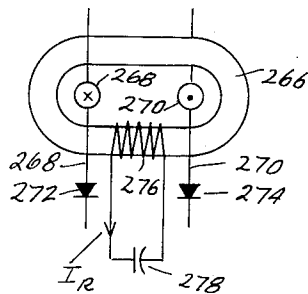


FIG. 20A.



FIG. 20B.

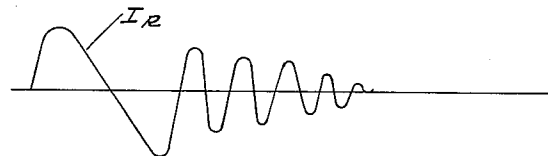


FIG. 21.

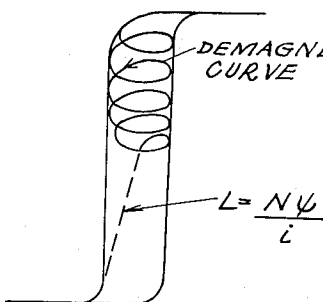


FIG. 22A.

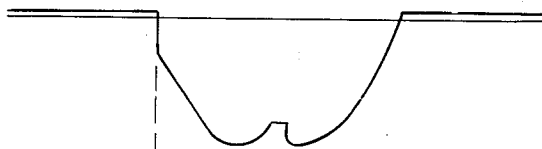


FIG. 22B.

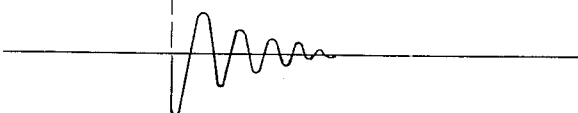
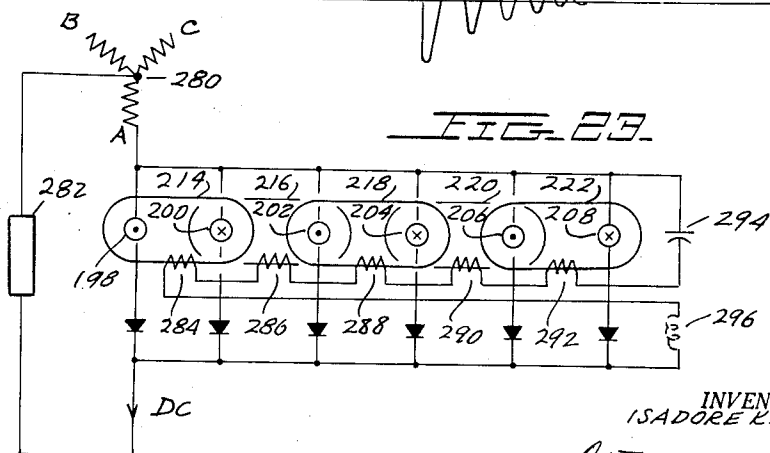


FIG. 23.



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CURRENT BALANCING REACTORS FOR RECTIFIER ELEMENTS

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Filed Dec. 14, 1956, Ser. No. 628,324

19 Claims. (Cl. 321-27)

My invention relates to a means for forcing a predetermined current distribution between parallel connected diodes of the semi-conductor or metallic type, and is more specifically directed to the connection of current balancing reactors for parallel connected diodes wherein the reactors are constructed to individually vary the voltage drop across individual diodes so that the same current flows through each of the diodes.

It is to be understood that the term diode used herein could encompass the emitter collector circuit of a transistor.

Present advances in the construction of the various types of diodes such as the metallic and semiconductor type with the use of the germanium and silicon elements has led to the increasing use of these members for high current capacity rectifying systems. Thus it is possible, in a multi-phase rectifier system, to connect a number of diode elements in parallel for each phase, whereby D.-C. current capacities of the order of 5000 amperes may be obtained. Since, however, individual diodes vary in their forward voltage characteristics, the current distribution between parallel connected diodes will not be equal unless the diodes are very closely matched in these characteristics. Furthermore, diode characteristics are changeable with age, temperature conditions, and many other uncontrollable parameters. Thus, even though the diodes may originally have been closely matched to conduct substantially the same forward current, this matching may be unbalanced after a relatively short period of operation.

The principal object of my invention is to provide a reactor means for forcing an equal or a substantially equal current distribution between a plurality of parallel connected diodes, even though their forward conducting characteristics are not matched to one another.

In general, I provide a reactor construction which is such that the forward voltage drop of any individual rectifier is automatically adjusted by inductive means depending upon the individual rectifier characteristics so that the total current through each of the diodes is substantially constant.

In one form of this novel invention, I provide a reactor system comprising a through-type balancing reactor in a so-called "white tree" arrangement. Thus, a main current carrying bus is divided into two branches. Each of these branches is then connected to form a first and second winding of a magnetic core, whereby the flux induced in the magnetic core due to the first and second winding are in opposing direction. Thus, if the current through the first branch exceeds the current in the second branch by the magnetizing current of the reactor, the voltage of the first branch will be reduced, and the voltage in the second branch increased by an equal amount, and in just sufficient amount to increase and decrease their currents respectively, so that they will differ by no more than the required magnetizing current.

In a similar manner, if the current in the second branch exceeds the current in the first branch by the magnetizing current of the reactor, the voltage of the first branch will be increased and the voltage of the second branch decreased.

It is to be noted that the flux of the reactor during any

conductive cycle is varied in only a single direction, this flux being decreased to its residual flux density during the blocking cycle of the respective series connected diode. For this reason, the reactor cores should be of the type having a low residual magnetization wherein small air gaps could be utilized to achieve this end in the absence of special reactor control systems as will be set forth hereinafter.

The first and second branch thus being balanced to carry a substantially equal current within the limits of the magnetizing current of the reactor may then each form a further first and second branch, each of which is taken through a reactor in a manner similar to that described above. The outputs of these two reactors will then have four current branches wherein the current in each of the branches is substantially equal within the limits of the magnetizing current of their controlling reactors.

If now a single diode is connected in each of the four output branches, then it is clear that they will each carry the same current magnitude differing only by the magnetizing currents of their varying reactors, regardless of their individual forward voltage characteristics.

If it is now desired to further increase the current rating of the system, it is obvious that each of the four output branches could be further subdivided with the use of further balancing reactors whereby eight output branches would be provided at which points diodes would be connected to carry an equally distributed load current.

A second embodiment of my novel invention could comprise a simple series reactor connected in series with each of the individual diodes wherein each of the impedances are substantially equal and fixed and are of such a value that the reactor impedance drop is substantially larger than the variation of forward resistance drop between diodes. Hence the variation in forward resistance from diode to diode which results in the current unbalance will be a smaller percentage of the total branch impedance whereby the current unbalance from branch to branch will be reduced similarly and effective current balancing will result.

The construction of these series reactors is so simple as to possibly offset the disadvantage of decrease in power factor in the rectifier system due to their use. By way of example, the reactors could be comprised of a substantially U-shaped iron core which is simply slipped over a conductor in series with an associated diode, the air gap between the adjacent ends of the reactor core providing a reactor which will not saturate at peak forward current, and having the desired low residual magnetization to prevent the subsequent saturation of the reactor which would occur since this reactor is subject to repetitive uni-directional pulses. If desired, this U-shaped lamination could be a substantially circular lamination having an air gap cut therein wherein laminations are stacked around the conductor to be connected in series with the diode until the required reactor size is achieved.

In the event of the application of this invention to a rectifying system wherein additional eddy current and hysteresis losses within the reactors can be tolerated, the reactor core could be constructed of an extremely cheap solid block of soft iron or solid iron having a hole therethrough and a slot or providing the required air gap.

In order to provide a more accurate balancing in the above described system with lower overall impedance and less effect on power factor, using the inexpensive and compact series reactor having only a single turn comprising the main conductor for each diode, each reactor core may be provided with a small secondary winding wherein the secondary windings of each reactor are

connected in series to thereby reduce the effective impedance and still force proper current division within the limits of the magnetizing currents of the reactors in a manner similar to that described by the through-type reactor.

A still further embodiment of my novel invention would be in the utilization of the "couplet" type reactor used in a chain or cascaded arrangement. More specifically, in the "couplet" type of system, the conductors of a first and second diode will be coupled by a magnetic core so that magnetic motive forces are induced in the core in opposite directions. The conductor of a third diode is then coupled to the conductor of the second diode by a second magnetic core so that once again fluxes are induced in the second magnetic core in opposite directions by the currents in the second and third diode conductors.

In the same manner, any desired number of conductors which include diodes which are to be connected in parallel may be added to the above noted chain by providing a magnetic core for coupling to adjacent diode conductors so that the fluxes in the core will be induced in opposite directions. So long as the chain arrangement is utilized and the first diode conductor is not coupled to the last diode conductor added to the system, the maximum current unbalance between the individual diodes cannot exceed the total magnetizing currents of all the core used minus one.

If, however, an even number of parallel connected diodes are used in the above described chain, it is possible to close the chain by coupling the first and last diode conductor whereby the maximum current unbalance cannot exceed the magnetizing current of one-half the total number of reactors. If it is desired to reduce the current unbalance in the straight chain relationship to the value of one-half the magnetizing current given inherently in the closed chain arrangement, I have found it possible to close the straight line arrangement even though an even number of parallel elements are utilized by providing an extra core on each end of the straight line arrangement and to thereafter connect auxiliary windings of each core to one another.

Accordingly, a primary object of this invention is to provide novel means for forcing a predetermined current distribution between parallel connected diodes of the metallic or semi-conductor type.

Another object of this invention is to provide a novel reactor means for allowing parallel connection of a plurality of diodes so that a substantially equal current distribution is forced between the diodes regardless of their forward voltage characteristics.

Another object of my invention is to provide a reactor control system for equally distributing current between parallel connected diodes wherein the forward voltage drop of each of the diodes is adjusted by an associated reactor so that substantially the identical current flows through each of the diodes.

Still another object of this invention is to provide a reactor control means for equally distributing current between parallel connected diodes which utilizes balancing reactors connected in a whiffle tree arrangement wherein an individual diode is placed in each of the final branches and are subjected to substantially equal currents within the limits of the magnetizing current of their associated reactors.

A further object of this invention is to connect substantially fixed and equal impedances of the straight-through reactor type in series with each of the diodes of a plurality of parallel connected diodes wherein the impedances of the reactor is substantially higher than the forward resistance of its individual diode and unbalance of current through the individual diodes due to differences in their forward resistance are substantially reduced.

A still further object of this invention is to provide an individual through-type reactor in series with each diode of a plurality of parallel connected diodes wherein the core comprises a substantially hollow magnetic structure having an air gap therein wherein the conductors of associated diodes pass straight-through the openings of their associated reactor cores.

Yet another object of this invention is to connect the above noted type of straight-through reactor in each parallel branch of a system of parallel connected diodes and to further provide secondary windings for each of the reactors, these secondary windings being connected in series so as to reduce the overall impedance and maintain the current balance between each of the diodes within the limits of the magnetizing currents of the reactors.

Another object of this invention is to interconnect parallel branches of a system of parallel connected diodes by means of couplet reactors which comprise magnetic cores which encompass adjacent pairs of conductors so that flux is induced in opposite directions within each individual core by its associated adjacent conductors.

Still another object of this invention is to utilize the above noted couplet reactor system for forcing substantially equal current distribution between parallel connected diodes wherein the chain of reactors is closed when an even number of parallel elements is utilized.

Yet another object of this invention is to close a couplet reactor chain of the above noted type having an odd or even number of parallel elements by provided auxiliary cores for the first and last conductor of the chain, and thereafter interconnecting the two auxiliary cores by associated auxiliary windings.

As has been pointed out above, it is necessary to utilize a reactor having a low residual magnetization since the flux reversing operation on the reactor will be uni-directional and the operation of the reactor will occur somewhere between its point of residual flux density and saturation flux density. Thus, by providing a low residual magnetization for a low residual flux density, the core will be able to achieve a relatively large flux change and may be made relatively small as compared to cores having a relatively high residual magnetization.

It would, however, be desirable to utilize a material of the grain oriented type, since magnetizing currents in these type cores is extremely low. This would normally be prevented, however, since the residual magnetization of these cores is extremely high as compared to the heretofore described cores which could be constructed of normal transformer steel and having air gaps therein.

I have found, however, that I can utilize a core material of the highly grain oriented type by providing control circuitry for reducing the residual flux of the control cores to zero during the blocking period of the diode associated with the reactor. By way of example, I can provide an auxiliary coil for the reactor which is connected in series with a capacitor wherein the coil and capacitor form a resonant circuit whose operation is initiated during inverse voltage conditions so as to oscillate at a frequency which is relatively high when compared to the frequency of the A.-C. source being rectified. The oscillating current of this resonant circuit is therefore so applied to the core that a gradually diminishing magnetomotive force is applied to the core during inverse voltage conditions of the diode so as to return the core to a zero or very low residual flux.

Accordingly, another important object of this invention is to provide reactor means for forcing an equal current distribution between a plurality of parallel connected diodes wherein the reactor is of the type having a relatively small magnetizing current.

Still another object of this invention is to utilize a reactor having a material of high residual flux density for forcing equal current distribution between a plurality of parallel connected diodes wherein auxiliary oscillator means are provided for recycling the reactor residual flux to an extremely low value during inverse voltage conditions of the diode associated with the reactor.

These and other objects of my invention will become apparent from the following description when taken in connection with the drawings in which:

FIGURE 1 shows a single phase half-wave rectifier having a plurality of diodes connected in parallel.

FIGURE 2 shows the forward voltage characteristics of the diodes of FIGURE 1.

FIGURE 3 shows the application of balancing reactors to the circuit of FIGURE 1 for forcing a substantially equal current distribution between the diodes.

FIGURE 4 shows the forward voltage drop on two of the diodes of FIGURE 1.

FIGURE 5 shows another embodiment of balancing type reactors.

FIGURE 6 shows a still further embodiment of balancing type reactors.

FIGURE 7 illustrates my novel invention wherein straight-through reactors are applied to the circuit of FIGURE 1.

FIGURE 8 is an exploded perspective view showing the mechanical construction of the through-type reactors of FIGURE 7.

FIGURE 9 shows the manner in which secondary windings may be applied to the reactors of FIGURES 7 and 8 for forcing a more nearly equal current balance between their associated diodes, while reducing the effect of the reactors on power factor.

FIGURE 10 shows an application of my novel invention wherein couplet reactors are applied in an open chain relationship.

FIGURE 11 shows a further application of the couplet type reactors to a closed chain system.

FIGURE 12 shows how an open chain of couplet reactors for an odd number of diodes may be connected in a closed chain relationship.

FIGURE 13 shows how an even number of diodes connected in an open chain by couplet reactors may be connected in a closed chain relationship.

FIGURE 14 illustrates one possible physical arrangement of an open chain couplet reactor system.

FIGURE 15 shows the bus and bus flanges of the device of FIGURE 14.

FIGURE 16 shows a view of FIGURE 15 when taken across lines 16-16.

FIGURE 17 shows a view of FIGURE 14 when taken across the lines 17-17.

FIGURE 18 shows a view of FIGURE 14 when taken across the lines 18-18.

FIGURE 18A shows how the coupling reactors may be modified to allow conductor entrance to the bus of FIGURE 14 from the same side of the bus rather than from alternate sides.

FIGURE 18B shows a side view of FIGURE 18A.

FIGURE 18C shows another manner in which the device of FIGURES 18A and 18B could be constructed.

FIGURE 18D and 18E show side views of the laminations of the devices of FIGURE 18C.

FIGURE 19 illustrates how the reactors of my novel invention may be adapted to allow the use of high residual flux density material having relatively low magnetizing current.

FIGURES 20A and 20B show current time characteristics for the diode of FIGURE 19, and resonant circuit current as a function of time for the resonant circuit of FIGURE 19 respectively.

FIGURE 21 shows the demagnetization curve of the reactor of FIGURE 19.

FIGURES 22A and 22B illustrate the characteristics

of forward and inverse voltage drop as a function of time and coil voltage as a function of time for the embodiment of FIGURE 23.

FIGURE 23 shows the application of the reactor of FIGURE 19 to a rectifying system of parallel connected diodes utilizing the open chain couplet reactor for forcing equal current distribution between the parallel connected diodes.

FIGURE 1 shows a single phase half-wave rectifier which will for the most part be used hereinafter in illustrating my novel invention. It is to be specifically noted, however, that the use of a single phase rectifying system is to be taken for illustrative purposes only, since my novel invention is clearly applicable to any type of rectifier connection so long as diodes in any branch are to be connected in parallel.

In a similar manner, while the use of four parallel connected diodes has been used for the most part in the following description, this number has been arbitrarily selected and my novel invention is equally adapted in the paralleling of from two to any desired number of diode elements which are to have a substantially equal current flow therethrough.

Thus, FIGURE 1 shows a single phase A.-C. voltage source 30 connected to energize a D.-C. load 32 through the parallel connected diodes 34, 36, 38, and 40. The forward voltage characteristic of each of diodes 34 through 40 is shown in FIGURE 2 where it is seen that since each of the diodes of FIGURE 1 has a forward voltage drop V_1 , the current through each parallel branch is different. That is to say, diodes 34, 36, 38 and 40 conduct currents having the magnitudes I_1 , I_2 , I_3 , and I_4 respectively.

Clearly this unbalance in current distribution is due to the difference in the forward voltage characteristic of each of the diodes as is clearly seen in FIGURE 2.

The principle of my invention is to provide a reactor control means which is so constructed that the currents in each of the parallel branches will be forced to maintain a substantially equal distribution. Thus, reference to FIGURE 4 which, for illustrative purposes, shows the wave shapes of the forward voltage drops of the branches containing diodes 34 and 36 of FIGURE 1 as voltage drops V_1 and V_2 respectively, these voltage drops are to be controlled by the reactor means of my invention so that an equal current distribution will result. That is to say, the reactor means operating on the current I_2 will cause a difference in forward voltage drop for the two diode branches in accordance with the voltage time area which is given by the shaded area of FIGURE 4, this area being equal to the integral of V_1 minus V_2 where V_2 is the voltage drop on diode 36 times the differential in time. Thus the diode currents may now be adjusted to the same value.

One type of reactor means which satisfies the above condition in accordance with my novel invention is set forth in FIGURE 3 wherein the circuitry of FIGURE 1 has been modified to include the through-type reactors 42, 44 and 46 which are connected in a whiffle tree type arrangement for forcing the desired current equalization. More specifically, the right hand end of source 30 is broken into a first and second branch which include windings 48 and 50 respectively on the core 42. These two windings are so connected that they will induce M.M.F.'s in the core 42 in opposing directions. Accordingly, as soon as the magnetizing current of core 42 is exceeded because of an unbalance in the ampere turns of the flux due to a higher current in one winding, a voltage will be induced in winding 50 and the voltage in the branch winding will assume a reactance and the current therethrough containing winding 48 will be reduced until the currents in windings 48 and 50 are equal (within the magnetizing current of core 42).

Each of the two branches including windings 48 and 50 are then further branched, the branch including wind-

ing 48 being subdivided into branches including windings 52 and 54 while the branch including winding 50 is subdivided into the branches including windings 56 and 58.

Here again current equalization takes place in the branches including windings 52 and 54 and the windings 56 and 58 in the same manner as previously described for windings 48 and 50. Thus, the current flow through diodes 34, 36, 38 and 40 will be substantially identical, differing only by the magnetization current of the cores acting thereon regardless of their forward voltage characteristics. Hence, if current unbalance would normally exist between the diode branches including diodes 34 and 36, it is seen that winding 54 will have induced in it a voltage of such a value to alter the voltage drop across diode 36 to a value V_2 , this voltage drop value being seen in FIGURE 2 to correspond to the current I_1 which is the current flowing through the diode 34. Clearly diodes 38 and 40 will have their voltage drops similarly adjusted to have their current magnitudes equalized to those diodes 34 and 36 through the operation of windings 50 and 58.

Another type of balancing reactor system is set forth in FIGURE 5 which shows a double Y secondary wherein the neutral points of the Y connected secondary windings 60 and 62 are connected through an interphase transformer 64, the center of which is connected to one side of a load 66. Each phase of secondary windings 60 and 62 is then taken out in the manner substantially identical to that shown in FIGURE 5 for the case of phase A which is the only phase shown, in order to simplify the diagram.

A multi-legged core (one leg for each positive and negative rectifier element) is then provided for each of the phases wherein the D.-C. component fluxes are cancelled out by having diametrically opposite phases connected through opposing windings. By way of example, phase A of winding 60 is connected to the coils 68, 70 and 72 which are in turn connected in series with rectifiers 74, 76 and 78 respectively which then connect to the opposite side of load 66. In a similar manner, phase A' is connected to windings 80, 82 and 84 having their associated diodes 86, 88 and 90 respectively similarly connected to load 66.

In order to reduce the overall impedance and its effect on power factor, and improve voltage distribution, a polygon connected tertiary including windings 92, 94 and 96 is further provided. Clearly each of the three phases of the rectifying system of FIGURE 5 would be provided with a similar three legged core as that described in conjunction with phase A.

In operation, the interaction between windings 68, 70 and 72 of the balancing reactor will maintain an equal current distribution between diodes 74, 76 and 78 in the same manner as has been set forth in the case of FIGURE 3. Similarly, windings 80, 82 and 84 will maintain equal current distribution between their associated diodes 86, 88 and 90 respectively. Because of almost complete cancellation of D.-C. ampere-turns, almost the complete flux change can be utilized.

A similar arrangement may be provided for the three phase bridge connected rectifier system of FIGURE 6 where three parallel diodes are connected in each leg of the bridge. If more than three rectifier elements are connected in parallel, the balancing reactor has more than three legs—one for each element. The tertiary winding is then connected as a regular polygon. In FIGURE 6 a delta connected secondary winding 98 for energizing a D.-C. load has a three legged core which includes windings 100, 102 and 104 for maintaining equal current distribution through diodes 106, 108 and 110 respectively. Similarly, windings 112, 114 and 116 maintain equal current distribution between diodes 118, 120 and 122. Windings 112, 114 and 116 are connected in

opposite polarity to windings 100, 102 and 104 to cancel the D.-C. ampere turns. Once again, overall impedance is reduced, power factor improved, and voltage distribution is improved by the delta connected tertiary which includes windings 124, 126 and 128.

Clearly my novel invention has been shown in FIGURE 6 as applied to only one of the phases of secondary winding 98 and the other two phases will be connected in a substantially identical manner.

FIGURE 7 shows how the circuit of FIGURE 1 could be adapted by reactance means of the series connected type. Thus in FIGURE 7, reactors 130, 132, 134, and 136 are connected in series with diodes 34, 36, 38 and 40. By constructing reactances 130 through 136 so that they will have a substantially higher impedance drop than the resistive drop of their corresponding diodes 34 to 40 and further making the reactance of reactors 130 through 136 a substantially identical value, then the current unbalance which is now controlled by a much higher impedance will be substantially independent of the diode resistance in the forward direction thereby allowing a relatively greatly improved current balance between the diode branches. This system is highly desirable since it lends itself to extremely simple manufacturing techniques.

By way of example, FIGURE 8 shows that each of the reactors could be comprised of stacks of laminations 138, 140, 142 and 144 which have openings therein for allowing the passage of associated diode conductors as well as air gaps such as air gaps 146, 148, 150 and 152 respectively. More specifically, the device of FIGURE 8 shows the A.-C. source 30 as being connected in series with a main bus 154 to which conductors 156, 158, 160 and 162 are attached. Each of conductors 156 through 162 is further provided with threaded ends which as will be seen hereinafter cooperate with fastening nuts 164 through 170 respectively. Each of conductors 156 through 162 therefore comprise a single turn winding for the reactor cores 138 through 144 respectively.

The individual diode assemblies 130, 132, 134 and 136 are commonly provided with flexible conductors terminated by electrical connecting means 180, 182, 184 and 186 respectively, while their other ends are connected to a second common bus 188 in any desired manner. Accordingly, by inserting conductors 156 through 162 through their respective reactor cores and corresponding diode terminals 180 through 186 respectively and thereafter tightening nuts 164 through 170 so as to achieve mechanical positioning of the reactors as well as electrical engagement of diode terminals 180 through 186 and conductors 156 through 162, the A.-C. source 30 may deliver rectified power to the D.-C. load 32 as indicated in FIGURE 7. Clearly, the material utilized in cores 138 through 144 could be in laminated form or solid form, depending upon allowable eddy current and hysteresis conditions.

Regardless of the type construction utilized in cores 138 through 144, however, it is necessary that air gaps 146 through 152 respectively be provided (in the absence of auxiliary means which are to be described hereinafter) since it is necessary to avoid saturation at peak forward currents and to have a small residual flux density within the core in view of the unidirectional energization thereof. That is to say, while the core is operative, its fluxchange occurs only from the point of residual magnetization to a point near saturation magnetization. Hence if as low as possible a residual magnetization is used, the core will be capable of a large flux excursion and would therefore be smaller than one having a small flux excursion because of a high residual magnetization.

As noted above, current balance between the various parallel branches in the embodiment of FIGURE 7 is achieved by making the impedance of reactors 130 through 136 high enough to make the forward resistance differences of diodes 34 through 40 substantially negligible. It is, however, possible to modify the circuit of FIGURE 7 so as to force a true current distribution between the

parallel connected diodes which is within the limits of the magnetizing currents of the reactors.

This may be accomplished as set forth in FIGURE 9 wherein the reactor cores 138, 140, 142 and 144 which have air gaps 146, 148, 150 and 152 respectively (see FIGURE 8) are provided with auxiliary secondary windings 190, 192, 194 and 196 respectively, these secondary windings being connected in series relationship. By this means all the reactors are forced to participate in the correction of a deviation of current in any one rectifier element, and there is a great reduction of the effective impedance of the reactors and their effect on power factor. In view of this connection, the current unbalance between any of diodes 34, 36, 38 or 40 is held within the limits of the magnetizing current of the associated reactors, without the undesirable effects of straight series reactors.

FIGURE 10 illustrates still another embodiment of my novel invention wherein couplet reactors are utilized for coupling the individual diode conductors of parallel connected branches. By way of example, FIGURE 10 schematically illustrates a system of parallel connected diodes wherein conductors 198, 200, 202, 204, 206, 208, 210 and 212 each have a single diode connected in series therewith. Thus the circuit corresponding to the schematic illustration of FIGURE 10 would be similar to FIGURE 1 wherein eight rather than four diodes are connected in parallel and are to have equal current distribution imposed upon parallel connected diodes.

In FIGURE 10, however, coupled reactors 214, 216, 218, 220, 222, 224 and 226 couple adjacent branches of the parallel system in such a manner that the current flow in adjacent branches is in opposite directions as indicated by the dots and crosses of conductors 198 through 212 which show current flow into and out of the drawing respectively.

Thus reactor 214 couples branches 198 and 200 in such a manner that the fluxes induced in the core 214 due to conductors 198 and 200 are in opposing directions. In a similar manner, reactor 216 couples branches 200 and 202, reactor 218 couples branches 202 and 204, and so on down the line until the chain is completed by the coupling of conductors 210 and 212 by the core 226.

During operation of a circuit constructed in accordance with the circuit of FIGURE 10, the current unbalance will not exceed the total magnetizing current of all the cores minus one, as is obvious in considering the arrangement.

Here again, cores 214 through 226 should be of material having a low residual magnetism in order to prevent saturation of the cores by an accumulation of uni-directional volt-seconds in successive conducting periods.

If it is desired, a small air gap may be inserted in each of the cores to lower its residual magnetism. However, it is possible by auxiliary circuitry to be described hereinafter, to construct these cores of a grain oriented material having an extremely low magnetizing current. This, of course, would be highly desirable since the maximum current unbalance in the system of FIGURE 10 will be limited to the total magnetizing current of all the cores minus one, as was set forth above.

In the event that there are an even number of parallel elements in the arrangement of FIGURE 10, it is possible to close the loop as shown in FIGURE 11 by providing the additional core 228 which couples conductors 212 and 198. In the closed loop, the maximum current unbalance is decreased from the case of the straight chain to the magnetizing current of one-half the total number of reactors. However, in the absence of auxiliary equipment, the loop can only be closed as seen in FIGURE 11 with an even number of conductors. For if an odd number of conductors were used, the conductors at each end of the chain would conduct current in the same direction and could not be directly coupled to one another.

It is, however, possible to close a straight chain of either an odd or even number of conductors by use of

auxiliary reactors and auxiliary windings therefor, as set forth in FIGURES 12 and 13. By way of example, FIGURE 12 shows the manner in which a parallel group of conductors corresponding to an odd number of diodes may be closed without having to physically circle the configuration. It is to be noted that the configuration of FIGURE 12 is substantially identical to that of FIGURE 10 with the exception of the omission of core 226 and conductor 212.

In order to allow closing of the chain or of the loop, the auxiliary core 230 having an air gap 232 is coupled to conductor 198 while core 234 having an air gap 236 is coupled to conductor 210 which is the last conductor of the chain. Each of the cores 230 and 234 are then provided with auxiliary windings 238 and 240 respectively which can be connected to one another in any desired polarity so as to effect closing of the loop by a simple electrical connection which allows any desired choice of configuration of the chain, yet still providing the desired current balance which is limited to only one-half the magnetizing current of all the cores.

In a similar manner, the configuration of FIGURE 13 which is identical to that of FIGURE 10 may close the loop by means of the same type auxiliary reactors 230 and 234 having auxiliary windings 238 and 240 which are connected as is required to achieve proper polarities of the fluxes in cores 230 and 234 with respect to the flux induced by conductors 198 and 212 respectively.

Here again, however, the coupling of the cores is achieved by purely electrical connecting means rather than by the physical configuration of the core, as was the case in FIGURE 11.

FIGURES 14 through 18 show one method by which the open chain construction of FIGURE 10 could be accomplished in a rectifier circuit. FIGURE 14 shows the A.-C. voltage source 30, which is to deliver D.-C. power to the load 32 as being connected to a bus bar 242 which, as is best seen in FIGURES 15 and 16, has conducting flanges 244 and 246 fastened thereto in any desired manner. If desired, the bus may be hollow as shown in FIGURE 16 to allow passage of a cooling medium. Each of flanges 244 and 246 is provided with alternate through holes and tapped openings so as to allow electrical connection by extensions of conductors 196, 198, 200, 202 and 204 to pass through their corresponding coupling reactors 214, 216, 218 and 220 (see FIGURE 10) in alternate directions.

Thus the flange plate 244, seen in FIGURE 15, has a through hole 248, a tapped opening 250, a through hole 252, and then a further tapped opening 254 while flange plate 246 is provided with alternate tapped openings which register with the through hole of flange plate 244 and through holes which register with the tapped openings 250 and 254 of flange plate 244.

Thus, as may be best seen in FIGURE 17, conductor 198 has a flexible portion fastened to a conducting bolt member 256 which passes through a through hole in flange plate 246 through the balance reactor cores 214 and 216 and thereafter threadably engages flange plate 244 in a current carrying engagement. Conversely, the conductor 200 which was to initiate a flux in core 216 which is in a direction opposite to the flux initiated by conductor 198 passes through hole 248 of flange plate 244 and then through the cores 216 and 218 and terminates in a threaded engagement with flange plate 246. Clearly, this alternate type of construction is continued for each of the current conductors of the particular rectifier phase in question.

Thus, although the rectifiers associated with conductors 196, 198, 200 and 202 and 204 which are each connected to the common bus 258 so as to properly energize load 32, the current directions of the conductors of a common coupling reactor are opposite to one another in order to allow the desired current equalization or equal current

distribution of current flowing through each of the parallel connected diodes.

If desired, the structure set forth in FIGURES 14 through 18 may be easily modified so as to allow the conductor entrance through the reactor from the same direction or from the same side of the bus while opposite fluxes may still be induced in the coupling reactors by constructing these reactors to have the figure 8 shape set forth in FIGURES 18A and 18B, 18C and 18D. More specifically, FIGURE 18A shows a coupling core 260 which could be used as any of the coupling cores 214 through 220 of FIGURE 14 as being constructed of a roll of magnet wire twisted in a figure 8 shaped and formed to nest in any desired manner as shown in FIGURE 18B. Clearly, by passing two conductors 262 and 264 through the two openings formed by the figure 8 as seen in FIGURE 18A, each having current conduction in the same direction will give rise to opposing fluxes within the core 260. While FIGURES 18A and 18B show this configuration as being formed by a roll of magnet wire, it could clearly be constructed of punched and formed laminations as shown in FIGURES 18C, 18D and 18E where FIGURE 18C shows the reactor as comprising a first set of laminations 300, one of which is seen in side view in FIGURE 18D and a second set of laminations 302, one of which is seen in side view in FIGURE 18E. If desired, air gaps in alternate laminations can be alternated as seen in FIGURE 18C to decrease the reluctance of the core. In any case, it is clear that the core can be constructed in any desired manner so long as the residual magnetization is relatively small. For instance, there would be considerable advantage in making the cores by powder-metallurgy techniques, or of molded ferro-ceramic materials.

As has been heretofore mentioned, it would be desirable to use a reactor core in any of the above applications of material having as low as possible a magnetizing current since the current unbalance from diode to diode is usually dependent upon this magnitude of magnetizing current. However, it is well known that cores exhibiting very low magnetizing currents such as the square hysteresis loop type of core also exhibit an extremely high residual flux density. This high residual flux density is extremely undesirable for applications of my novel invention since it would require an extremely large core if the core is to be kept from saturating due to the accumulation of unidirectional volt seconds in successive conducting periods.

I have found, however, that I can provide a core such as the core 266 of FIGURE 19 which is of rectangular loop material which is utilized in coupling conductors 268 and 270 of diodes 272 and 274 respectively in the manner set forth hereinabove with an auxiliary winding 276 which is connected in series with a condenser 278, the condenser being chosen in combination with the average inductance of the coil taken to the knee of the saturation curve of FIGURE 21 to form a resonant circuit which will oscillate at a frequency considerably higher than the supply frequency. The operation of this novel circuit of FIGURE 19 may now be considered in conjunction with FIGURES 20A and 20B.

During operation, as has been previously set forth, the reactor will operate to absorb a forward voltage difference as indicated by the shaded area of FIGURE 20A. Because of this voltage, the current in the resonant circuit I_R will oscillate at a frequency such as that set forth in FIGURE 20B, until the point at which the forward voltage drop on the diode has decreased to zero. At this point, it is to be realized that there will be a rapid decay of current in the diodes produced by the commutating voltage which will induce a transient voltage in the auxiliary coil 276 so as to cause the rapid oscillation seen in FIGURE 20B at the end of the forward voltage drop across the diode.

In view of this rapidly oscillating current of decreasing

magnitude, the flux within core 266 will be cycled along the demagnetization curve shown in FIGURE 21 until its resultant residual flux is very small. Hence, upon the next cycle of forward conduction of the associated diodes, the reactor will be able to change in flux from this very small value to its saturation value and offer current differences for the diodes cooperating therewith which are very small in view of the very small magnetizing current of the type material utilized in the core 266.

While initiation of oscillation in the resonant circuit including coil 276 and capacitor 278 depended upon transients due to rapid decay of current in the diodes due to commutating voltage, it will be apparent to those skilled in the art that the sudden rise of inverse voltage at the end of the conducting period of the diode as seen in FIGURE 22A could be utilized in initiating this operation. Thus, the coil voltage in this type of system would be that seen in FIGURE 22B whereby demagnetization of the associated reactor core is achieved.

One application of this novel flux control system to the couplet reactor system of the type shown in FIGURE 10 is set forth in FIGURE 23 in conjunction with a three phase half-wave rectifier system, only one phase of which is shown for purposes of clarity. Thus phase A of transformer 280 is connected to the parallel system of diodes having associated conductors 198 through 208 (see FIGURE 10) so that D.-C. energization of load 282 may proceed. Furthermore, adjacent conductors are coupled by the reactors 214 through 222 as was further set forth in FIGURE 10, whereby the current through the diodes in series with conductors 198 through 208 have a maximum current unbalance which does not exceed the total magnetizing current of all the cores 214 through 222 minus one.

So as to reduce this maximum current unbalance due to magnetizing current, it is, of course, necessary to utilize cores having the smallest possible magnetizing current while still providing means for reducing the inherently high residual flux density to a minimum during inverse voltage conditions of the diode as set forth above in connection with FIGURE 19. Accordingly, each of reactors 214 through 222 is provided with auxiliary windings 284 through 292 respectively which are connected in series with a resonating capacitor 294 and an additional external reactor 296 which may be needed in the event that the inductance of windings 284 through 292 is so low that a prohibitively large capacitor 294 would be required.

Clearly, however, the operation of this circuit proceeds in a manner identical to the operation described above in connection with FIGURES 19, 20A, 20B and 21 wherein the oscillatory current through windings 284 through 292 operates to reduce the flux of each of cores 214 through 222 along a demagnetization curve so that the effective residual flux density at the end of each operation of the reactor will be extremely small.

Furthermore, since these reactors may be of a material which has an extremely small magnetizing current, the current unbalance between the diodes of the system of FIGURE 23 will be more closely maintained than if the reactor material had been of normal transformer type steel having a relatively high magnetizing current.

Clearly, the same recycling control could be applied to any of the reactor control embodiments set forth in this patent application and its specific application to the couplet reactors of FIGURE 10 has been intended for illustrative purposes only.

Although I have here disclosed preferred embodiments of my novel invention, many variations and modifications will now be obvious to those skilled in the art and I prefer therefore to be limited not by the specific disclosure herein, but only by the appended claims.

I claim:

1. A current balancing system for a first and second parallel connected diode, said current balancing system

comprising a reactor means including a first and second reactor winding connected in series with said first and second parallel connected diodes; said reactor windings being constructed to adjust the forward voltage drop on their said respective diodes until the forward current through each of said diodes is substantially similar regardless of their forward voltage characteristics; said reactor means comprising straight through reactors having air gaps therein and a substantially equal impedance which is substantially greater than the forward resistance of said first and second diodes; each of said straight through reactors being subjected to flux change throughout the forward voltage cycle of their respective diodes; each of said straight through reactors having an auxiliary winding; each of said auxiliary windings being connected in series.

2. A current balancing system for a plurality of parallel connected diodes; said current balancing system comprising a respective reactor means winding connected in series with each of said parallel connected diodes; each said reactor means winding being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; said reactor means comprising at least a first and second couplet reactor core for magnetically coupling at least three conductors connected to three respective diodes of said plurality of diodes into pairs; the conductors of each of said pairs formed by said three conductors being directed to induce opposing magnetomotive forces in their said reactor cores.

3. A current balancing system for a plurality of parallel connected diodes; said current balancing system comprising a respective reactor means winding connected in series with each of said parallel connected diodes; each said reactor means winding being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; said reactor means comprising at least a first and second couplet reactor core for magnetically coupling at least three conductors connected to three respective diodes of said plurality of diodes into pairs; the conductors of each of said pairs formed by said three conductors being directed to induce opposing magnetomotive forces in their said reactor cores; each of said couplet reactor cores having a low residual magnetism.

4. A current balancing system for a plurality of parallel connected diodes, said current balancing system comprising a respective reactor means winding connected in series with each of said parallel connected diodes; each said reactor means winding being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; said reactor means comprising a respective couplet reactor core for magnetically coupling conductors connected to each of said plurality of diodes into pairs; the conductors of each of said pairs being directed to induce opposing magnetomotive forces in their said respective reactor core; each of said reactor cores being constructed to have a low residual flux density; said couplet reactors forming a closed chain.

5. A current balancing system for a plurality of parallel connected diodes, said current balancing system comprising a respective reactor means winding connected in series with each of said parallel connected diodes; each said reactor means winding being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; said reactor means comprising a respective couplet reactor core for magnetically coupling conductors connected to each of said plurality of diodes into pairs; the conductors of each of said pairs being directed to

induce opposing magnetomotive forces in their said respective reactor core; each of said reactor cores being constructed to have a low residual flux density; said couplet reactors forming an open chain having a first and second auxiliary couplet reactor connected to the first and last diode conductor respectively of said chain; each of said auxiliary reactors having auxiliary windings thereon connected in series to close said chain.

6. In a rectifier system for energizing a D.-C. load from an A.-C. source, said rectifier system including a plurality of parallel connected diodes for achieving a predetermined current rating, a current balancing system for forcing a substantially equal current distribution between each of said plurality of diodes; said current balancing system comprising inductive means connected in series with each diode of said plurality of diodes; said inductive means being constructed to adjust the forward voltage across each of said diodes to force equal current through each of said diodes regardless of the forward voltage characteristics of said diodes, said inductive means being operative throughout the forward voltage conduction cycle of said plurality of diodes; said inductive means comprising a respective couplet reactor core for magnetically coupling conductors connected to each of said plurality of diodes into pairs; the conductors of each of said pairs being directed to induce opposing magnetomotive forces in their said respective reactor core; each of said couplet reactor cores having a low residual magnetism; said couplet reactors forming a closed chain to maintain a maximum current unbalance no greater than the magnetizing current of one-half of the total magnetizing current of the couplet reactor cores.

7. In a rectifier system for energizing a D.-C. load from an A.-C. source, said rectifier system including a plurality of parallel connected diodes for achieving a predetermined current rating, a current balancing system for forcing a substantially equal current distribution between each of said plurality of diodes; said current balancing system comprising inductive means connected in series with each diode of said plurality of diodes; said inductive means being constructed to adjust the forward voltage across each of said diodes to force equal current through each of said diodes regardless of the forward voltage characteristics of said diodes, said inductive means being operative throughout the forward voltage conduction cycle of said plurality of diodes; said inductive means comprising a respective couplet reactor core for magnetically coupling conductors connected to each of said plurality of diodes into pairs; the conductors of each of said pairs being directed to induce opposing magnetomotive forces in their said respective reactor core; each of said couplet reactor cores having a low residual magnetism; said couplet reactors forming an open chain having a first and second auxiliary couplet reactor connected to the first and last diode conductor respectively of said chain; each of said auxiliary reactors having auxiliary windings thereon connected in series to close said chain.

8. A current balancing system for a plurality of parallel connected diodes, said current balancing system comprising a respective reactor means winding connected in series with each of said parallel connected diodes; each said reactor means winding being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; each of said reactor means comprising a core of material having high residual flux density and low magnetizing current, resonant circuit means for each of said reactor means including a capacitor and an auxiliary reactor winding, said resonant circuit being energized to oscillate after the end of forward current conduction through said diodes to recycle said magnetic core to a small residual flux density.

9. A current balancing system for a first and second parallel connected diode, said current balancing system

comprising a first and second reactor winding connected in series with said first and second parallel connected diodes; said reactor windings being constructed to adjust the forward voltage drop on their said corresponding diodes until the forward current through each of said diodes is substantially similar regardless of their forward voltage characteristics; said first and second reactor windings being wound on a common magnetic core in a direction to induce opposing magnetomotive forces in said core; said magnetic core material being of high residual flux density, low magnetizing current type, and oscillatory means connected to said magnetic core for recycling the flux of said magnetic core to a low flux density after the end of forward conduction through said diodes.

10. The current balancing system of claim 9 wherein said oscillatory means comprises an auxiliary winding on said magnetic core and a capacitor, the resonant oscillating frequency of said auxiliary winding and said capacitor being substantially higher than the frequency of voltage applied to said diodes.

11. In a rectifier system for energizing a D.-C. load from an A.-C. source, said rectifier system including a plurality of parallel connected diodes for achieving a predetermined current rating, a current balancing system for forcing a substantially equal current distribution between each of said plurality of diodes; said current balancing system comprising respective inductive means connected in series with each diode of said plurality of diodes; each of said inductive means being constructed to adjust the forward voltage across each of said diodes to force equal current through each of said diodes regardless of the forward voltage characteristics of said diodes, each of said inductive means being operative throughout the forward voltage conduction cycle of said plurality of diodes; each of said inductive means including a magnetic core of square hysteresis loop material; and oscillatory means connected to each magnetic core for recycling the flux of said magnetic core to a low flux density after the end of forward conduction through said diodes.

12. The current balancing system of claim 11 wherein said oscillatory means comprises an auxiliary winding on said magnetic core and a capacitor, the resonant oscillating frequency of said auxiliary winding and said capacitor being substantially higher than the frequency of voltage applied to said diodes.

13. A current balancing system for a plurality of parallel connected diodes, said current balancing system comprising a respective reactor means connected in series with each of said parallel connected diodes; each said reactor means being constructed to adjust the forward voltage drop on its corresponding diode until the forward currents of each of said diodes are substantially similar regardless of their forward voltage characteristics; said plurality of parallel connected diodes terminating on a common bus bar; each said reactor means being physically supported by said bus bar.

14. A current balancing system for a first and second parallel connected diode, said current balancing system comprising a first and second reactor winding connected in series with said first and second parallel connected diodes, respectively; said reactor windings being constructed to adjust the forward voltage drop on their said corresponding diodes until the forward current through each of said diodes is substantially similar regardless of their forward voltage characteristics; said first and second parallel connected diode terminating on a common bus bar system; said current balancing system including said first and second reactor windings being physically supported from said bus bar system.

15. The current balancing system of claim 4 wherein said current balancing system is supported from a bus bar system associated with said plurality of parallel connected diodes.

16. The current balancing system of claim 5 wherein said current balancing system is supported from a bus

bar system associated with said plurality of parallel connected diodes.

17. In a rectifier delivering energy from an A.-C. source to a D.-C. load; said rectifier comprising a plurality of parallel connected diode conductors; each of said plurality of parallel connected diode conductors having a diode connected therein; a current balancing reactor system for distributing the current flow in said parallel connected diode conductors; said current balancing reactor system including at least a first and second reactor core; each of said first and second reactor cores having a first and second winding; said first winding of said first reactor being connected in series with a first diode conductor of said plurality of diode conductors; said first winding of said second reactor being connected in series with a second diode conductor of said plurality of diode conductors; said second winding of said first reactor and said second winding of said second reactor being connected in series with one another and in series with a third diode conductor of said plurality of diode conductors; said diodes of said first, second and third conductors being connected in a direction to permit current flow for generating opposing magnetomotive forces in said first and second reactors.

18. In a rectifier delivering energy from an A.-C. source to a D.-C. load; said rectifier comprising a plurality of parallel connected diode conductors; each of said plurality of parallel connected diode conductors having a diode connected therein; a current balancing reactor system for distributing the current flow in said parallel connected diode conductors; said current balancing reactor system including at least a first and second reactor core; each of said first and second reactor cores having a first and second winding; said first winding of said first reactor being connected in series with a first diode conductor of said plurality of diode conductors; said first winding of said second reactor being connected in series with a second diode conductor of said plurality of diode conductors; said second winding of said first reactor and said second winding of said second reactor being connected in series with one another and in series with a third diode conductor of said plurality of diode conductors; said diodes of said first, second and third conductors being connected in a direction to permit current flow for generating opposing magnetomotive forces in said first and second reactors; said current balancing means forcing a substantially equal balance between the ampere turns of said first, second and third windings.

19. In a rectifier delivery energy from an A.-C. source to a D.-C. load; said rectifier comprising a plurality of parallel connected diode conductors; each of said plurality of parallel connected diode conductors having a diode connected therein; a current balancing reactor system for distributing the current flow in said parallel connected diode conductors; said current balancing reactor system including at least a first and second reactor core; each of said first and second reactor cores having a first and second winding; said first winding of said first reactor being connected in series with a first diode conductor of said plurality of diode conductors; said first winding of said second reactor being connected in series with a second diode conductor of said plurality of diode conductors; said second winding of said first reactor and said second winding of said second reactor being connected in series with one another and in series with a third diode conductor of said plurality of diode conductors; said diodes of said first, second and third conductors being connected in a direction to permit current flow for generating opposing magnetomotive forces in said first and second reactors; said current balancing means forcing a substantially equal balance between the ampere turns of said first, second and third windings; at least said first windings of said current balancing reactors being formed

by straight-through portions of said first and second diode conductors.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 2,994,028

July 25, 1961

Isadore K. Dortort

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 16, line 50, for "delivery" read -- delivering --.

Signed and sealed this 28th day of May 1963.

(SEAL)

Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents

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