

April 28, 1953

L. J. HIBBARD

2,636,997

RECTIFIER-POWERED EQUIPMENT

Filed Feb. 10, 1951

2 SHEETS—SHEET 1

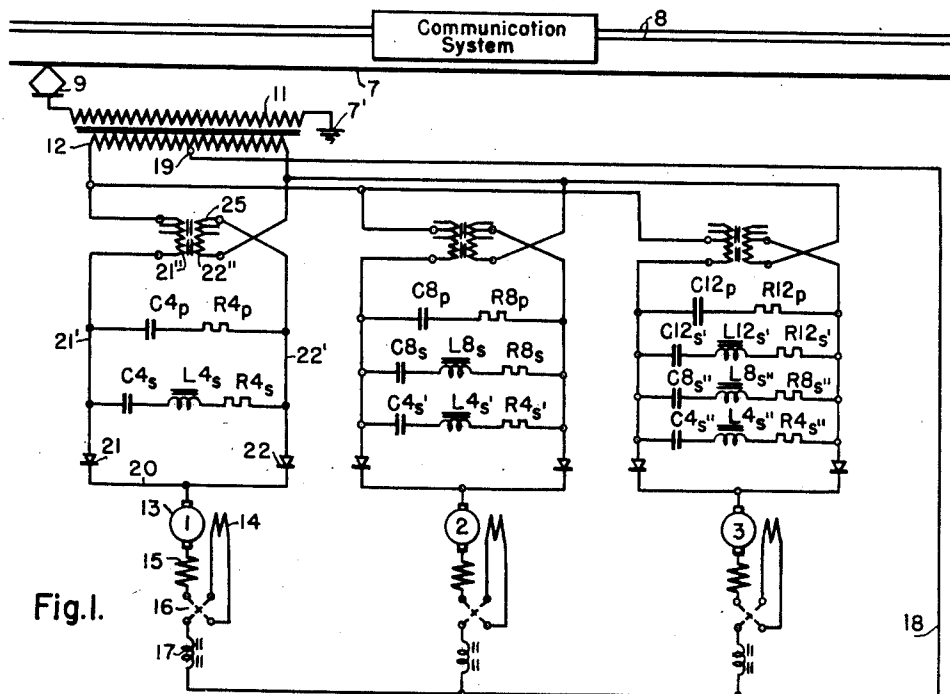


Fig. 1.

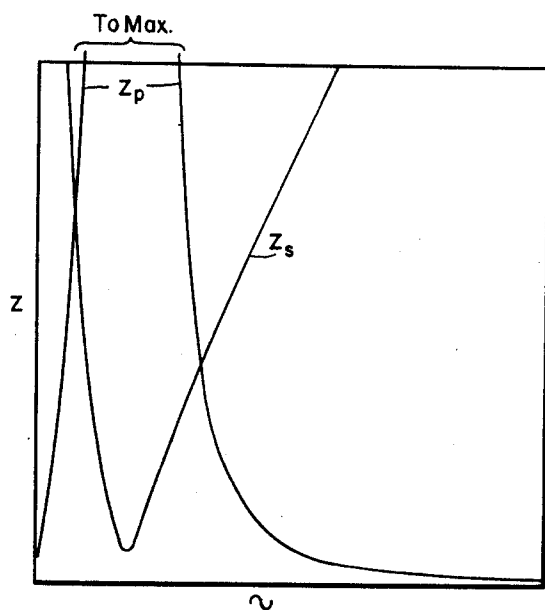


Fig. 2.

WITNESSES:

E. A. McHenry
Wm. L. Grouse

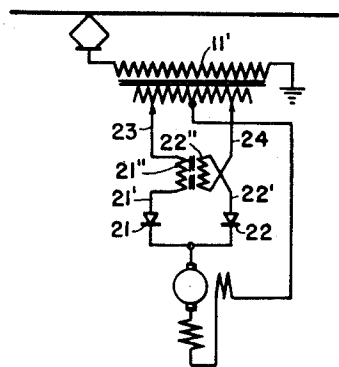


Fig. 3.

INVENTOR

Lloyd J. Hibbard.

BY *O. B. Buchanan*
ATTORNEY

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2 SHEETS—SHEET 2

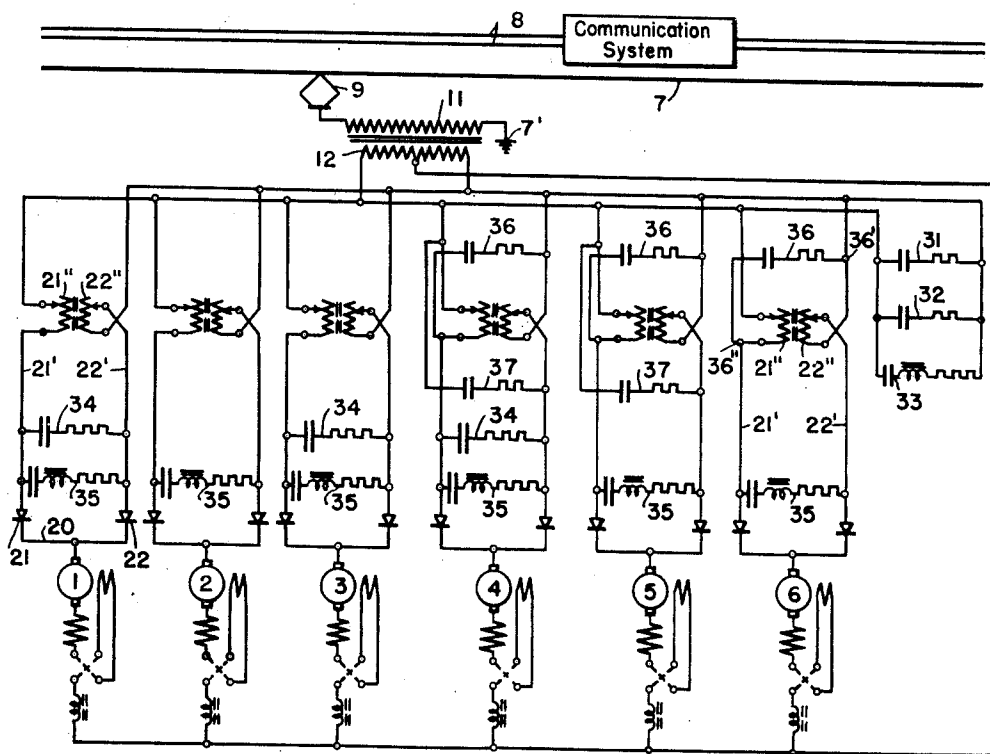


Fig. 4.

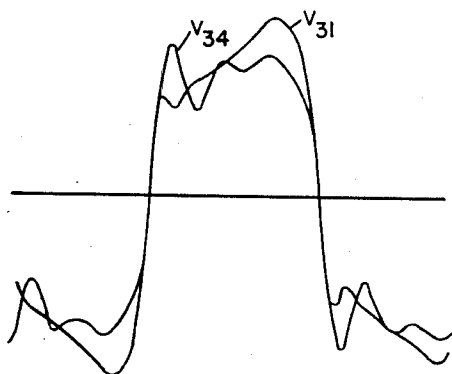


Fig. 5.

WITNESSES:

E. A. M. Locking
Wm. L. Groome

INVENTOR

Lloyd J. Hibbard.

BY *O. R. Buchanan*

ATTORNEY

UNITED STATES PATENT OFFICE

2,636,997

RECTIFIER-POWERED EQUIPMENT

Lloyd J. Hibbard, Pittsburgh, Pa., assignor to
Westinghouse Electric Corporation, East Pitts-
burgh, Pa., a corporation of Pennsylvania

Application February 10, 1951, Serial No. 210,390

25 Claims. (Cl. 307—105)

1

My invention relates to rectifier-powered trolley-energized equipments, particularly rectifier-powered traction-motor equipments for electric-railway and other vehicles. My invention relates to the filtering means and the series-reactance means, and to combinations of both, whereby the performance of the vehicle-driving motors is improved, whereby the wave shape of the alternating-current supply-line current is improved by the removal or reduction of low-order harmonics, and whereby I also remove or reduce the higher-order harmonics which cause inductive interference with communication-circuits which parallel the alternating-current supply-line.

My present invention is an improvement over the broad subject matter which is described and claimed in my application Serial No. 120,331, filed October 8, 1949, for Inductive-Interference Preventive-Means, in which a direct-current load-circuit, containing the traction-motor, and having a large direct-current ripple, is energized, from a single-phase trolley which is subject to inductive interference considerations, through a rectifier-system under such conditions that there is enough series inductance, on the supply-circuit side of the rectifiers, to produce a substantial angle of overlap of the half-wave rectifier-currents, during each half-cycle of the supply-current. Where it is necessary (as is usually the case), a harmonic-reducing filter is also provided, as described and claimed in my copending application just mentioned.

My present invention also involves improvements over my copending application Serial No. 140,475, filed January 25, 1950, for Dephased Inductive-Interference Prevention, in which the alternating-current supply-currents which are fed into a plurality of rectifier-powered traction-motor assemblies are caused to be slightly out of phase with each other, so that certain high-frequency harmonics will be approximately 180° out of phase with each other, or so related as to constitute a practically balanced polyphase system, which reduces the line-harmonics to a low value in the frequency-range which is the most critical from the standpoint of inductive interference. As most trolley-energized motor-driven vehicles are provided with a plurality of driving or traction motors, my present invention involves the provision of a plurality of rectifier-assemblies on each vehicle, each powering its own motor or group of motors, and each involving its own anode-reactance which more effectively snuffs out backfire-currents, and provides more or better series-reactance for voltage-regulation during

2

low-voltage motor-operation, and provides a ready means for dephasing the objectionable interference-causing supply-line harmonics according to the principles covered in my last-mentioned copending application.

My present invention also relates broadly to the use of a special anode-reactor for each rectifier-assembly, said anode-reactor being in the form of a reactor-transformer having two closely coupled, substantially identical-turn windings, on a common magnetic circuit which includes an air gap and which preferably also includes some iron or other magnetizable material. The two reactor-windings are serially included in the respective anode-leads of the two rectifiers with which they are associated, and are connected in such polarity that the two reactor-windings are in series for the commutating currents which flows between the two rectifiers during their overlapping conducting periods, and also in series for the back-firing currents which flow during backfire-conditions. This series reactor-winding relationship thus produces a maximum reactance in the reactor-transformer, which is desirable in order to obtain a high angle of overlap during the commutating conditions and to reduce the magnitude of the backfire-currents, while reducing the amount of voltage-reducing reactance which is effective during the normal load-carrying periods, and at the same time reducing the overall size of the two reactor-windings.

When there are a plurality of rectifier-powered loads, energized from the same alternating-current leads, the presence of individual anode-reactors, individual to each rectifier-assembly, makes the overlap-angles of the several rectifier-assemblies more nearly equal than would be the case without the anode-reactors, and thus avoids the necessity for installing balance-coils for balancing the currents drawn by the several rectifier-assemblies.

My present invention also includes a special connection of the filters which were described and claimed in my first-mentioned copending application. These filters are what I call parallel filters, being untuned filters consisting of a capacitor in series with a damping resistance, the capacitor being tuned to parallel resonance with the supply-circuit inductance, as seen from the terminals of the filter, at a frequency such as to reduce an interference-provoking range of high-order harmonics.

According to one aspect of my present invention, the parallel filters of the different rectifier-assemblies on any locomotive or car, or on any

group of parallel-energized cabs or cars, can be differently connected, with respect to the anode-reactance, such as being connected with some filters on the supply-line side of the anode-reactance, and some on the rectifier-side, or some crisscrossed with one terminal on the power-supply side of one anode-reactor winding, and the other terminal on the rectifier-side of the other anode-reactor winding. In this way, particularly if the reactance of the step-down transformer is relatively low, it is possible not only to filter out the high-frequency interference-provoking supply-current harmonics drawn by each rectifier-assembly, and to throw said high-frequency harmonics out of phase with each other, in a certain critical range or ranges of interference-provoking harmonics, but it is also possible to throw the low-order harmonics out of phase with each other, so as to reduce the amount of third harmonic, and other low-order harmonics, which are drawn from the line by the plurality of rectifier-assemblies which are mounted on each vehicle, thus improving the wave-form of the power-line currents.

One of the disadvantages of the parallel-resonant filter is that it aggravates the low-order harmonics, which have frequencies lower than the parallel-resonant frequency of the filter, and which do not cause much telephone-interference, as a price which had to be paid for reducing the high-order harmonics which caused the really serious telephone-interference in the communication-lines which parallel the right of way of the trolley-wire and its alternating-current feeders. The diverse connections of the parallel filters, on different sides of the several anode-reactors, constitute an effective means whereby these low-order harmonics can be thrown out of phase with each other, so that they more or less cancel each other, thus considerably improving the wave form of the supply-currents, particularly when the different rectifier-powered motors are energized from different step-down transformers.

A further feature of my present invention involves the use of one or more damped series filters, in addition to the above-described parallel filter. Each series filter includes a capacitor and an inductor which are tuned to be in series resonance at a frequency which is either of the approximate order of range of the associated parallel filter, or at some lower frequency-range.

The two or more filters, all connected across the anode-leads or power-supply leads of the two rectifiers of any given rectifier-assembly, have individual filtering effects, in addition to any composite or joint filtering effects which they may have. In other words, the filtering effect of the plurality of filters is not merely the joint effect which would be obtained by mathematically calculating the impedances of the several filter circuits connected in parallel with each other and producing a joint effect which is different from the filtering-effect of any one of the filters acting alone. On the contrary, each filter produces its own effect, somewhat as if the other filter or filters were not present. I am not sure whether this is due to the presence of damping resistors in each filter, or whether it is due to the rectifier-circuit application in which the filters are more or less short-circuited during each commutating period of the rectifiers, during each half-cycle of the supply-line frequency. At any rate, the individual filtering effects are present, and are very useful.

As has been stated, the parallel filters, which are needed to reduce the high-order harmonics which cause the objectionable inductive interference, accomplish this result only at the expense of aggravating harmonics in the vicinity of the parallel-resonance of said filters, and also aggravating all harmonics of a still lower order. By my present invention, it is possible, by the use of series filters, to remove these aggravated harmonics, or as many of them as may be necessary.

With the foregoing and other objects in view, my invention consists in the circuits, systems, combinations, apparatus and parts of apparatus, as hereinafter described and claimed, and illustrated in the accompanying drawings, wherein:

Figure 1 is a much simplified circuit-diagram, indicating circuits and apparatus which illustrate the general principles of some of the aspects of my present invention, particularly the supplementary effects of the parallel and series filters;

Fig. 2 is a curve-diagram which crudely illustrates the contrasting impedance-effects of my parallel and series filters, at the different frequencies corresponding to the different harmonics;

Fig. 3 is a simplified diagrammatic view illustrating the importance of the anode-reactor in a combination in which motor-control is obtained by means of taps on a power-supply transformer which is interposed between the trolley and the rectifier-equipment;

Fig. 4 is another simplified circuit-diagram, illustrating the effects of diverse filter-connections with respect to the anode-reactors, and

Fig. 5 is a curve-diagram showing the contrasting oscillographic records of supply-current wave-shapes which are obtained with diversely connected parallel filters.

In the much simplified diagrammatic circuit of Fig. 1, I have shown, by way of example, a single-phase power-supply circuit, one side of which is connected to, and includes, a trolley wire 7, while the other side of the supply-circuit is grounded, as indicated at 7'. The trolley wire 7 is paralleled by a communication circuit 8, such as a telephone circuit, which makes it essential to consider the inductive interference effects of the power-line harmonics in the telephone circuit. The power-supply frequency may be either a previously known railway-electrification frequency, such as 25 cycles, or it may be a usual commercial frequency, such as 60 cycles, such as is used for commercial power and light circuits.

In Fig. 1, I have diagrammatically indicated some of the essential electrical parts of a single locomotive or railway-car, which is energized from the trolley wire 7 through a pantograph 9 and a step-down power-supply transformer 11 for that particular locomotive or car. The power-transformer 11 is provided with a secondary winding 12 which is used to energize three traction-motor equipments, represented by three direct-current motors 1, 2 and 3. Each motor comprises an armature 13, a main series field winding 14, an interpole winding 15, a reversing switch 16, and a serially connected reactance or choke coil 17. The negative terminals of each of these motor-equipments are connected to a common negative conductor 18 of the direct-current load-circuit, this negative conductor 18 being connected to the midpoint 19 of the power-transformer secondary 12.

The positive terminal of each of the motor

5

assemblies 1, 2 and 3 is supplied with power from its own rectifier assembly. Thus, each positive motor-terminal is connected to the common cathode-terminal 20 of two diagrammatically indicated rectifiers 21 and 22, each of which may be an ignitron or other single-phase rectifying device of a type which becomes substantially non-conducting, after a conducting period, only in response to a current-decrease to substantially zero. In other words, once a current-conducting arc is formed in either one of the rectifier-devices 21 or 22, that arc will sustain itself, and will not become extinguished, until substantially current-zero. The rectifiers 21 and 22 have anode-leads 21' and 22', respectively, which are connected to the opposite-potential terminals of the secondary winding 12 of the power-transformer 11. Preferably, in accordance with my present invention, these anode-leads 21' and 22' include serially connected anode-reactor windings 21'' and 22'', respectively.

Preferably also, in accordance with my present invention these anode-reactor windings 21'' and 22'' are mutually coupled, on a common magnetic circuit, which may be all air, but which preferably comprises both magnetizable material and an air gap. The two reactor-windings 21'' and 22'' are preferably coupled as closely as is practicable, as by having their respective coils interleaved with each other. There are the same number of turns in each of the reactor-windings. The polarity of the reactor-winding connections is such that the two reactor-windings 21'' and 22'' are in series-circuit relation to each other, producing a maximum reactance in the reactor-transformer of which they are a part, for the commutating currents which flow between the two rectifying devices 21 and 22 during their overlapping conducting periods.

The overlapping conducting periods of the two rectifiers 21 and 22 are caused by the supply-line inductance of the supply-circuit up to the rectifiers. This supply-circuit inductance includes the internal reactance of the alternating-current generator and any transmission line and power-line transformers associated therewith (not shown), the reactance of the trolley conductor 7 up to the load, the reactance of the power-transformer 11 on the vehicle, and the reactance of the reactor-transformer halves 21'' and 22'' in series, which are both carrying current during the overlap-period. Preferably, in practicing my invention, the power-transformer 11 has as small a leakage-reactance as practicable, so that it merely serves as a voltage-reducing means, and usually also has a voltage-varying means, as shown in Fig. 3, wherein the power-transformer 11' is provided with secondary voltage-changing taps 23 and 24. Preferably also, in practicing my invention the amount of supply-circuit reactance which is supplied by the two serially connected halves 21'' and 22'' of the anode-reactor transformer, is about of the same order of magnitude as the rest of the supply-circuit inductance, up to these anode-reactors, although I am not limited to this detail.

It is frequently a desirable feature of my present invention to make the plurality of anode-reactor transformers 21''—22'', which are associated with the respective rectifier-assemblies of the locomotive-equipment, have different reactances, such as by having different numbers of turns, as has been diagrammatically indicated, in Fig. 1, by means of reactor-taps 25; different taps being brought into play for the three different motor-equipments which are illustrated in Fig. 1.

6

The effect of these different taps is to cause the power factors of the alternating currents drawn by the three different motor-loads to be slightly different from each other, thus causing a small phase-difference between the single-phase supply-currents of the respective motor-loads. This small phase-difference, when multiplied by the harmonic order-number of the harmonic which causes the most trouble, from the standpoint of inductive interference, will (or may) produce a harmonic-current phase-difference which is large enough to substantially cancel out that particular harmonic, and to materially reduce the magnitudes of the harmonics in the adjacent frequency-range, as set forth in my second-mentioned copending application, which has already been identified.

While I have described my rectifier-assemblies, for convenience in description, as if their cathodes were connected to one motor-terminal 20, and as if their anodes were connected to, or energized by, the power-supply leads which I have designated as the anode-leads 21' and 22', in accordance with a common rectifier-connection, it will be understood, of course, that these rectifier-polarities might be reversed. Furthermore, while I have described and illustrated rectifier-assemblies, each of which comprises only two rectifiers 21 and 22, which are used to energize only one of the terminals of the direct-current load-circuit, the other direct-current terminal being brought back to the midpoint 19 of the supply-transformer secondary 12, it will be understood that the return-circuit 18 for the direct-current load circuit could be brought back to the power-supply means in any other known way, such as by means of the second half of a rectifier-bridge connection (not shown).

In Fig. 1, I also show the use of both parallel and series filters, in accordance with my present invention. These filters are connected across the respective pairs of anode-leads 21'—22' of the respective rectifier-assemblies which are used in any particular locomotive or other trolley-powered vehicle using my invention. In Fig. 1, these anode-lead filter-connections are shown as being on the rectifier-sides of the anode-reactor transformers 21''—22'' of the respective rectifier-assemblies, although, as will be discussed more explicitly in connection with Fig. 4, the filters could be connected to any other portions of the anode-leads 21'—22'.

In each of the three rectifier-assemblies which are shown in Fig. 1, the first (or top) filter-circuit is a parallel filter, such as is described and claimed in my first-mentioned copending application. These parallel filters do not all need to be tuned to the same frequency, but may be tuned anywhere in the frequency-range from about the third harmonic to a frequency of the order of 900 cycles. An advantage is obtained if the parallel-resonant frequencies of the three different parallel filters are all different from each other, in that phase-differences will thereby be produced in the various harmonic current-components in the several supply-currents for the several loads, thus assisting materially in causing the objectionable interference-provoking harmonics to tend to cancel each other out, as pointed out in my second-mentioned copending application.

As shown in Fig. 1, therefore, the rectifier-assembly which powers motor No. 1 is indicated, by way of example, as having an untuned fourth-harmonic parallel filter, consisting of a capacitor

$C4_p$ and a damping resistor $R4_p$. When I designate the filter-frequency by a particular harmonic order, I do not mean to limit myself to any particular precise tuning, as this is not necessary, and besides, the supply-circuit reactance varies under different operating conditions and in accordance with the varying distance of any particular locomotive of the supply-source (not shown). For example, when I say the fourth harmonic, I means to include any frequency in the range between somewhere around the third and somewhere around the fifth harmonic. The parallel-resonant frequency in question is the frequency at which the filter-capacitor, such as $C4_p$, is in parallel resonance with the power supply reactance as seen from the terminals of the filter.

By way of illustration, the second and third parallel filters, which are associated with the rectifier-assemblies for motors Nos. 2 and 3, in Fig. 1, are tuned for the eighth and twelfth harmonics, approximately, as indicated by the numerals 8 and 12, in place of the numerals 4 which characterize the capacitor C and the damping resistance R of the respective parallel filters, these parallel-resonant filter-tunings being only by way of example.

In accordance with one feature of my present invention, each of the parallel filters may be associated with one or more damped series filters, which are also connected across the pair of anode-leads 21'-22'. In every such case, it will usually be desirable to have at least one series filter which is tuned approximately to the same frequency as the associated parallel filter, by which I do not mean that the frequencies must be precisely and exactly identical, but merely of the same order of magnitude, so that the impedance-humps or depressions of the respective filter-impedances shall come somewhere around the same range of frequencies.

Thus, the fourth-harmonic parallel filter $C4_p-R4_p$ is shunted by a fourth-harmonic series filter which consists of a capacitor $C4_s$, an inductor $L4_s$ and a resistor $R4_s$. The size of the series-filter capacitor $C4_s$ is determined solely by the size of the series-filter inductor $L4_s$, these two reactors being tuned to be in series resonance with each other at about the frequencies of (say) the fourth harmonic of the supply-circuit frequency. The series-filter damping-resistance, such as $R4_s$, should preferably have a magnitude such as to give a breadth of tuning which approximately corresponds to the breadth of tuning of the associated parallel-resonant filter, so that the harmonic-shunting effect of the series filter, in the vicinity of the series-filter resonant-frequency, shall be spread out over a frequency-range approximately corresponding to the frequency-range in which the associated parallel-resonant filter produces its most damaging harmonic-increasing effect whereby the parallel filter, if it were used alone, would tend to magnify the line-current harmonics in the vicinity of the parallel-filter resonance.

In like manner, the second parallel-resonant filter $C2_p-R2_p$ in Fig. 1, which is in parallel resonance with the supply-line inductance, up to the filter-terminals, at approximately the eighth harmonic of the supply-line currents, is shunted by a damped eighth-harmonic series-resonant filter $C8_s-L8_s-R8_s$, which takes out the parallel-filter-augmented line-circuit harmonics in the vicinity of the parallel-resonant

frequency which is somewhere around the eighth harmonic.

Since the effect of a parallel-resonant filter is to augment not only the line-frequencies in the immediate vicinity of the parallel-resonant frequency, such as the seventh and ninth harmonics, in the case of an eighth-harmonic parallel filter, but such a parallel filter also increases or augments all of the lower harmonics, such, for example, as the third and the fifth, it may be desirable, when the most perfect supply-current wave-forms are desired, to provide a second parallel-connected series-resonant filter which is tuned to some lower harmonic-frequency, that is, to some frequency between about the frequency of the third harmonic and some frequency which is below that of the frequency of the associated parallel-resonant filter. Thus, in the case of an eighth-harmonic parallel-filter, I may use, not only an eighth-harmonic series filter, but also a parallel-connected fourth-harmonic series filter $C4_s-L4_s-R4_s$, as shown in Fig. 1.

Thus, also, in the case of the third rectifier-powered motor-equipment of Fig. 1, the twelfth-harmonic parallel filter $C12_p-R12_p$ is illustrated as being shunted by three series-resonant filters, tuned approximately to the twelfth, eighth and fourth harmonics, respectively, as indicated at $C12_s-L12_s-R12_s$, $C8_s-L8_s-R8_s$ and $C4_s-L4_s-R4_s$, so as to remove or reduce the third, fifth, seventh, ninth, eleventh, and thirteenth harmonics, while also reducing to a diminishing extent, some of the harmonics which are of a little higher order than the thirteenth. Of course, if there should be any even harmonics present, in the frequency-ranges of the series filters, they would be reduced too.

The general effect of the parallel and series filters is indicated roughly in Fig. 2, only by way of example, and without any attempt at indicating optimum dampings or anything of the sort. For example, the eighth-harmonic parallel-resonant filter $C8_p-R8_p$ will have an impedance-frequency curve of the general type which is indicated at Z_p in Fig. 2. This practically short-circuits out the high-order harmonics, but it has a damaging effect at the lower harmonic frequencies, particularly in the vicinity of the eighth harmonic. The general type of impedance-frequency curve which is obtained for a damped eighth-harmonic series-resonant filter, such as the filter $C8_s-L8_s-R8_s$ in Fig. 1, is indicated in Fig. 2 by the curve Z_s , which shows that it shorts out harmonics in the frequencies which are close to the range in which the series-resonant tuning is provided, while having relatively small effect on the frequencies which are remote from the series-resonant tuning.

The operation of my system, as shown in Fig. 1, can therefore be briefly summarized as follows. The supply-line reactance during the angle of overlap (which is an inductive reactance), up to the terminals of the rectifiers 21, 22, determines the angle of overlap of the two rectifiers of each pair of rectifiers. Preferably this reactance should be sufficient to make the angle overlap at least about 20° during each half-cycle during maximum load-conditions, although in some cases, an angle of overlap as high as 40°, or more, might be desirable, while, at other times, any material amount of angle of overlap might be acceptable, when other features are used in accordance with my present invention. The overlap-controlling line-reactance always includes

the anode reactors 21'' and 22'', because these reactors are always connected in series with the supply-side of the rectifiers 21 and 22.

In the case of the parallel-filters, such as C4_p—R4_p, C8_p—R8_p, and C12_p—R12_p, the line-reactance with which the parallel-filter capacitors will be in parallel resonance is the line-reactance as seen from the terminals of the parallel filter. This filter-effective line-reactance will, or will not, include the anode-reactors 21'' and 22'', or either of them, depending upon whether said line-reactors are included on the line side, or the rectifier side, of the parallel-filter terminals. The line-reactance has no effect on the tuning or adjustment of the series filters. 15

The mutual coupling between the anode-reactor windings 21'' and 22'', and their series-circuit connection with respect to the circulating or commutating currents which flow when both rectifiers are conducting, are desirable and novel features. Because of the presence of air in the magnetic circuit, the two reactor-windings, for the best results, have to have their individual coils carefully interleaved, as distinguished from an arrangement whereby each of the two windings is a compact unit spaced from the other winding. The mutual coupling makes the core-magnetization go from a maximum positive flux to a maximum negative flux in successive half-cycles, instead of going from positive to zero, or from negative to zero, as would be the case if two separate anode-reactors were used, without any mutual coupling between them. The size of the double reactor is thus reduced, as distinguished from what would have been required if two uncoupled reactors were used. 30

The high series-circuit, or commutating-current, reactance is desirable, in many rectifier-powered vehicles, in order to produce some desired slope or regulation in the speed-tractive effort curves of the locomotive or car, and also to produce a large angle of overlap, which is necessary in order to reduce inductive telephone-interference, as pointed out in my first-mentioned copending application. But of even greater importance is the fact that a large series-connection circulating-current reactance is needed for the purpose of limiting the magnitude of backfire-currents, in case one of the tubes or rectifiers should become conducting in the wrong direction, after its current-zero state has passed. It is very necessary to limit such backfire-currents, in order to avoid damage to the faulty rectifier, and also to avoid a power-outage condition due to the operation of overcurrent fuses or breakers (not shown). 35

The introduction of a considerable portion of the supply-circuit reactance on the secondary side of the power-transformer 11, by means of the anode-reactance 21'' and 22'', is particularly useful, also, in a system in which a plurality of similar separate rectifier-powered motor-equipments are operated from the same power-transformer. If there are N rectifier-equipments, energizing N direct-current motors from the same power-transformer 11, then the anode-reactors 21''—22'' are N times as effective as a backfire-protective means, when they are connected in series with the individual pairs of anode-leads 21', 22', on the secondary side of the power-transformer 11, than would be the case if an equivalent amount of reactance (for some predetermined value of regulation in the locomotive speed-tractive effort curves), had been built into the power-transformer 11, or had been connected 40

in series with the primary circuit of said transformer. This is true, because, when a backfiring condition arises, it occurs in only one rectifier at a time, as a rule, and hence an individual backfire-suppressing reactance-coil, which is specially included in the circuit of that one transformer, is much more effective in reducing the backfire-current than if the reactor had been placed in the primary circuit where it is traversed by the currents drawn from all N rectifier-assemblies where, for a predetermined regulating-effect and angle of overlap, it could have only 45

$$\frac{1}{N}$$

times the reactance it can have in the single motor-current circuit.

The use of individual anode-reactors, on the secondary side of the power-transformer is also desirable, in my preferred combination in which a plurality of rectifier-powered-motor-circuits are energized from a common power-transformer, because such anode reactors make possible the choice of different amounts of supply-circuit reactances, which are effectively connected in series with different ones of the plurality of rectifier-assemblies. This makes it possible to cause the several rectifier-assemblies to draw supply-currents which are slightly out of phase with each other, thus throwing the high-order harmonics considerably out of phase with each other, and making it possible to make critical groups of harmonics substantially balance each other out, so that they do not appear in the supply-circuit 7 where they would cause inductive interference in the adjacent communication system 8. 50

To a similar end, the connection of the parallel filters C4_p—R4_p, C8_p—R8_p and C12_p—R12_p on the rectifier or load-side of the anode-reactors 21''—22'' is quite desirable, in a system wherein a plurality of separate rectifier-powered motor-circuits are energized from the same power-transformer 11. This connection makes it possible to use different sizes of parallel-filter capacitors C4_p, C8_p, and C12_p, which not only tune the various parallel rectifiers to different frequencies, thus in itself tending to throw the harmonics out of phase with each other, but the very considerable line-frequency capacity-currents, which are drawn by these parallel-filter capacitors of different sizes, cause the supply-currents which are drawn by the several rectifier-assemblies to be out of phase with each other, having different power factors, and this phase-displacement, when multiplied by the order of any particular harmonic, will produce a rather significant harmonic phase-displacement, when harmonics of the higher order are considered, as pointed out in my second-mentioned copending application. 55

It is also desirable, as set forth in my first-mentioned copending application, to make the total inductance of each of the direct-current circuits 13—14—15—17 sufficiently small to permit at least a 20% ripple to be present in some part of said direct-current load-circuit during maximum short-time load-conditions, defining the percent ripple as one-half of the difference between the maximum and minimum instantaneous values of the direct-current wave, divided by one-half of the sum of said maximum and minimum values. In some cases, at least a 40% ripple may be desirable. These are unusually 60 65 70 75

high ripple-contents for the direct-current load-circuit of any rectifier-assembly.

This high ripple-contact is made possible, in rectifier-powered locomotive-installations and the like, because the direct-current load-circuits of such installations are not subject to inductive-interference considerations, because such circuits do not extend in inductive-interference relation to any communication circuit. Furthermore, it has been found that the direct-current motors 1, 2 and 3 are much more tolerant of ripples than was once assumed to be the case. Thus the ripples do not substantially hurt the motors, and they are very useful in reducing the harmonics which are reflected back into, or produced in, the alternating-current supply-circuit 7, which is very much subject to inductive-interference considerations.

Fig. 3 is presented for the purpose of illustrating the fact that practically all rectifier-powered trolley-energized vehicles will use alternating-current or supply-circuit voltage-control, for controlling the rectified voltage which is applied to the motors, and thus controlling the speed of the motors. Practically always, therefore, the power-supply transformer, such as the transformer 11 which was shown in Fig. 1, will be a variable-voltage transformer, and practically always, the variable voltage will be obtained by means of secondary taps 23 and 24 such as are shown on the power-transformer 11' in Fig. 3. Herein lies another advantage of using my anode-reactors 21'' and 22'', connected in series-circuit relation in the anode leads 21' and 22' on the secondary side of the power-transformer 11'. This is particularly true on low-voltage tap-connections, when the effect of the transformation-ratio is to make the line reactance, as seen from the secondary-winding taps, very small indeed, being relatively negligibly small, whereas the effective reactance of the anode-reactance 21'' and 22'' remains substantially the same under these low-voltage conditions as under the high-voltage conditions which prevail under normal running-conditions of the motors.

Hence, my use of the anode-reactors 21''—22'' provides a system where there is some substantial amount of effective supply-circuit reactance in series with the input-sides of the rectifiers 21 and 22, even during the lowest-voltage operating-conditions of these rectifiers. This supply-circuit reactance is desirable, in order to provide a certain amount of voltage-regulation, by which is meant that the voltage which is applied to the rectifier-powered motors will drop or fall off by a certain amount as the motor-load increases, and conversely, the motor-voltage will gradually rise, by itself, as the motor-speed increases during the acceleration of the vehicle, this effect being obtained without changing either of the secondary taps 23 or 24 of the power-transformer 11'. A certain amount of this voltage-regulation effect is quite desirable in reducing the number of transformer-taps, and the number of controller-notches which are required on the motor-controller (not shown) which controls these taps.

Fig. 4 is a simplified diagrammatic view which is illustrative of the possibility of connecting the various filters (parallel filters and/or series filters), in different positions with respect to the input and output sides of the several anode-reactances 21''—22'' of the various rectifier-equipments which are energized from any given power-transformer 11 on a locomotive or other rectifier-powered trolley-energized vehicle. In Fig. 4, the

number of direct-current traction-motors is shown as six, which is a more usual number than the three motors which are illustrated in Fig. 1, these six motors being indicated, in accordance with the usual convention, by the numbers 1 to 6, respectively.

In Fig. 4, it will be observed that two parallel-filter circuits 31 and 32 are shown on the power-input sides of the several anode-reactors 21'', 22''; that is, connected across the secondary winding 12 of the power-transformer 11. These two parallel filters may be tuned either to approximately the same frequency as each other or to different frequencies, within the frequency-range between the third harmonic and 900 cycles.

In Fig. 4, also across the input-sides of the several anode-reactors 21''—22'', that is, across the power-transformer secondary-winding 12, I have shown a series-filter circuit 33, which might be tuned to approximately the same frequency as one or both of the parallel filters 31 or 32, or at any lower harmonic frequency (higher than the supply-line frequency).

Fig. 4 also shows, by way of examples, other places where both the parallel and series filters could be connected, either instead of the filter-circuits 31, 32 and 33 which have just been described, or in addition thereto. Thus, the first pair of single-phase power-supply leads or anode-leads 21', 22', of the No. 1 motor, are shunted, on the rectifier-side of the anode-reactors 21''—22'', with a parallel-filter circuit 34 and a series-filter circuit 35. A similar series-filter circuit 35 is shown also, in a similar connection, across the anode-leads of all of the other rectifier-assemblies, which energize motors Nos. 2 to 6, respectively. A parallel-filter circuit 34, connected as just described, is shown also for the rectifier-assemblies of the motors Nos. 3 and 4. The rectifier assembly for the No. 6 motor is shown as having a parallel-filter circuit 36 which is connected with one filter-terminal 36' on the power supply side of one of the anode-reactor windings, such as 22', while the other filter-terminal 36'' is connected on the rectifier side of the other anode-reactor winding 21'. In the case of the rectifier-assemblies for energizing the motors Nos. 4 and 5, I have shown two crisscross-connected parallel-filter circuits 36 and 37, each having its filter-circuits connected on opposite sides of the respective anode-reactor windings.

These various filters 31 to 37 may be tuned in parallel and series resonance, as the case may be, at any of the frequencies which have already been discussed, either at all the same frequency, or at different frequencies, for the purposes already stated.

I have found that there is a considerable difference in the operation of the filters, according to their location with respect to the anode-reactors 21''—22''. This is particularly true of the parallel filters, in which the filter-capacitors draw and supply material amounts of filter-currents during the respective capacitor-charging and capacitor-discharging periods of each half-cycle of the line-frequency currents.

These filter-connection effects are closely related to the effects of the anode-reactances and the effect of using a low-reactance power-transformer 11, as will now be described. In fact, it is desirable that the power-transformer reactance shall be negligibly small, as compared with the reactances of the various anode-reactors 21'' and 22'', so that, during the commutating period, when circulating current is flowing through both

13

of the rectifiers 21 and 22 of any given rectifier-assembly, the impedance-drop, or the voltage necessary to drive the commutating current through the reactance of the commutating circuit, will thus be consumed substantially entirely in the anode-reactors 21'—22'', and substantially none of this commutating-voltage drop will be obtained across the terminals of the power-transformer secondary-winding 12. Hence, the largeness of the angle of overlap will cause very little voltage-regulation in the transformer windings. This feature is desirable on account of other loads on the transformer.

Thus, when the terminal-potential of the right-hand half of the secondary winding 12 first begins to be more positive than the terminal potential of the left-hand half, a circulating current will flow through the anode-reactor winding 22'' of the anode-lead 22', the newly fired rectifier 22, the common cathode-circuit 20, the previously firing rectifier 21, and the other anode-reactor winding 21'' of the anode-circuit 21', and thence back to the power-transformer secondary-winding 12.

The effects just described are enhanced by the presence of the filters, particularly any parallel filters such as 31, 32, 34, 36 and 37, because the capacitors of these parallel filters, as a rule, draw larger charging and discharging currents than do the capacitors of the series filters 33 and 35 which have material inductances associated in series resonance therewith, as parts of their filter-circuits.

Thus, when only one filter is used, such as the parallel-resonant filter-circuit 31 (Fig. 4), located on the power side of the anode-reactors 21'', 22'', the alternating-current wave-form, as determined in the primary circuit of the power-transformer 11, has a shape somewhat of the type shown at V_{31} in Fig. 5, which does not necessarily represent the optimum design-conditions. However, if the filter had been connected on the rectifier-side of the anode-reactors 21'—22'', as shown at 34 in Fig. 4, the primary-circuit wave-form would have had an appearance such as is depicted at V_{34} in Fig. 5. It will be noted that the humps and hollows in the two wave-forms V_{31} and V_{34} are approximately 180° out of phase with each other, so that, if one of the rectifier assemblies draws a primary current of one type, and another rectifier-assembly draws primary current of the other type, or if several rectifier-assemblies draw currents of various intervening types, there will be a considerable amount of wave-smoothing effect, due to the simultaneous flowing of the primary currents of all of the several types. This is true if the different motors are energized from different step-down transformers 11, or even from different secondaries (not shown) on the same transformer, or if the mutual transformer-reactance in the charging-circuits of the different filter-capacitors is quite small as compared to the anode-lead reactances. In other words, if the reactance of the transformer 11 is negligibly small as compared to the anode lead reactances, or with respect to the power-line reactance, the above-described ripple-canceling effects can be expected in the wave-form of the total line-current.

It will be noted that the humps and depressions on the wave-forms V_{31} and V_{34} in Fig. 5 are of rather low harmonic-orders (considerably under the thirteenth harmonic, for example), so that any harmonic-depressing effect, due to the varied connections of the filters with respect to

14

the power and load sides of the anode-reactors, would be of benefit mainly from the standpoint of obtaining more nearly sinusoidal total currents, than from the standpoint of suppressing the high-order harmonics which are the ones which cause the most telephone-interference troubles. Both the high-order and the low-order harmonics ought to be suppressed, however, and my present connections, as shown in Fig. 4, are of considerable benefit in this regard.

The positions of the series-filter circuits, such as the circuits 33 and 35 of Fig. 4, with respect to the power and load sides of the anode-reactors 21'—22'', are also significant. Harmonics are generated in the inductance of the direct-current motor-circuit and enter the transformer-secondary 12 at its midtap connection. When only one series-filter is used, and placed on the rectifier-side, as shown at 35 in Fig. 4, it provides a path for the circulation of harmonics flowing in a closed path-including the transformer-secondary 12 and the anode-reactors 21' and 22'', so far as its particular tuned frequency is concerned, or any harmonics close to that frequency. The mutual reactance between the anode-reactors 21'' and 22'' assists the mutual reactance between the two halves of the transformer-secondary 12 in forcing these low-order harmonic components of the circulating currents to flow in equal strengths and opposite directions through the two halves of the transformer-secondary 12. The capacitor of the filter 35 or 34 must charge up at the beginning of each line-frequency half-cycle, through a charging circuit including the anode-reactance, the transformer-reactance, and the line-reactance, and the sum of these charging-circuit reactances L determines the critical damping-resistance $R=L/C$ of the series filter 35. The filter-capacitor discharges through a discharge-circuit which includes the almost-zero reactance of the rectifier-tubes 21 and 22.

On the other hand, if only one series filter is used, connected on the power-input side of the anode-reactor transformer 21'—22'', as shown at 33 in Fig. 4, the mutual anode-reactor coupling does not assist the flow of the harmonics in the two halves of the transformer-secondary 12. On the contrary, the voltage-drop due to the flow of the harmonic currents through one of the anode-reactors 21'' or 22'', as the case may be, adds to the volts per turn which must be generated in the active half of the transformer-secondary 12, in order to force the harmonics to flow through the inactive half and through the series filter 33, and thence through the aforesaid anode-reactor 21'' or 22'', and the direct-current circuit, and back to the midpoint of the transformer-secondary 12. Thus, the anode reactor exercises a voltage-drop effect, in the case of the power-side series filter 33, instead of having a harmonic-balancing effect as in the case of the rectifier-side series filter 35.

The capacitor of the power-side series filter 33 charges through only the line-reactance and the transformer-reactance, and hence it has a smaller critical damping-resistance (and hence a smaller resistance-loss for a given size of capacitor), than is the case with the rectifier-side series filter 35. The power-side filter 35 discharges its capacitor through the anode-reactor reactance, as well as the tube-reactance. If the reactances of the charging and discharging circuits of this power-side filter 35 are made equal, the critical damping resistance will be the same for charge and discharge, and will be less than the damping

15

resistance which is required in the rectifier-side filter 33.

The same remarks regarding the charging and discharging circuits, and the necessary amounts of damping resistances, apply to the power-side and rectifier-side parallel-filter circuits, such as the circuits 31, 32 and 34 of Fig. 4, as well as to the series-filter circuits 33 and 35 which have just been discussed.

One of the disadvantages of the parallel-resonant filters of my first-mentioned copending application was the necessity for adding a sufficient damping-resistance, such as the resistance R_{4p} of Fig. 1, to suitably limit the charging and discharging currents of the filter-capacitor, such as the capacitor C_{4p} . These parallel-filter damping-resistances entail a certain amount of continuous energy-loss, because the parallel-filter capacitors (such as C_{4p}) draw really material amounts of line-frequency capacity-current from the line. According to my present invention, it is believed that smaller and less critical amounts of damping-resistances can be used, in the parallel filters, if some of these filters are placed on the power side, and some on the rectifier side, or crisscrossed in various ways, with respect to the anode-reactance, as shown and discussed in connection with Fig. 4.

An important advantage of rectifier-powered locomotives is that they are operable on 60-cycle supply-circuits, so that they do not need the special 25-cycle power which is required by alternating-current rectifications using series commutator alternating-current motors. When 60-cycle power is used, my various filters and filter-connections become all the more important, because of the greater magnitude of the harmonic interference-difficulties which arise when a 60-cycle supply-circuit is used, rather than a 25-cycle supply-circuit.

Many railway-electrifications already in existence, however, use a 25-cycle power-supply, and it is necessary for my invention to be usable successfully on such existing systems. In many such 25-cycle railway-electrifications, cab-signals are used (not shown), which are usually operable on 100 cycles, corresponding to the fourth harmonic of the supply-frequency. In such cases, my fourth-harmonic series-resonant filters, such as the filters $C_{4s}-L_{4s}-R_{4s}$, $C_{4s}'-L_{4s}'-R_{4s}'$, and $C_{4s}''-L_{4s}''-R_{4s}''$, will usually be necessary or at least quite desirable, in order to avoid interference with the cab-signalling system, when using rectifier-powered locomotives on the electrified railway-system.

The relative advantages of the positions of the filter connections, whether on the transformer-side of the anode-reactors 21''-22'' or on the rectifier-side, depend upon a number of considerations. In general, when the rectifiers 21 and 22 have substantially no firing-delays, a rectifier-side filter, such as the filter 34 of Fig. 4, is slightly more efficient as an interference-noise-suppressor, than a transformer-side filter such as 31 or 32. However, if any material amount of delayed firing is used in the rectifiers 21 and 22, the increased amount of inductive interference which is caused by such delayed firing is much better suppressed by a transformer-side filter, such as 31 or 32, than by a rectifier-side filter such as 34.

While I have described only a few extremely simplified and illustrative or exemplifying forms of embodiment of my invention, designed to be indicative rather of the general principles of my

16

invention than showing precise details of the actual complicated connections such as would be used in practice, I wish it to be understood that my invention is not limited to the illustrated forms or circuits. I desire, therefore, that the appended claims shall be accorded the broadest construction consistent with their language.

I claim as my invention:

1. A rectifier-powered equipment, comprising, in combination, a direct-current load-means, a rectifier-assembly comprising at least two single-phase rectifying devices of a type which becomes substantially non-conducting, after a conducting period, only in response to a current-decrease to substantially zero; a pair of single-phase power-supply leads, connected to said two rectifying devices, respectively, at rectifying-device terminals of one polarity; circuit-means for connecting the other terminals of said two rectifying devices to one terminal of said direct-current load-means; the supply-circuit inductance, up to said first-mentioned terminals of said two rectifying devices, being sufficient to cause the conducting periods of said two rectifying devices to overlap for at least about 20° during each half-cycle during maximum short-time load-conditions; an untuned parallel-resonant filter, connected in parallel-circuit relation across said power-supply leads, with at least a substantial part of said supply-circuit inductance on the power-supply side of said parallel-filter connection, said parallel-resonant filter comprising a capacitor and a damping resistance, said capacitor having such capacitance as to be in parallel resonance with the supply-circuit inductance as seen from the terminals of said parallel-resonant filter, at a frequency in the range between the third harmonic of the supply-circuit and 900 cycles, during at least some operating-conditions; and a damped, series-resonance, tuned filter, connected in parallel-circuit relation across said power-supply leads, with at least a substantial part of said supply-circuit inductance on the power-supply side of said series-filter connection, said series-resonance filter comprising a capacitor and an inductor which are tuned to approximately the same frequency as said parallel-resonant filter.

2. The invention as defined in claim 1, characterized by the parallel-filter resonance being in the frequency-range between the third and fifth harmonics of the supply-circuit.

3. The invention as defined in claim 1, characterized by the parallel-filter resonance being in the frequency-range between the fifth harmonic of the supply-circuit and 900 cycles; in combination with a lower-frequency damped, series-resonance, tuned filter, connected in parallel-circuit relation across said power-supply leads, with at least a substantial part of said supply-circuit inductance on the power-supply side of said series-filter connection, said lower-frequency series-resonance filter comprising a capacitor and an inductor which are tuned to a frequency in the range between the third harmonic of the supply-circuit and the frequency of the parallel-resonant filter.

4. The invention as defined in claim 1, characterized by each of said two rectifying devices becoming conductive when the supply-circuit voltage reaches a relatively small value in the polarity which is conductive for that rectifying device.

5. The invention as defined in claim 1, characterized by the direct-current load-circuit having

17

a total inductance which is sufficiently small to permit at least a 20% ripple to be present in some part of said direct-current load-circuit during maximum short-time load-conditions.

6. The invention as defined in claim 1, characterized by said power-supply leads including a reactor-transformer having two closely coupled, substantially identical-turn windings and a common magnetic circuit including an air gap, said two reactor-windings being serially included in said power-supply leads in such polarity that the two reactor-windings are in series, producing a maximum reactance in the reactor-transformer, for the commutating currents which flow between said two rectifying devices during their overlapping conducting periods.

7. A rectifier-powered equipment, comprising, in combination, a direct-current load-means, a rectifier-assembly comprising at least two single-phase rectifying devices of a type which becomes substantially non-conducting, after a conducting period, only in response to a current-decrease to substantially zero; a pair of single-phase power-supply leads, connected to said two rectifying devices, respectively, at rectifying-device terminals of one polarity; and circuit means for connecting the other terminals of said two rectifying devices to one terminal of said direct-current load-means; the supply-circuit inductance, up to said first-mentioned terminals of said two rectifying devices, being sufficient to cause the conducting periods of said two rectifying devices to overlap during each half-cycle during some load-conditions; and said power-supply leads including a reactor-transformer having two closely coupled, substantially identical-turn windings and a common magnetic circuit including an air gap, said two reactor-windings being serially included in said power-supply leads in such polarity that the two reactor-windings are in series, producing a maximum reactance in the reactor-transformer, for the commutating currents which flow between said two rectifying devices during their overlapping conducting periods.

8. The invention as defined in claim 7, characterized by said overlapping conducting periods lasting for at least 20° during maximum short-time load-conditions; and further characterized by the direct-current load-circuit having a total inductance which is sufficiently small to permit at least a 20% ripple to be present in some part of said direct-current load-circuit during maximum short-time load-conditions.

9. The invention as defined in claim 7, in combination with an untuned parallel-resonant filter, connected in parallel-circuit relation across said power-supply leads, with at least a substantial part of said supply-circuit inductance on the power-supply side of said parallel-filter connection, said parallel-resonant filter comprising a capacitor and a damping resistance, said capacitor having such capacitance as to be in parallel resonance with the supply-circuit inductance as seen from the terminals of said parallel-resonant filter, at a frequency in the range between the third harmonic of the supply-circuit and 900 cycles, during at least some operating-conditions.

10. The invention as defined in claim 9, characterized by said parallel-resonant filter being connected on the power-supply side of said reactor-windings.

11. The invention as defined in claim 9, characterized by said parallel-resonant filter being connected between the power-supply side of one

18

of said two reactor-windings and the rectifier side of the other reactor-winding.

12. The invention as defined in claim 9, characterized by having two crisscross-connected parallel-resonant filters as defined in claim 9, each connected between the power-supply side of one of said two reactor-windings and the rectifier side of the other reactor-winding.

13. The invention as defined in claim 9, characterized by said parallel-resonant filter being connected on the rectifier side of said reactor-windings.

14. The invention as defined in claim 9, characterized by having two parallel-resonant filters as defined in claim 9, one on the power-supply side, and the other on the rectifier side, of said reactor-windings.

15. The invention as defined in claim 9, in combination with a damped, series-resonance, tuned filter, connected in parallel-circuit relation across said power-supply leads, on the power-supply side of said reactor-windings, said series-resonance filter comprising a capacitor and an inductor which are tuned to approximately the same frequency as said parallel-resonant filter.

16. The invention as defined in claim 9, in combination with a damped, series-resonance, tuned filter, connected in parallel-circuit relation across said power-supply leads, on the rectifier side of said reactor-windings, said series-resonance filter comprising a capacitor and an inductor which are tuned to approximately the same frequency as said parallel-resonant filter.

17. Rectifier-powered equipment, comprising, in combination, a plurality of similar direct-current load-means, a rectifier-assembly for each of said direct-current load-means, each rectifier-assembly comprising at least two single-phase rectifying devices of a type which becomes substantially non-conducting, after a conducting period, only in response to a current-decrease to substantially zero; a pair of single-phase power-supply leads for each of said rectifier-assemblies, each pair of power-supply leads being connected to said two rectifying devices, respectively, of their own rectifier-assembly, at rectifying-device terminals of one polarity; circuit-means for connecting the other terminals of said two rectifying devices to one terminal of their associated direct-current load-means; a common single-phase supply-circuit; and energizing-means for energizing said plurality of pairs of power-supply leads from said common single-phase supply-circuit; each pair of power-supply leads including a reactor-transformer having two closely coupled, substantially identical-turn windings and a common magnetic circuit including an air gap, said two reactor-windings being serially included in said power supply leads in such polarity that the two reactor-windings are in series, producing a maximum reactance in the reactor-transformer, for the commutating currents which flow between said two rectifying devices during their overlapping conducting periods.

18. The invention as defined in claim 17, characterized by said energizing-means being a common transformer for energizing a plurality of rectifier-assemblies.

19. The invention as defined in claim 17, characterized by a plurality of said reactor-transformers having materially diverse reactances.

20. The invention as defined in claim 17, characterized by a plurality of untuned parallel-resonant filters for each of a plurality of pairs

of power-supply leads, each parallel-resonant filter being connected in parallel-circuit relation across their power-supply leads, each parallel-resonant filter comprising a capacitor and a damping resistance, said capacitor having such capacitance as to be in parallel resonance with the supply-circuit inductance as seen from the terminals of said parallel-resonant filter, at a frequency in the range between the third harmonic of the supply-circuit and 990 cycles, during at least some operating-conditions.

21. The invention as defined in claim 20, characterized by a plurality of parallel-resonant filters being diversely connected with respect to the reactor-windings of their respective power-supply leads.

22. The invention as defined in claim 20, characterized by a plurality of parallel-resonant filters being diversely resonant in parallel resonance at different frequencies.

23. The invention as defined in claim 22, characterized by each of a plurality of said diversely resonant parallel-resonant filters having at least one of its terminals connected to its associated power-supply lead on the rectifier side of the associated reactor-winding.

24. The invention as defined in claim 23, in combination with a plurality of damped, series-resonance, tuned filters, connected in parallel-circuit relation across a plurality of pairs of power-supply leads in complementary relation to said plurality of diversely resonant parallel-resonant filters, each series-resonance filter comprising a capacitor and an inductor which are tuned to approximately the same frequency as their associated parallel-resonant filter.

25. A rectifier-powered equipment, comprising,

in combination, a direct-current load-means, a rectifier-assembly comprising at least two single-phase rectifying devices of a type which becomes substantially non-conducting, after a conducting period, only in response to a current-decrease to substantially zero; a pair of single-phase power-supply leads, connected to said two rectifying devices, respectively, at rectifying-device terminals of one polarity; circuit means for connecting the other terminals of said two rectifying devices to one terminal of said direct-current load-means; a single-phase supply-circuit; and a variable-voltage transformer connected between said single-phase supply-circuit and said single-phase power-supply leads; said power-supply leads including a reactor-transformer having two closely coupled, substantially identical-turn windings and a common magnetic circuit including an air gap, said two reactor-windings being serially included in said power-supply leads in such polarity that the two reactor-windings are in series, producing a maximum reactance in the reactor-transformer, for the commutating currents which flow between said two rectifying devices during their overlapping conducting periods.

LLOYD J. HIBBARD.

References Cited in the file of this patent

UNITED STATES PATENTS

Number	Name	Date
993,899	Steinmetz	May 30, 1911
1,157,823	Thomas	Oct. 26, 1915
1,434,346	Jonas	Oct. 31, 1922
2,456,910	Brown	Dec. 21, 1948
2,548,579	Bedford	Apr. 10, 1951