Aug. 1, 1950 F. G. LOGAN 2,517,396

MEANS FOR INCREASING FREQUENCY

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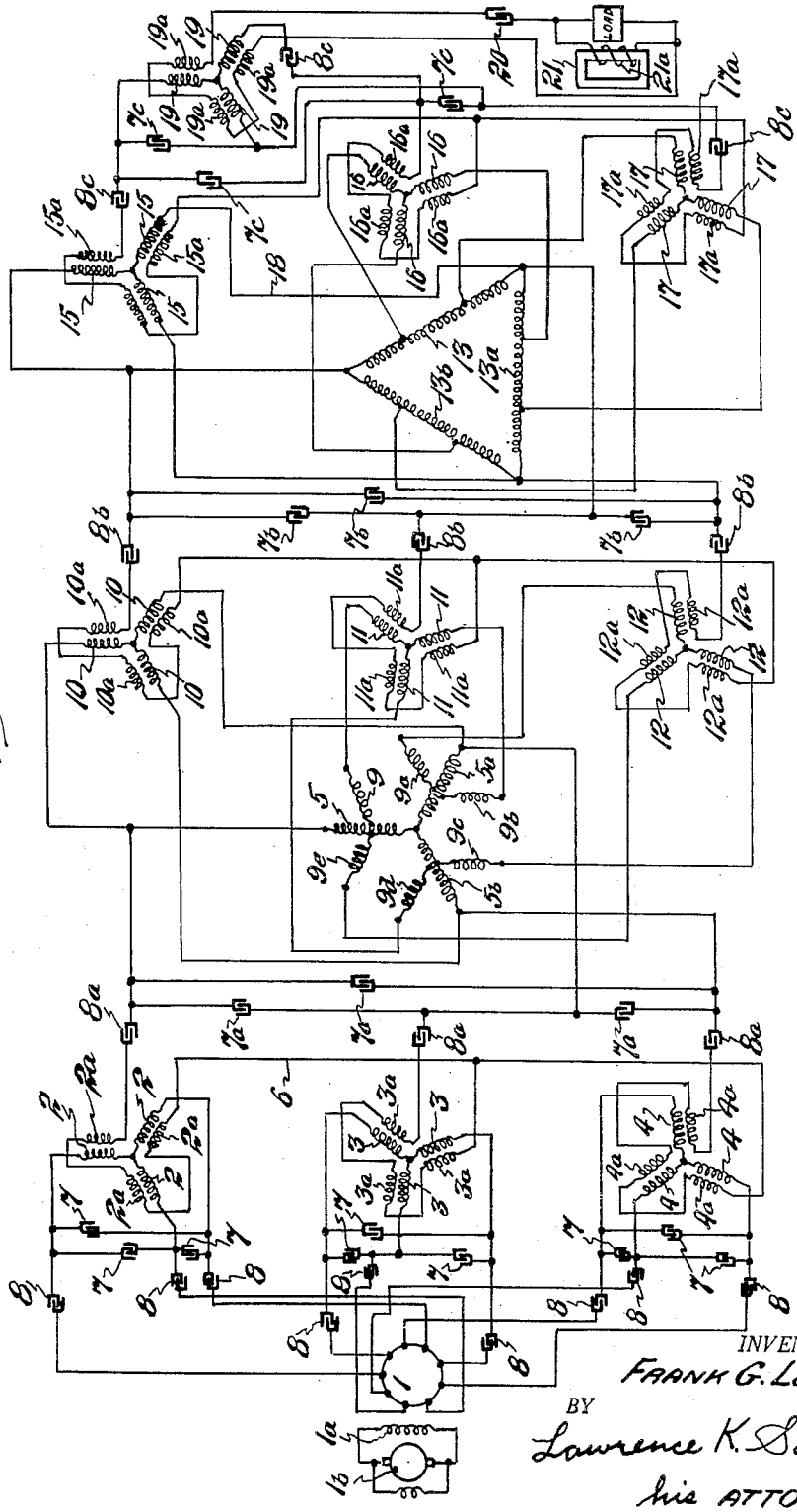


Fig. 1.

INVENTOR.
FRANK G. LOGAN
BY
Lawrence K. Sager
his ATTORNEY

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Fig. 2.

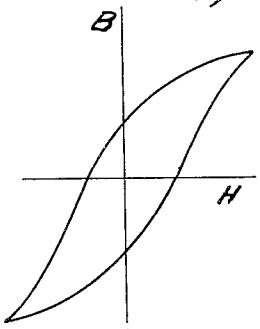


Fig. 3.

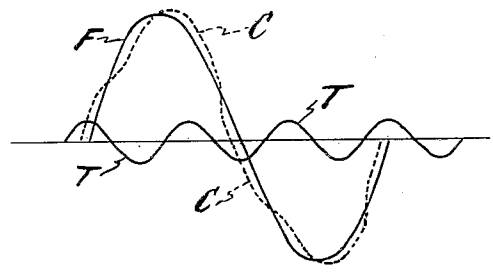


Fig. 4.

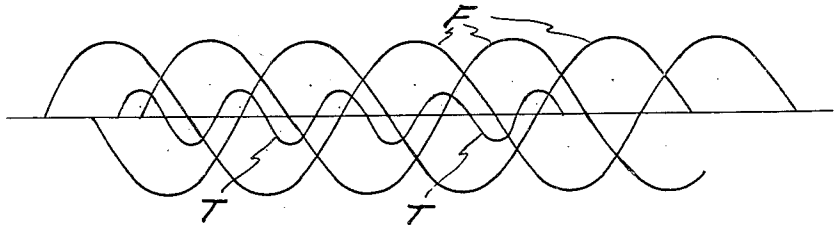
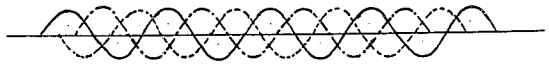


Fig. 5.



INVENTOR.
FRANK G. LOGAN
BY
Lawrence K. Sager
his ATTORNEY

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MEANS FOR INCREASING FREQUENCY

Frank G. Logan, Kirkwood, Mo., assignor to Vickers Incorporated, Detroit, Mich., a corporation of Michigan

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10 Claims. (Cl. 321—68)

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This invention relates to improved methods and means for increasing the frequency of an electric current from a comparatively low value to a higher value which may be many times the value of the initial frequency from which the increased frequency is derived.

Although there are a number of different ways to produce high frequencies, they require special apparatus which is not usually available in electrical installations or plant equipment. One object of the present invention is to provide a method for deriving high frequency currents from sources of current which are commonly available. Another object is to provide apparatus for accomplishing this purpose which may be conveniently manufactured. A further object is to provide apparatus which avoids the necessity of using tubes or other devices which are likely to deteriorate or break down in operation and which require spare parts to be kept on hand for replacements. Thus a further object is to provide apparatus which will be durable and dependable under long continued use. Other objects and advantages will be understood from the following description and accompanying drawings.

Fig. 1 is a diagram illustrating one embodiment of the invention; and Figs. 2 to 5 are explanatory charts.

Before considering the disclosures of Fig. 1, some general explanations are desirable as to the method employed and the mode of operation. The invention is based upon the production and utilization of third harmonics. Fig. 2 shows a hysteresis loop of a magnetic core and is of a form which is a desirable one for explaining the derivation of third harmonics. When the loop is more narrow it tends to produce a higher order of harmonics in the exciting current. In Fig. 2 the abscissas H represent the field intensity and for a given structure represent the exciting current. Other factors affecting H are the number of turns in the exciting winding and the mean length of the magnetic path and these are fixed for a given structure. The ordinates B of Fig. 2 represent the flux density of the core and for a given structure and frequency is a function of the impressed electromotive force. The flux density also depends upon the cross-sectional area of the magnetic core and for a given structure this is fixed. It may be assumed for present purposes that a core structure and winding have been designed as determined by the above-mentioned factors for producing a hysteresis loop of the general form shown in Fig. 2.

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If an electromotive force having a sine wave form be impressed on the exciting winding or primary winding of a transformer, the circuit of the secondary winding being open, the resulting flux wave will also be sinusoidal but will be displaced 90° in time from the exciting current. If a sine wave of electromotive force be applied to a structure such as would produce a hysteresis loop as shown in Fig. 2, the exciting current wave would be somewhat distorted in order to produce the flux in the core. This is generally represented in Fig. 3 where the dotted line C represents the distorted current wave. This wave may be resolved by Fournier's analysis to obtain essentially a fundamental sine wave designated as F in Fig. 3 and a sine wave designated by T in Fig. 3 of a frequency which is triple that of the fundamental wave and commonly referred to as the third harmonic. The amount of the third harmonic produced depends upon the shape of the hysteresis loop which depends upon the magnetic material in the core and the flux density imposed thereon. Although higher harmonics also appear in the current wave, the third harmonic predominates.

If three similar single phase transformers or a three-phase transformer be supplied from a three-phase source to their respective primaries with their primaries connected in Y and their secondaries connected in delta, a third harmonic will be developed in the delta connection. Assuming balanced conditions, the fundamental voltage across an open corner of the delta will be zero. The only voltage then appearing will be due to harmonics, primarily the third. The three fundamental voltages in the delta will be 120° displaced and the third harmonic will have the same relative displacement with reference to each of the three fundamental voltages. This is shown in Fig. 4 where F indicates the three fundamental secondary voltages and T indicates the third harmonic in the delta connected secondaries.

Now assume that three similar separate sets of Y-delta connected transformers be supplied respectively from three sources of three-phase currents and that the phase relation of the three sources is 40° apart. Then there will be developed in the secondaries of each set of transformers a third harmonic as already explained; but in view of the fact that the three sources have their phases displaced 40° as assumed, the third harmonics in each of the three delta connected secondaries will be displaced 120° relatively to each other. It follows that if the current waves of the three third harmonics of the

sets be superimposed there results three phases of sine waves displaced from each other 120° and each having triple the frequency of each of the three-phase sources. This is shown in Fig. 5 where the full line shows one phase of the third harmonic, the dotted line the second phase and the dot and dash line the third phase. The loads on the three-phase output of the secondaries can be connected in Y or in delta depending upon the particular application. Also by repeating the method of tripling the frequency as already described in another stage of multiplication, a third harmonic of a third harmonic may be obtained giving nine times the original supply frequency. An additional stage will result in twenty-seven times the original frequency and so on.

The three-phase sources having relative phase displacements of 40° can be derived from a single three-phase source by using phase adjusters for obtaining the relative displacement. The 40° degree displaced three-phase sources are equivalent to a nine-phase source and therefore a nine-phase generator may be used as a single source. The nine phases may be derived also from a three-phase Y and zig-zag transformer connection and also from a three-phase delta autotransformer connection with tapped connections, as later explained.

Referring to Fig. 1, a nine-phase generator 1 is indicated as the initial source provided with a field winding 1*a* energized from a separate exciter 1*b*. Three sets of similar three-phase transformers, or three groups of three single phase transformers have their primary windings connected in Y and are supplied from the nine-phase generator. The primary windings 2 of the upper group are connected to the terminals of the generator to cause the phase displacement of the electromotive forces supplied thereto to be 120° apart. The primary windings 3 of the middle group are similarly connected to the generator and the electromotive forces supplied thereto are displaced 40° relatively to the electromotive forces supplied to the upper group. The primary windings 4 of the lower group are similarly connected and its phases are displaced 40° from those of each of the other groups. This relative phase displacement of the electromotive forces supplied to the three groups is indicated by a corresponding angular displacement of the three groups on the drawing. The secondary windings 2*a* of the upper group are connected in delta except at one corner or apex for supplying the third harmonic current to the next stage. The secondaries 3*a* of the middle group and 4*a* of the lower group are similarly connected. If the frequency of the electromotive forces of the generator be 400 cycles per second, it is apparent from the foregoing explanations that the frequency of the current output from the secondaries of the three groups will be 1200. Three capacitors 7 are shown connected across the lines supplying the primary windings of each group for improving the power factor of the energy supplied to each group; and three capacitors 8 are shown connected in series in the lines supplying the primary windings of each group to compensate for reactance in these windings.

A nine phase source is next derived from the output of the secondaries of the first stage. A three-phase Y transformer connection is shown having the main windings 5, 5*a* and 5*b*. They are respectively supplied with the third harmonic currents from one terminal of each group of secondaries 2*a*, 3*a* and 4*a*, the remaining terminals thereof being connected to a common connection 6. Three capacitors 7*a* are connected across the circuits of these secondaries for improving the power factor of the energy supplied to the succeeding stage; and three capacitors 8*a* are connected in series in the circuits of the secondaries to compensate for reactance in the primary circuits of the next stage.

In order to derive the nine phase from the Y-connected transformer windings 5, 5*a* and 5*d*, the zig-zag connection as shown in Fig. 1 is utilized. The secondary winding 9 is related to the primary winding 5*b* for generating an induced electromotive force therein corresponding to the phase of the primary 5*b* but displaced therefrom 180°. This secondary winding 9 has one terminal connected to a tap in the primary winding 5 at such a location as will result in the winding 9 combined with a portion of the winding 5 delivering an electromotive force 40° displaced from that of the winding 5 and of the same value. Thus a line drawn from the mid-connection of the Y-connected primaries to the outside terminal of the winding 9 will represent the phase and value of the electromotive force delivered from the outside terminal of the winding 9. The secondary winding 9*a* is applied in relation to the winding 5*b* to receive an induced electromotive force therefrom and is connected at a location in the winding 5*a* such that the combined forces of the winding 9*a* and inner portion of winding 5*a* will give a resultant electromotive force at the outside terminal of winding 9*a* displaced 40° in phase from that of winding 9 and from that of winding 5*a* and having an electromotive force equal to that of the primary Y-connected windings. In the same manner the winding 9*b* is located in relation to the primary winding 5 and connected to an intermediate point of winding 5*a* to deliver an electromotive force equal to that of the primary windings and displaced 40° from the electromotive force of winding 5*a*. The secondary winding 9*c* is likewise related to the winding 5 and connected to an intermediate point in the winding 5*b* for obtaining another resultant electromotive force displaced 40° from that of the output from winding 9*b* and winding 5*b*. Likewise the winding 9*d* is related to the primary winding 5*a* and connected to an intermediate point of the winding 5*b*; and similarly the secondary winding 9*e* is related to the primary winding 5*a* and connected to an intermediate point in the winding 5. Thus the nine phases of electromotive force having a phase displacement of 40° are derived from the three-phase Y-connected primaries 5, 5*a* and 5*b*. The secondary windings 9*a* to 9*e* are shown displaced from their relationship to their respective primary windings for clearness but their angular positions correspond with that of the primary windings to which they are related.

At the middle of Fig. 1 is shown another three groups of transformers, each group having their primary windings respectively connected in proper phase relationship to the nine terminals of the zig-zag transformer connection already described. Thus the primary windings 10 of the upper group are connected in Y and their outside terminals to the primary windings 5, 5*a* and 5*b*. The primary windings 11 of the middle group are connected in Y with their outside terminals to the windings 9, 9*b* and 9*d*. The primary windings 12 of the lower group are connected in Y and their outside terminals connected respectively to the outside terminals of the windings 9*a*, 9*c* and 9*e*. The secondary windings 10*a*, 11*a* and 12*a* of each

group are connected in delta in the same manner as described with reference to the secondaries of the three left-hand groups. The frequency of the third harmonic currents delivered from the secondary windings 10*a*, 11*a* and 12*a* will be three times that delivered from the secondaries 2*a*, 3*a* and 4*a*, or 3600 cycles per second under the assumption of an initial 400 cycles.

At the middle right-hand portion of Fig. 1 are shown three auto-transformer windings 13, 13*a* and 13*b* connected in delta. One terminal from the delta connected secondary windings 10*a* is connected to the junction between the windings 13 and 13*b*; one terminal of the delta connected secondary windings 11*a* is connected to the junction between the windings 13 and 13*a*; and one terminal of the delta connected windings 12*a* is connected to the junction between the windings 13*a* and 13*b*. The remaining terminals of the delta connected secondaries are connected to a common neutral connection 14. Capacitors 7*b* are connected across the lines of the delta connected secondaries similarly to the capacitors 7*a*; and capacitors 8*b* are connected in series in the circuits of the secondaries similarly to the capacitors 8*a* for the purposes previously stated.

The delta connected auto-transformer windings 13, 13*a* and 13*b* are utilized for deriving therefrom nine phases of electromotive force displaced 40° and show another method of deriving nine phases from that previously discussed. At the right of these windings are shown three groups of Y open-delta connected transformer windings having primary windings 15, 16 and 17, each being Y-connected and secondary windings 15*a*, 16*a* and 17*a*. The three primary windings 15 are connected respectively to the apex junctions of the windings 13, 13*a* and 13*b* giving a 120° displacement in phase of the electromotive forces applied to the windings 15. The windings 16 of the next lower group are connected to intermediate points in the windings 13, 13*a* and 13*b* respectively at locations which result in applying electromotive forces to the windings 16 displaced 120° from each other and displaced 40° respectively from the electromotive forces applied to the windings 15. The lower group of primary windings 17 are connected respectively to intermediate points in the windings 13, 13*a* and 13*b* at such locations as will apply electromotive forces to the windings 17 displaced 120° from each other and 40° from the electromotive forces applied to the windings 16. The phase difference applied to the three groups of primary windings 15, 16 and 17 is indicated by the relative angular position of the windings. The value of the electromotive forces applied to the primary windings 15 is greater than that applied to the windings 16 and 17 and in order to impose equal values of electromotive forces on the secondary windings of each group, this may be accomplished by providing a correspondingly greater number of turns in the primary windings 15 than in the primary windings 16 and 17, as indicated in the drawing.

The secondary windings 15*a* of the upper group of transformer windings at the right of Fig. 1 are connected in open delta and the secondary windings 16*a* and 17*a* of the middle and lower groups are similarly connected. One terminal of the open delta of each group is connected to a common neutral 18 and the other terminals are connected respectively to the terminals of Y-connected primary transformer windings 19. The secondaries 19*a* of these windings are connected in open delta to a load circuit, as indicated. Capacitors 7*c* are connected across the lines of the delta connected secondaries; and capacitors 8*c* are connected in series in the circuits of the secondaries for the purposes previously described.

The frequency of the current delivered to the primary windings 19 is three times the frequency derived from the previous stage of multiplication and as this was assumed to be 3600 cycles per second, the frequency of the current delivered to the primary windings 19 is 10,800 cycles.

The Y open-delta transformer windings 19 and 19*a* serve to again triple the frequency of the current supplied thereto which results in the current supplied to the load having a frequency of 32,400 cycles, or 81 times the assumed 400 cycle frequency of the initial supply.

A capacitor 20 is shown connected in series in the load circuit for compensating for reactance in the circuit. A saturating reactor having a closed magnetic core 21 and having a reactive winding 21*a* connected across the load circuit is provided for maintaining an approximately constant current in the output circuit of the series connected secondary windings; otherwise the voltage would change considerably with change of load as the apparatus is not self-regulating. This reactor is maintained at saturation resulting in a pronounced change of current through its winding under small changes of the applied voltage. Thus upon increase of the load and a small drop in voltage of the output circuit, the current taken by the reactor winding 21*a* is considerably decreased. When the load is decreased, the current taken by the winding 21*a* is increased correspondingly. In this manner the reactor serves to maintain an approximately constant current in the output circuit regardless of the change in load. Instead of using a saturating reactor, any other suitable device or resistor having a non-linear relationship of current change with reference to the applied voltage may be used.

Although four multiplications of the initial frequency have been disclosed, a lesser number may be utilized or, where desired, additional stages of multiplication may be used. In tests of this apparatus the volt-ampere efficiency was found to be approximately 20% per stage without the use of compensating capacitors. The power efficiency depends on the losses in the core material and in the copper. The use of very thin laminations and of high permeability core materials aids in improving the power efficiency. The volt-ampere efficiency is improved by the use of capacitors in the input circuits to each stage, as indicated in Fig. 1.

It will be appreciated from the foregoing disclosures that the three groups or sets of Y open-delta connected transformer windings serve to deliver three third harmonic currents out of phase with each other by 120° and of triple the frequency applied to the groups. These are utilized in each succeeding stage of frequency multiplication for deriving nine phases therefrom for supplying another three groups or sets of Y open-delta connected transformer windings for obtaining an additional stage of multiplication. The output currents of tripled frequency from any of the groups may be applied directly to and utilized in a three-phase consumption circuit or to three single phase circuits when so desired or applied to a single set of three-phase transformer windings having Y-connected primaries and open-delta or series connected secondaries supplying a single-phase consumption

circuit giving a further tripling of the frequency as in the last stage of Fig. 1.

Instead of using three groups energized from a nine-phase supply, a different number of groups could be used according to the number of phases availed of for supplying the different groups. Also, instead of using a nine-phase generator as the initial source shown herein for convenience, the desired number of phases could be derived from a two-phase supply, a three-phase supply and so on, using any of the known methods for deriving therefrom the desired number of phases. And instead of using three-phase transformer windings in Y open-delta connection in each group, a different number of phases could be used having the primary windings connected in star to a common neutral and the secondary windings of each group connected in series to their output circuits provided that the resultant of the fundamental electromotive forces of such output circuits is substantially zero.

Although a particular embodiment of this invention has been disclosed, it will be understood that various modifications may be made without departing from the scope thereof.

I claim:

1. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, and polyphase transformer windings having their primaries connected in star and respectively connected to said output circuits and having their secondaries connected in series with each other for supplying an output circuit.

2. Apparatus for increasing the frequency of electric currents comprising three groups of three-phase transformer windings, each of said groups having its primary windings connected in Y and its secondary windings connected in series with each other to their respective output circuits, means for supplying three-phase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, and three-phase transformer windings having their primaries connected in Y and respectively connected to said output circuits and having their secondaries connected in series with each other for supplying an output circuit.

3. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to the primary windings of each group, said polyphase currents supplied to each group being displaced in phase from the currents supplied to each of the other groups, polyphase transformer windings respectively supplied with current from the output circuits of said groups, means for deriving currents from said last named polyphase transformer windings having an increased number of phases, and a second plurality of groups of polyphase transformer windings, each of the latter groups having its secondary windings connected in series with each other to their respective output circuits, the primary windings of each of said second groups being connected to receive out of phase currents from said last named means and the currents supplied to each of said second groups being displaced in phase from the currents supplied to each of the other second groups

4. Apparatus for increasing the frequency of electric currents comprising three groups of three-phase transformer windings, each of said groups having its primary windings connected in Y and its secondary windings connected in series with each other to their respective output circuits, means for supplying three-phase currents to the primary windings of each group, said three-phase currents supplied to each group being displaced in phase from the currents supplied to each of the other groups, three-phase transformer windings respectively supplied with current from the output circuits of said groups, means for deriving nine-phase currents from said last named three-phase transformer windings, each of the latter groups having its primary windings connected in Y and its secondary windings connected in series with each other to their respective output circuits, the primary windings of each of said second groups being connected to receive three-phase currents from said last named means and the currents supplied to each of said second groups being displaced in phase from the currents supplied to each of the other second groups.

5. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, and capacitors respectively connected in series in the input circuits to said groups.

6. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, and capacitors respectively connected across the input circuits of said groups.

7. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the current supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, capacitors respectively connected in series in the input circuits of said groups, and capacitors respectively connected across said input circuits.

8. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected

in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, polyphase transformer windings having their primaries connected in star and respectively connected to said output circuits and having their secondaries connected in series with each other for supplying an output circuit, and a capacitor connected in series in said output circuit.

9. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, polyphase transformer windings having their primaries connected in star and respectively connected to said output circuits and having their secondaries connected in series with each other for supplying an output circuit, and a device connected across said output circuit for use in parallel with the load on the circuit,

said device having a pronounced change of current under small change of voltage applied thereto.

10. Apparatus for increasing the frequency of electric currents comprising a plurality of groups of polyphase transformer windings, each of said groups having its primary windings connected in star and its secondary windings connected in series with each other to their respective output circuits, means for supplying polyphase currents to each of said groups, the phase of the currents supplied to each of said groups being displaced from the phase of the currents supplied to each of the other groups, polyphase transformer windings having their primaries connected in star and respectively connected to said output circuits and having their secondaries connected in series with each other for supplying an output circuit, and a saturable reactor connected across said output circuit for use in parallel with the load on the circuit.

FRANK G. LOGAN.

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