March 2, 1948. H. M. HUGE 2,437,093

MAGNETIC FREQUENCY CHANGER

Filed May 13, 1944 6 Sheets-Sheet 1

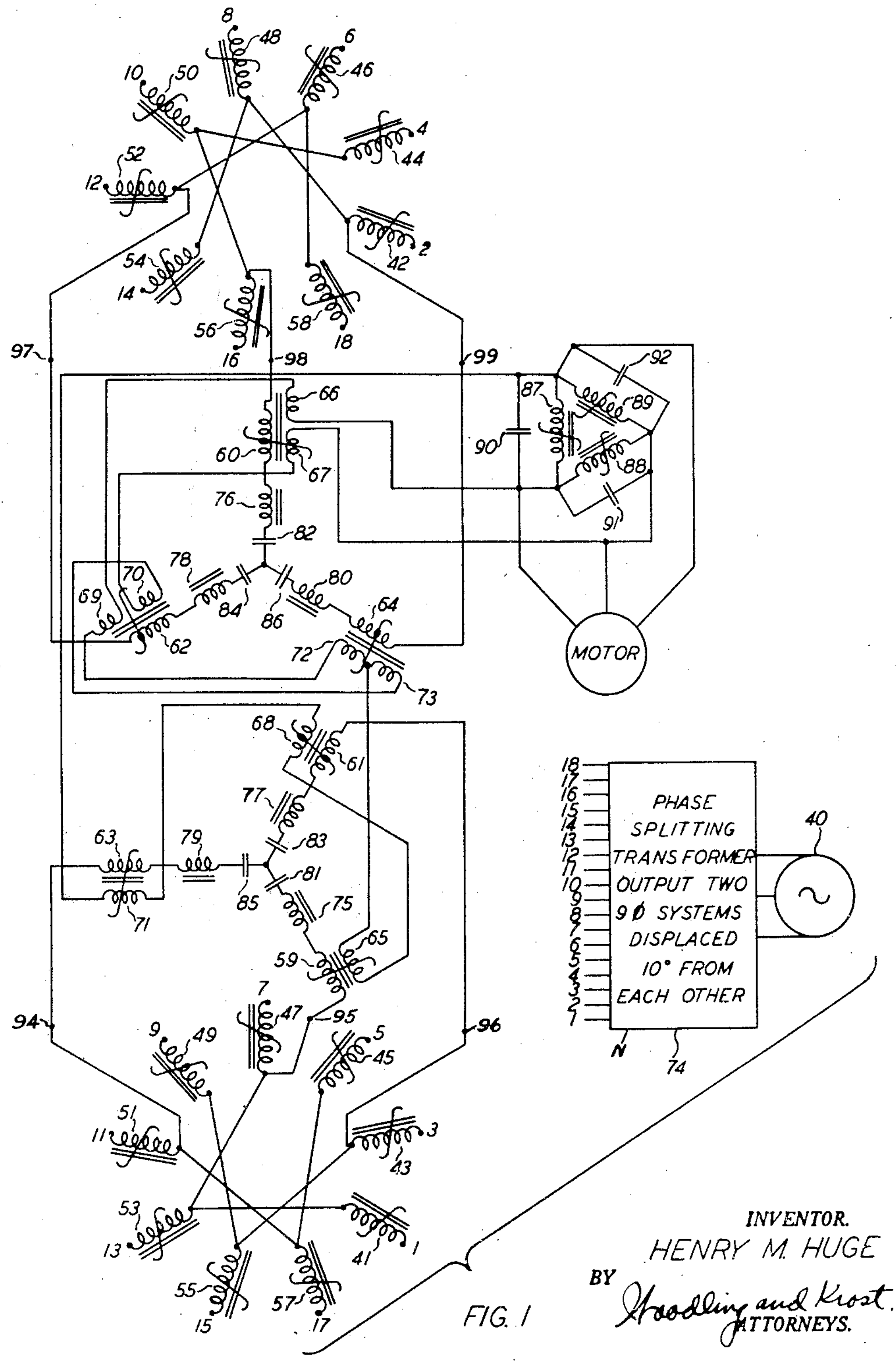

FIG. 1

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MAGNETIC FREQUENCY CHANGER

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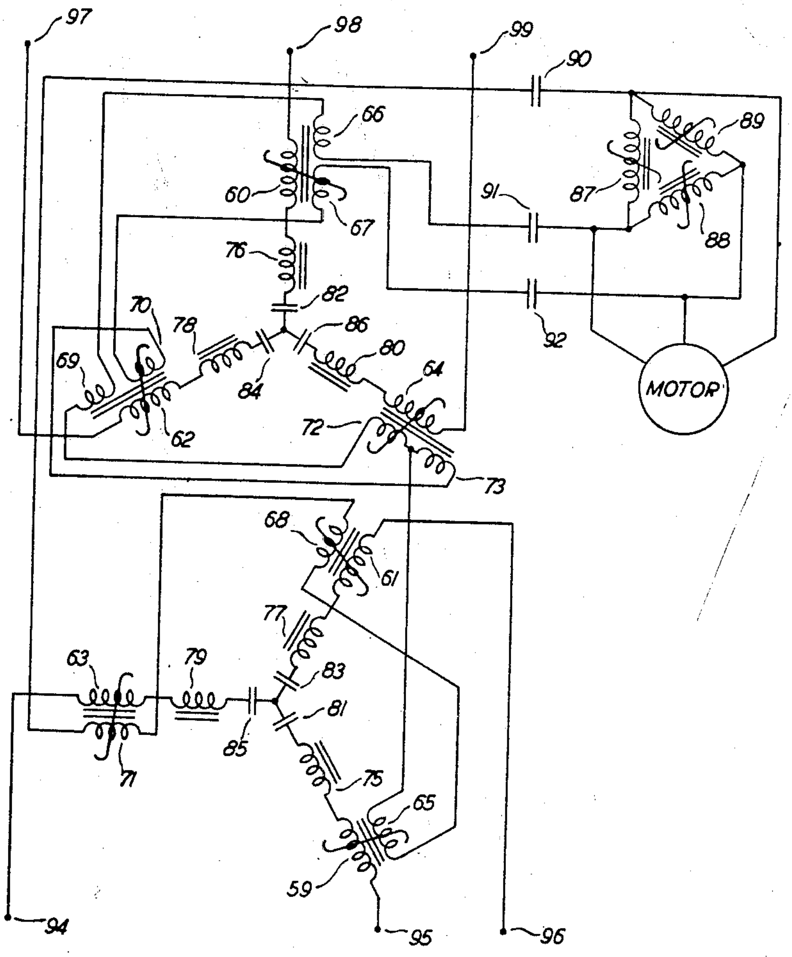

FIG. 2

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MAGNETIC FREQUENCY CHANGER

Filed May 13, 1944 6 Sheets-Sheet 3

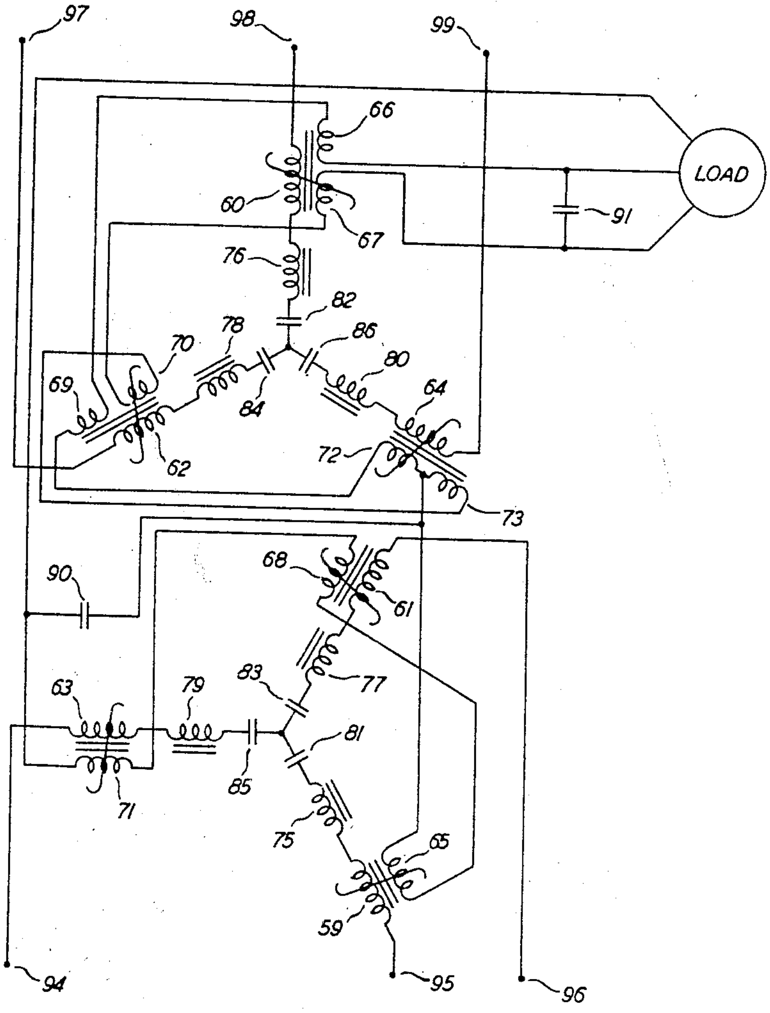

FIG. 3

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MAGNETIC FREQUENCY CHANGER

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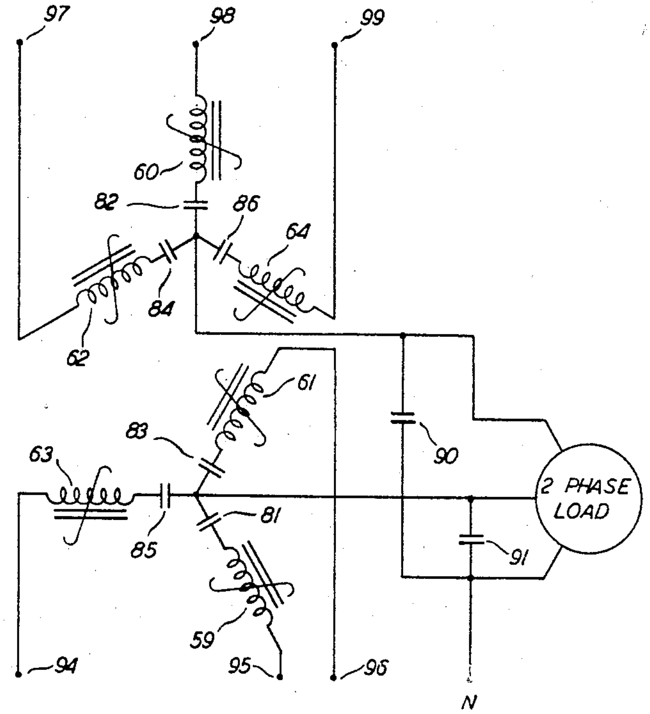

FIG. 4

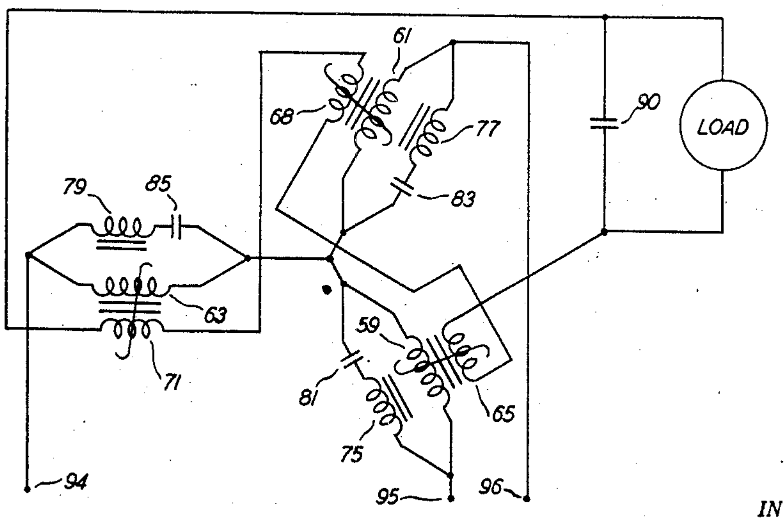

FIG. 5

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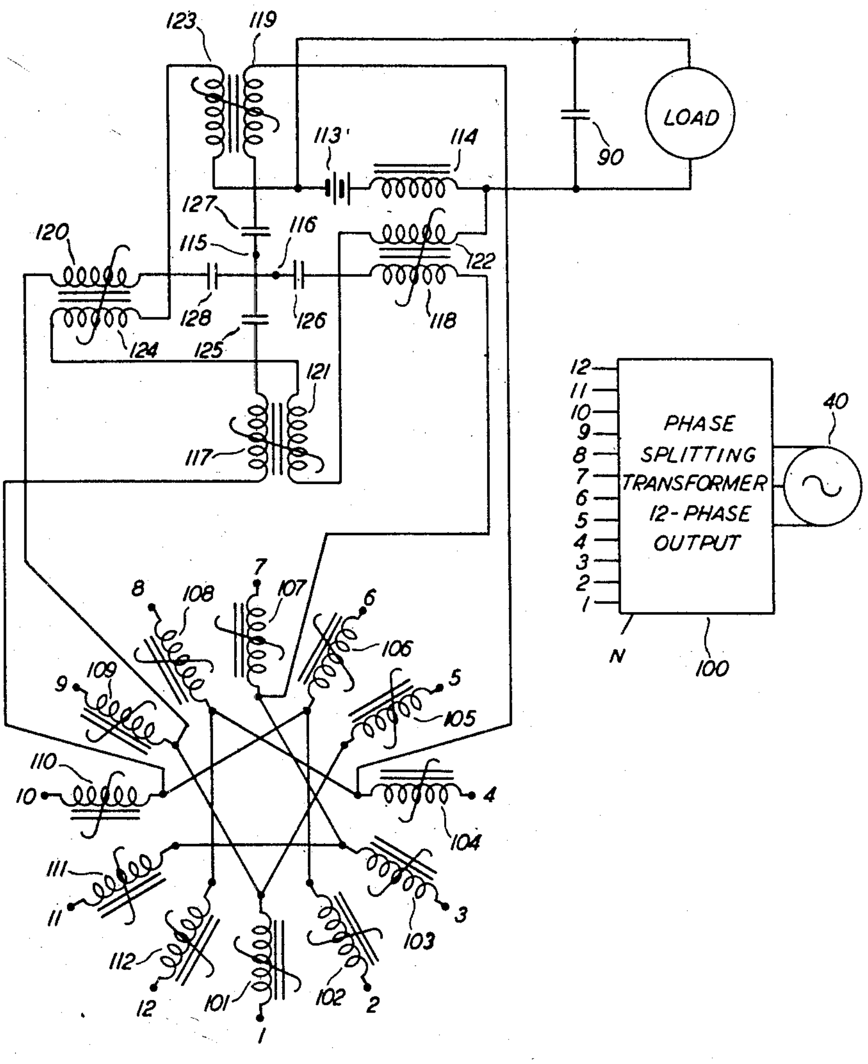

FIG. 6

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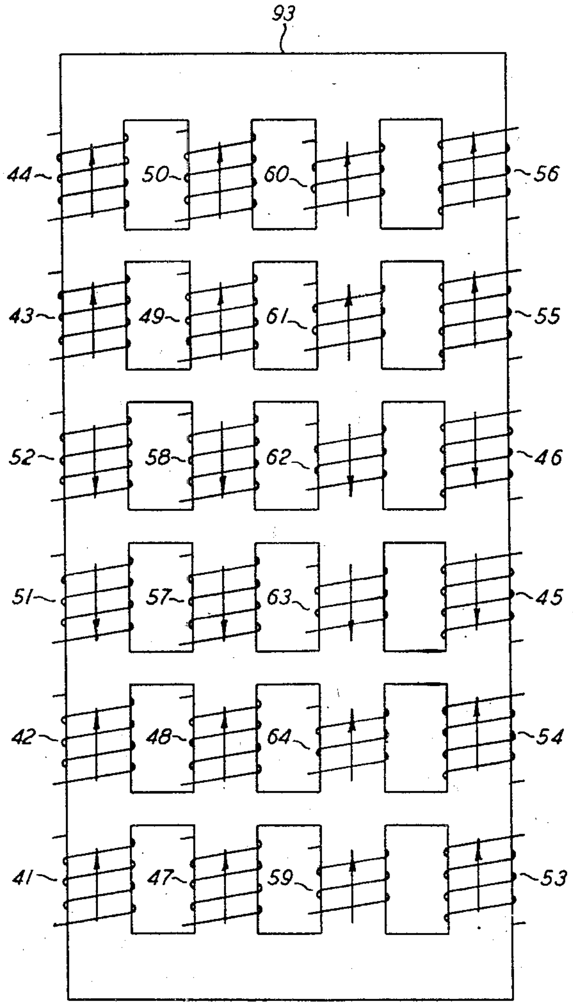

FIG. 7.

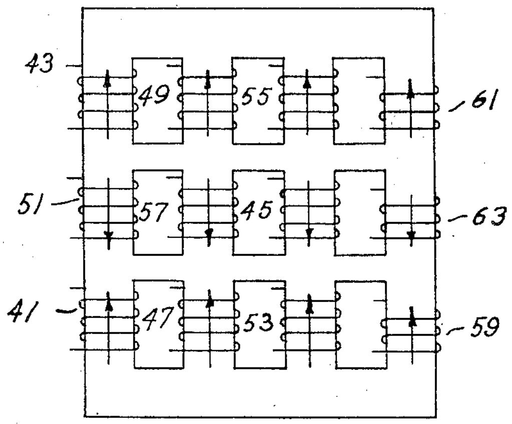

FIG. 8.

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UNITED STATES PATENT OFFICE

2,437,093

MAGNETIC FREQUENCY CHANGER

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Application May 13, 1944, Serial No. 535,479

31 Claims. (Cl. 172—281)

This invention pertains to magnetic frequency changers and in particular to a magnetic frequency changer for producing a great increase in frequency and adapted to be energized with polyphase alternating current. The frequency changer of my invention is particularly applicable for supplying polyphase voltages of a high frequency.

It is an object of my invention to magnetically generate a high order harmonic of an alternating current source.

It is another object of my invention to provide a static frequency changer for supplying polyphase power of a relatively high frequency.

Another object of my invention is to provide a magnetic frequency multiplier of high efficiency.

An additional object of my invention is to drive a polyphase induction motor with the output from my frequency multiplier.

Another object of my invention is to combine the saturable elements of my magnetic frequency changer on a single magnetic core structure.

A further object of my invention is to produce a two-stage frequency multiplier of high efficiency.

A still further object is to generate the output frequency in both stages of a two-stage frequency multiplier.

Another object of my invention is to provide both inductive and conductive coupling between the primary and secondary stages of a two-stage frequency multiplier.

An additional object is to energize two frequency-changing systems according to my invention from polyphase sources displaced in phase from each other so that the systems provide output voltages displaced in phase from each other for supplying a polyphase output.

Other objects and a fuller understanding of my invention may be obtained by referring to the following specification and claims in conjunction with the accompanying drawings in which

Figure 1 is the schematic diagram of a static frequency changer having a number of saturable inductances combined according to my invention for supplying a three-phase output voltage of nine times the input frequency,

Figure 2 is a diagram of a modification of the secondary arrangement of Figure 1, with capacitors in series with the load,

Figure 3 is a diagram of another modification of the same portion of Figure 1 with the capacitors connected in the two-phase portion of the circuit,

Figure 4 is still another modification, adapted

to supply a two-phase load from the star midpoints of the secondary circuit,

Figure 5 is another modification of a portion of Figure 1, supplying single-phase output,

Figure 6 is a diagram of another form of my invention adapted to supply the twelfth harmonic of the source frequency,

Figure 7 shows an arrangement for combining the saturable inductances of Figure 1 on a single magnetic core structure, for reducing the losses and providing improved operation, and

Figure 8 shows a common core structure similar to that of Figure 7 but having half as many elements, and being adaptable to the production of a single-phase output as with the circuit of Figure 6.

In general, the frequency changers made according to this invention use groups of saturable inductances energized from a polyphase source to generate harmonics of the source frequency and to balance the input frequency out of the output. The frequency changers have two stages, both of which utilize saturable inductances to generate harmonics; the secondary stage being energized with harmonic frequencies generated in the primary stage. Each group of primary saturable inductances supplies one phase of a polyphase system having a fundamental frequency which is a harmonic of the source frequency. The order of this harmonic is the same as the number of inductances in the primary group. The secondary inductances are energized directly from the polyphase system of the harmonic frequency and therefore reflect a nonlinear impedance into the primary stage.

When a star-connected group of saturable inductances is energized by a polyphase source, as is done in my invention, the midpoint of the star is not at the potential of the source neutral. Even though the system is perfectly balanced, so that voltage of the source frequency is neutralized at the star midpoint, a voltage still appears between the star midpoint and the source neutral. This voltage is of a frequency which is a harmonic of the source frequency, and the order of the harmonic is determined by the number of phases in the system. Thus, if three identical saturable inductances are star-connected to a balanced three-phase source, the third harmonic voltages generated in the saturable inductances are all in the same phase and appear at the star midpoint as a voltage of three times the source frequency between the source neutral and the star midpoint. Likewise, if five identical saturable inductances are star-connected to a balanced five-phase source, a voltage of five times the source frequency appears between the source neutral and the star midpoint.

According to my invention, the source neutral is not necessarily used as a terminal for supplying output voltage of a harmonic frequency, because I obtain a polyphase output of the harmonic frequency. For obtaining a three-phase output of the harmonic frequency, three groups of star-connected reactors are used. In the case of a third harmonic output, each group has three reactors, as just described, for producing the third harmonic voltage between their star midpoint and the source neutral. The three groups are not energized in the same phases, but are energized 40 degrees apart so that the third harmonic voltages are 120 degrees displaced. Under this condition the three star midpoints become the terminals of a three-phase system of three times the source frequency. This three-phase system may be connected to a secondary star-connected group of three saturable inductances to obtain a further frequency increase, producing the third harmonic of the third harmonic frequency, or the ninth harmonic of the source frequency.

Thus the primary and secondary stages cooperate to generate an output frequency which is a multiple of the source frequency, the multiplying factor being the product of the number of primary inductances in each primary group times the number of saturable inductances per secondary group. In the example given, there are three primary inductances per primary group and three secondary inductances per secondary group, so the multiplying factor is three times three and the output frequency is nine times the source frequency. The ninth harmonic voltage is generated not only in the secondary saturable inductances, but also in the primary saturable inductances, and these voltages also are substantially in phase with each other so they aid in supplying the load.

In order to obtain a polyphase output of nine times the source frequency, two complete frequency changers of the type just described are used, and are energized 10 degrees out of phase with each other. At the ninth harmonic, the phase displacement becomes 90 degrees to provide the basis for the desired polyphase output arrangement.

As in the primary star-connected inductances, the harmonic voltages appear between the source neutral and the secondary star midpoints. If the source neutral is available, the load may be connected to it and the secondary star midpoints. Alternatively, three complete frequency changers of the type previously described may be used, energized 13⅓ degrees apart to provide 120 degrees ninth harmonic displacement so the three secondary star midpoints become the terminals of a three-phase source of nine times the input frequency, just as in the primary stage the three star midpoints become the terminals of a three-phase source of three times the input frequency.

The output circuit may be insulated from the input circuit by providing each secondary saturable inductance with an insulated output winding. Connecting the windings in series with each other cancels the third harmonic voltages and adds the ninth harmonic voltages to provide a ninth harmonic output circuit.

The particular arrangement shown and described herein is arranged to supply three-phase output of nine times the input frequency and is shown as it may be applied to drive a high-speed three-phase motor.

With more particular reference to Figure 1, there is shown a polyphase source of alternating current **40** supplying a phase splitting transformer **74**. The neutral wire is designated N and the remaining output leads of transformer **74** are numbered from 1 to 18 with each lead being connected to a saturable inductance terminal bearing the corresponding number. In order to simplify the schematic these connecting wires are not shown in the diagram, but are merely indicated by corresponding numbers. Thus, terminal **1** on saturable inductance **41** is electrically connected to lead No. 1 on transformer **74**, terminal **2** on saturable inductance **42** is electrically connected to lead No. 2 on transformer **74** and so on for terminals **3** to **18** on saturable inductances **43** to **58**, which are respectively tied to the leads numbered 3 to 18 on transformer **74**. The internal connections and winding arrangement of the phase-splitting transformer **74** are not shown on Figure 1 because various arrangements can be used with substantially the same final results. The fundamental method of obtaining any required number of phases from a polyphase source by adding together properly proportioned voltages from the different phases can be applied in any one of several different circuit arrangements in the transformer **74**. The source **40** may be the commercial three-phase supply and transformer **74** may consist of three individual units preferably delta-connected and having the necessary taps on the primary windings and the required individual insulated secondary windings, or instead of three individual units, a single three phase transformer can be used to advantage, with windings and core arranged according to best design practices.

The phasing of the output voltages of transformer **74** can be visualized from the positioning of the primary saturable inductance coils in Figure 1, in that their position corresponds respectively to the phase of the voltage with which they are supplied. The nine odd-numbered coils **41** to **57** are supplied from a substantially balanced nine-phase system, as are the nine even-numbered coils **42** to **58**. The two nine-phase systems are displaced from each other by approximately ten electrical degrees, thus the voltage across coil **42** leads the voltage across coil **41** by ten degrees and the voltage across coil **43** leads that across coil **42** by approximately thirty electrical degrees.

The primary saturable inductances **41** to **58** are star-connected in groups of three, each group being supplied from a substantially balanced three-phase system. Thus, from the nine odd-numbered primary saturable inductances in the lower part of Figure 1, three star midpoints **94**, **95**, and **96** are produced. The voltages appearing between these star midpoints have a fundamental frequency three times that of the source **40**, and since their respective primary voltages are forty degrees displaced, the triple frequency voltages are displaced three times forty or one hundred twenty electrical degrees and the three star midpoints **94**, **95**, and **96** represent the terminals of a substantially balanced three-phase system of three times the frequency of source **40**. Similarly, from the nine even-numbered primary saturable inductances in the upper part of Figure 1 three star midpoints **97**, **98**, and **99** are obtained, representing the terminals of another substantially balanced three-phase system of three times the source frequency.

The two triple frequency three-phase systems thus obtained are connected to two star-connected secondary circuits with a saturable inductance in each branch of each circuit connected in series with a capacitor and a substantially linear inductance. Thus the three-phase system from the nine odd-numbered primary coils is connected to the secondary saturable inductances **59**, **61** and **63** in series with the capacitors **81**, **83** and **85** and the substantially linear inductances **75**, **77** and **79**. The three-phase system from the nine even-numbered primary coils is connected to the secondary saturable inductances **60**, **62** and **64** in series with the capacitors **82**, **84** and **86** and the substantially linear inductances **76**, **78** and **80**.

With the arrangement shown, the currents flowing through the secondary saturable inductances **59** to **64** produce voltages of nine times the frequency of source **40**. These voltages are produced not only in the secondary star-connected circuits of inductances **59** to **64** but also to a considerable extent in the primary circuits of inductances **41** to **58**. Thus in the operation of the frequency changer of my invention the function of the secondary star-connected circuits including the saturable inductance **59** to **64** is not only to generate in themselves the ninth harmonic of the source frequency but also to cause the primary inductances **41** to **58** to generate the ninth harmonic of the source frequency and thereby increase the total amount of ninth harmonic power generated and made available to the load.

Since the nine even-numbered primary inductances are supplied with voltage ten degrees out of phase with that supplied to the odd-numbered primary inductances, the ninth harmonic voltages generated by their respective circuits are displaced ninety degrees from each other. These phase-displaced output voltages may be utilized as a two-phase output of nine times the source frequency or by suitable transformer connections may be converted to three-phase output or any other required number of phases.

Figure 1 shows one possible arrangement for utilizing this polyphase output. The ninth harmonic voltage is obtained by adding together substantially equal voltages from each of the three saturable inductances in a secondary star-connected group. In the arrangement shown the output coils are internally arranged for Scott connection so a three-phase load can be supplied. The substantially equal output windings **65**, **68** and **71** on saturable inductances **59**, **61** and **63** respectively are connected in series to one phase of the output as the one branch of the Scott connection. There are two substantially equal output windings on each of the saturable inductances **60**, **62** and **64**, and one of each of these is connected in each of the other two branches of the Scott connection. Output windings **66**, **69** and **72** are connected in series to the second phase of the output and output windings **67**, **70** and **73** are connected in series to the third phase of the output. The saturable inductances **59** to **64** are preferably made substantially alike and the output windings are proportioned to supply a substantially symmetrical three-phase output voltage.

The three condensers **90**, **91**, **92** are energized from the output voltage and aid in its excitation. They are shunted with the three saturable inductances **87**, **88** and **89** respectively. This arrangement is particularly advantageous when a variable load is to be supplied, since it maintains a stable value of load voltage in spite of load variations. In particular, when the load is an induction motor, the capacitors **90**, **91** and **92** should be relatively large to start the motor quickly and the use of saturable inductances **87**, **88** and **89** makes it unnecessary to switch out the large capacitors as the motor comes up to speed. With increasing motor speed, the output voltage tends to rise, thus causing the inductances **87**, **88** and **89** to draw increasing exciting current and holding the load voltage down to the required level.

The circuit diagram shown in Figure 1 is the preferred embodiment of my invention as applied to the production of a three-phase output of nine times the source frequency, but numerous modifications may be made depending upon the operating requirements.

The three capacitors **90**, **91**, and **92** in the output circuit aid in the excitation of the output voltage but they need not be connected exactly as shown in Figure 1. Their function may be carried out in several other circuit arrangements, one of which is shown in Figure 2.

The circuit of Figure 2 is that of the secondary portion of a frequency changer for providing a three-phase output of nine times the source frequency as is done in the circuit of Figure 1. The terminals **94**, **95**, **96**, **97**, **98** and **99** which join the primary and secondary portions of the frequency changer of Figure 1 are identified in Figure 2 so the circuit of Figure 2 may be used to replace the secondary portion of Figure 1.

In Figure 2 the capacitors **90**, **91**, and **92** are connected in series with the load, while the saturable inductances **87**, **88** and **89** remain in parallel with the load as in Figure 1. The circuit operation of Figure 2 is essentially as described for Figure 1 with the capacitors **90**, **91**, and **92** aiding in the excitation of the output voltage and the saturable inductances **87**, **88**, and **89** serving to stabilize the output voltage.

Figure 3 is similar to Figure 2, and shows another manner of connecting the capacitors for excitation of the output voltage. In Figure 3, capacitor **90** is connected across the output of the odd-numbered saturable inductances **59**, **61**, and **63** obtained from windings **65**, **68**, and **71**, and capacitor **91** is connected across the output of the even-numbered saturable inductances **60**, **62**, and **64** obtained from windings **66**, **67**, **69**, **70**, **72**, and **73**. Thus the output voltage excitation is accomplished in a two-phase circuit with only two capacitors, while the load receives a three-phase voltage as before.

The saturable stabilizing inductances **87**, **88**, and **89** are omitted in Figure 3. Satisfactory circuit operation under many conditions is obtainable without these inductances, particularly when wide variations in load current are not experienced.

Figure 4 shows another circuit modification in which the secondary saturable inductances **59** to **64** are not provided with secondary windings but the output is obtained from the star midpoints as is done in the primary circuits. As previously described, the secondary star midpoints are not at the potential of the system neutral. A ninth harmonic voltage appears between each star midpoint and the neutral of the system, the voltages being ninety degrees displaced just as the ninth harmonic voltages in Figures 1, 2, and 3 are displaced.

The neutral wire N shown in Figure 1 may be obtained from suitable windings on the phase-splitting transformer **74**. In Figure 4, this neutral wire serves as one terminal of the two-phase output circuit, the other two terminals being the star midpoints of the secondary circuits. The two capacitors **90** and **91** are connected one across each of the output phases to aid in exciting the output voltage.

In Figure 4, the linear inductances **75**, **76**, **77**, **78**, **79** and **80** are omitted. I have found that under many operating conditions, satisfactory results may be obtained without these inductances, not only in the specific circuit shown in Figure 4, but also in the other circuits shown herein.

The circuit of Figure 5 is arranged to provide a single-phase output and may be connected to the terminals **94**, **95**, and **96** of Figure 1. In Figure 5, the capacitors **81**, **83**, and **85** together with their linear inductances **75**, **77**, and **79** are connected in parallel with their respective saturable inductances **59**, **61**, and **63**. The capacitors aid in the excitation of the third harmonic voltage as in the other arrangements shown, and the operation of the frequency changer is substantially as previously described. The single-phase output is supplied to the capacitor **90**, which functions as in the other arrangements. It will be apparent that the circuit arrangement shown is not restricted to single-phase output, but may be applied to Figures 1, 2, 3, and 4 for obtaining polyphase output. Conversely, single-phase output may be obtained from the circuits of Figures 1, 2, 3, and 4.

When other output frequencies are required the circuit may be rearranged to obtain other harmonics of the input frequency. The system as shown in Figure 1 may be thought of as consisting of two frequency changers energized with input voltages displaced in phase, one frequency changer for each of the two output phases. In describing forms of my invention which provide a single-phase output, it will be understood that polyphase output can be obtained by using two single-phase systems.

In the systems of Figure 1 it can be seen that each of the groups of primary inductances supplies one secondary saturable inductance, and that the number of primary coils is the number by which the input frequency is multiplied to obtain the output frequency. Thus with nine coils as in Figure 1 the ninth harmonic of the input frequency is obtained. For obtaining other harmonics of the source frequency, the principles described herein may be applied directly without departing from the spirit and scope of my invention.

My invention is also applicable to the production of even harmonics of the source frequency. It is possible to obtain the even harmonics with the same arrangement used for the odd harmonics using an even number of primary coils but I prefer to bias the coils to aid in the production of even harmonics. To obtain the twelfth harmonic, for example, twelve primary coils are used, they may be connected in four groups of three each, and tied to four secondary inductances, in which case the secondary inductance may be biased and the primary inductances unbiased.

A circuit arrangement of this type is shown in Figure 6, with the twelve primary saturable inductances **101** to **112** connected in four groups of three and with the four secondary inductances **118**, **119**, **120**, and **121** energized from the star midpoints of the four groups of primary inductances. The twelve primary inductances are connected to the twelve-phase output of the phase-splitting transformer **100** which is energized from the three-phase source **40**. The output leads of the transformer **100** are numbered from 1 to 12 and are electrically connected respectively to the terminals **1** to **12** of the inductances **101** to **112**. In order to avoid confusing the diagram, the actual connecting wires to terminals **1** to **12** are not shown.

The internal structure of the transformer **100** which provides the twelve-phase output and the neutral connection N is not shown, since transformers of this type are well known in the art, and a wide variety of winding arrangements may be used. The phasing of the output voltages is indicated by the positioning of the coils **101** to **112** in Figure 6. The operation of the primary stage of my frequency multiplier embodying these twelve inductances is substantially the same as the operation of the primary stage of Figure 1, except that a four-phase output of three times the source frequency is obtained in Figure 6. This four-phase output is supplied to the four secondary inductances **117**, **118**, **119**, and **120** which are connected in series with the four capacitors **125**, **126**, **127**, and **128** respectively. Capacitors **126** and **128** are connected at terminal **116** and capacitors **125** and **127** are connected at terminal **115**. When these terminals are connected together to form a common junction point, this junction point may be used as one output terminal and the neutral N as the other output terminal of the frequency changer.

The secondary windings **121**, **122**, **123**, and **124** of the secondary saturable inductances are connected in series, substantially cancelling voltages of the third and sixth harmonics of the source frequency and adding voltages of the twelfth harmonic of the source frequency. Capacitor **90** connected across these secondary windings aids in the excitation of the twelfth harmonic voltage which is supplied to the load.

Direct current source **113** is connected in series with blocking inductance **114** and connected to the windings **121**, **122**, **123**, and **124**. The direct current supplied by source **113** aids in the production of even harmonics in the secondary saturable inductances by biasing their magnetic cores. Except for the biasing action in Figure 6, the operation of the frequency changer is substantially as described in connection with Figure 1.

In the operation of my invention as exemplified in Figure 1 the frequency conversion is accomplished in two stages, designated as primary and secondary. Initially, the primary stage multiplies the input frequency by an integer n which is the same as the number of inductances in each primary group. Each primary group of inductances is energized with a substantially symmetrical n-phase voltage. The number of primary groups m is the same as the number of secondary saturable inductances and the secondary stage multiplies the frequency by the integer m. For this purpose, the m groups are energized symmetrically out of phase with each other from a substantially symmetrical m times n-phase source. The cooperation between the two stages, however, causes the primary stage to generate not only the nth harmonic of the input frequency, but also the m times nth harmonic, thereby increasing the available output power and increasing the converter efficiency. The output frequency is m times n times the input frequency, and in the output circuit a capacitor is connected, where it is energized with the output frequency and aids in exciting and controlling the output voltage. The secondary stage also includes capacitors which reflect a capacitive impedance to the output of the primary stage, which is fundamentally an m-phase voltage of n times the input frequency, but which also includes a large component which is of the output frequency.

Figure 1 shows schematically the electrical connections of one form of frequency changer embodying the features of my invention. Thus far nothing has been said regarding the physical or mechanical arrangement of the parts, and in fact, no special arrangement is necessary to obtain the results described. The eighteen primary saturable inductances are preferably made substantially alike and the six secondary saturable inductances are also preferably substantially alike with the exception of their output windings, which are arranged for Scott connection as previously mentioned. The other circuit elements are likewise substantially symmetrical in their values in order to obtain a balanced, symmetrical output voltage, substantially free of undesired harmonics of the source frequency.

In order to reduce the iron losses normally occurring in such a large number of inductances operating at high flux density, it is possible to combine certain of the inductances on common cores. Thus the three saturable inductances **87**, **88** and **89** connected across the output may be combined on a single three-phase core-type structure, with the added advantage of the phase balancing effect produced by the core construction. Similarly, the frequency-changing reactors can be combined on common cores in various manners, a limitation being that the core construction must not tend to suppress the desired harmonic.

The core structure shown in Figure 7 does more than simply save iron weight and reduce core losses; it combines both the primary and secondary saturable reactors of Figure 1 on a single core structure, **93**, and provides an inductive connection between the primary and secondary inductances. The numbers used in Figure 7 refer to the inductance numbers of Figure 1, no electrical connections being shown in Figure 7. The magnetic core structure comprises six sections magnetically in series. The term "magnetically in series" is used to indicate that at least part of the flux through a core member flows through the adjacent core member in the adjacent section. This constitutes a rather broad definition of a series magnetic circuit, but by referring to Figure 7, the series relationship becomes evident when it is noted that, for example, a large part of the flux through inductance coil **41** also flows through inductance coil **42**, as in a series magnetic circuit, although it is actually a series-parallel circuit.

By referring to Figure 1 it can be seen that coil **42** has induced in it a fundamental voltage ten electrical degrees behind the voltage in coil **42**. The arrows on Figure 7 show the phasing of the coils, with **41** and **42** phased in the same direction but with coil **51** phased opposite to **42**. Since the voltage in **51** is 170 electrical degrees out of phase, reversing the coil makes it only ten degrees away from **42**, so the fluxes through these adjacent primary core members in series are displaced ten electrical degrees just as between the fluxes in the core members within coils **41** and **42**. The same method of phasing is followed throughout the eighteen primary coils so that the fundamental fluxes through adjacent primary core members in series with each other are displaced in phase ten electrical degrees from each other, and the induced voltages in the coils on these core members are likewise displaced ten electrical degrees.

In each one of the six core sections in Figure 7 there are three primary core members magnetically in parallel with each other and with a secondary core member. Between the core sections, transverse core members are arranged to carry the flux which is the difference between the fluxes in adjacent series core members. These transverse core members are the connecting means which put the core members of a section effectively in a parallel magnetic circuit. Most of the magnetizing force supplied by each coil is expended in the core member within the coil so the external magnetomotive forces in the parallel magnetic circuit are relatively small. Nevertheless, since the magnetomotive forces spent in the transverse members are small in comparison with those spent in the core members within the inductance coils, the term "magnetically in parallel" seems to be applicable. The three primary coils on the three parallel primary core members are star-connected to a substantially symmetrical three-phase source and their fundamental voltages therefore differ in phase by 120 degrees. With this phasing, the secondary core members need carry practically no flux of the fundamental frequency, since the fundamental fluxes circulate through the primary core members and are substantially balanced out of the secondary core members.

The three-phase star connection of the primary inductances together with the saturation of the core members, produces a third harmonic component in the primary fluxes. Whereas the fundamental fluxes in the adjacent primary core members in parallel with each other are phased 120 degrees apart, the third harmonic fluxes have three times this phase displacement and are therefore in phase with each other. All the third harmonic fluxes of the section therefore must return through the secondary core member of the section. In this manner the secondary saturable inductance has a voltage induced in it before the primary and secondary circuits are electrically connected. When the inductances of Figure 7 are connected in the circuit of Figure 1 the frequency-changing action described in connection with Figure 1 is obtained, but at the same time the increased coupling between primary and secondary circuits provided by the core structure of Figure 7 increases the power which can be obtained and also improves the efficiency of the converter. Improved operation is also obtained by the interaction between primary and secondary at the output frequency. The primary saturable inductances generating the ninth harmonic of the input frequency supply their ninth harmonic fluxes directly through the secondary core members where they induce voltage in the output windings.

In the core structure **93** shown in Figure 7, the transverse members are preferably made large enough so that they operate at a relatively low flux density and relatively little magnetizing force is spent in them. Under this condition the magnetizing force of each primary coil is largely spent in the core member within the coil, and it is possible to obtain a high magnetizing force per unit length of flux path. At the same time it is possible to obtain a good output wave shape even though the core structure does not appear to be perfectly symmetrical in all respects, since the important part of the flux path is the same for each coil. The six core sections in Figure 7 may be separated, making six individual core structures, but this increases the size and weight of the core, and the arrangement shown is preferred.

Although Figure 7 shows the secondary core member inserted between two parallel primary core members, it is also possible to arrange the three primary core members side by side with the secondary adjacent to one of the outside primary coils as is done in Figure 8. As already stated, the transverse members are preferably made large enough so that little magnetomotive force is spent in them, so it can be seen that the position of the secondary core members with respect to the primary is not highly important.

The core structure shown in Figure 8 is adaptable to the practice of my invention when a single-phase output is to be obtained. For single-phase output, only half as many coils are required, and the core structure consists of three instead of six sections, with each section being the same as before. In this case, the phase displacement between the fundamental fluxes in adjacent series core members is twenty degrees instead of ten degrees as with six core sections. Coil **41** becomes adjacent to **51** which is in turn adjacent to **43**, and with the phasing indicated by the arrows, the induced fundamental frequency voltages from adjacent primary core members magnetically in series are twenty electrical degrees apart.

The principles of core construction disclosed in Figures 7 and 8 are not restricted to producing the ninth harmonic of the input frequency but can be adapted to the production of other frequencies just as the principles embodied in the circuit of Figure 1 are adaptable to the production of harmonics other than the ninth.

The number of primary saturable inductance groups *m* is the number of core sections, and the number of primary saturable inductances *n* in each group is the number of primary core members magnetically in parallel. In addition there is also a secondary core member in parallel with the primary core members. The foregoing relationships follow from the fact that the primary saturable inductance coils on each core section are star-connected to make a primary group, so the number of primary core members in parallel becomes the number of primary inductances in a group, and the number of groups, which is also the number of secondary saturable inductances, is the number of core sections. The type of core construction shown, as well as the principles of circuit arrangement as previously outlined, is applicable to the production of various harmonics, both even and odd, other than the ninth. As previously mentioned, the production of even harmonics can be aided by biasing the saturable inductances. The biasing can be accomplished by adding windings on the inductances and passing direct current through the windings as is done in Figure 6.

Although I have described my invention with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example and that numerous changes in the details of construction and the combination and arrangement of parts may be resorted to without departing from the spirit and the scope of the invention as hereinafter claimed.

I claim as my invention:

1. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three star midpoints of the first three groups, and a group of three capacitors, one connected in series with each of the inductances of the fourth group.

2. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three midpoints of the first three groups, and a group of three capacitors energized from the three star midpoints of the first three groups, and a fourth capacitor energized with nine times the source frequency.

3. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three midpoints of the first three groups, and a group of three capacitors energized from the three star midpoints of the first three groups, and a fourth capacitor energized with nine times the source frequency, said fourth capacitor being energized from voltage appearing between the star midpoint of the fourth group of inductances and the neutral of the nine-phase source.

4. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three midpoints of the first three groups, and a group of three capacitors energized from the three star midpoints of the first three groups, and a fourth capacitor energized with nine times the source

frequency, output winding means on each of the saturable inductances of the fourth group, said winding means being connected in series and energizing the fourth capacitor.

5. A frequency changer adapted to multiply the frequency of an alternating current source by m times n, and adapted to be energized from a substantially symmetrical polyphase source having m times n phases representing three substantially symmetrical n-phase systems, said frequency changer comprising m groups of saturable inductances having n inductances in each group, each group being star-connected to one of the n-phase systems, an additional group of m saturable inductances star-connected to the m-phase system of n times the source frequency represented by the star midpoints of the first m groups, a group of m capacitors energized by the m-phase system of n times the source frequency, an additional capacitor energized with m times n times the source frequency, the sum of the voltages across the inductances energized by the system of n times the source frequency being voltage of m times n times the source frequency, m and n being integers.

6. In combination, a plurality of frequency changers according to claim 5, adapted to be energized by polyphase sources displaced in phase from each other and adapted to supply polyphase power of the increased frequency.

7. In combination, two frequency changers according to claim 4, adapted to be energized by two polyphase sources displaced substantially ten electrical degrees from each other, producing two-phase power of nine times the source frequency, the outputs of the two frequency changers being internally arranged for Scott connection to provide three phase output of nine times the source frequency.

8. In combination, first saturable inductance means adapted to be energized by a polyphase alternating current source of m times n phases and to generate n phases of the mth harmonic of the source frequency, second saturable inductance means adapted to be energized with the n phase mth harmonic generated by the first means and to generate the m times nth harmonic of the source frequency, the second means cooperating with the first means in causing the first means to generate the m times nth harmonic thereby increasing the available power at this frequency, first capacitive means energized by the mth harmonic frequency and second capacitive means energized by the m times nth harmonic frequency, m and n being integers.

9. In combination, a saturable magnetic core structure comprising a plurality of core members in three sections arranged magnetically in series, each section having three primary core members in parallel with each other and in parallel with a secondary core member, a primary winding on each of said primary core members adapted to be energized from a polyphase source of alternating current, the three primary windings in each section being star-connected to a substantially symmetrical three-phase system, the phase displacement between the induced voltage from adjacent primary core members magnetically in series with each other being substantially twenty electrical degrees, the phase displacement between the induced voltages from adjacent primary core members in parallel with each other being substantially 120 electrical degrees, a secondary winding on each secondary core member, the three secondary windings being adapted to have induced in them three-phase voltage of a frequency three times the frequency of the alternating current source, and three capacitors in series with the three secondary windings in a star-connected circuit connected to the three star-midpoints of the primary windings.

10. In combination, a saturable magnetic core structure comprising a plurality of core members in three sections arranged magnetically in series, each section having three primary core members in parallel with each other, and in parallel with a secondary core member, a primary winding on each of said primary core members adapted to be energized from a polyphase source of alternating current, the three primary windings in each section being star-connected to a substantially symmetrical three-phase system, the phase displacement between the induced voltage from adjacent primary core members magnetically in series with each other being substantially twenty electrical degrees, the phase displacement between the induced voltages from adjacent primary core members in parallel with each other being substantially 120 electrical degrees, a secondary winding on each secondary core member, the three secondary windings being adapted to have induced in them three-phase voltage of a frequency three times the frequency of the alternating current source, and three capacitors in series with the three secondary windings in a star-connected circuit connected to the three star-midpoints of the primary windings, output circuit means comprising substantially equal output windings on each of said secondary core members, the output windings being connected in series, and a fourth capacitor energized from said output windings.

11. In combination, a saturable magnetic core structure comprising a plurality of core sections magnetically in series, each section comprising a plurality of primary core members and at least one secondary core member, magnetically in parallel with each other, primary windings on the primary core members adapted to be energized from a polyphase source of alternating current and to induce in the secondary core members fluxes of a frequency which is a harmonic of the frequency of the polyphase source, a plurality of capacitors adapted to be energized with said harmonic frequency and to aid in its excitation, a plurality of output windings on said secondary core members, said output windings being connected in series to cancel voltage of said harmonic frequency and to supply a load with voltage having a frequency which is a multiple of the harmonic frequency.

12. A two-stage magnetic frequency multiplier, the first stage comprising a plurality of primary saturable inductances adapted to be energized from a polyphase source of alternating current, to generate a harmonic of the source frequency, the second stage comprising a plurality of secondary saturable inductances and a plurality of capacitors adapted to be energized with the said harmonic to generate an output frequency which is a multiple of said harmonic, the second stage cooperating with the first stage in the generation of the output frequency in the primary saturable inductances as well as in the secondary saturable inductances.

13. A two-stage magnetic frequency multiplier, the first stage comprising a plurality of primary saturable inductances arranged in star-connected groups each group being adapted to be energized from a polyphase source of alter-

nating current and to supply one phase of a polyphase system having a fundamental frequency which is a harmonic of the source frequency, the second stage comprising a plurality of secondary saturable inductances and a plurality of capacitors, adapted to be energized with the said harmonic to generate an output frequency which is a multiple of said harmonic.

14. A two-stage magnetic frequency multiplier, the first stage comprising a plurality of primary saturable inductances arranged in star-connected groups, each group being adapted to be energized from a polyphase source of alternating current and to supply one phase of a polyphase system having a fundamental frequency which is a harmonic of the source frequency, the second stage comprising a plurality of secondary saturable inductances and a plurality of capacitors, adapted to be energized with the said harmonic to generate an output frequency which is a multiple of said harmonic, each secondary inductance being energized from the star-midpoint of one of the primary groups, magnetic core means providing inductive coupling between each secondary inductance and its energizing primary group, with flux of the source frequency being balanced out of the secondary inductances.

15. A two-stage magnetic frequency multiplier, the first stage comprising eighteen primary saturable inductances arranged in six star-connected groups, each group being adapted to be energized from a three-phase source of alternating current, the six three-phase energizing sources comprising two substantially symmetrical nine-phase systems, the second stage comprising six secondary saturable inductances connected with six capacitors in two substantially equal groups, each group being adapted to be energized from one of the nine-phase systems through the primary inductances which provide three-phase systems having a fundamental frequency three times the source frequency, output winding means on the secondary saturable inductances, the output windings of a group being connected in series, cancelling the triple frequency voltage and providing output voltage of nine times the source frequency.

16. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three midpoints of the first three groups, and a group of three capacitors, and three substantially linear inductances, one capacitor being connected in series with each of the linear inductances and in series with each of the inductances of the fourth group.

17. A frequency changer comprising in combination a plurality of saturable inductances adapted to be energized from a substantially symmetrical nine-phase source of alternating current, representing first, second, and third three-phase systems, a first group of three of the saturable inductances star-connected to the first three-phase system, a second group of three of the saturable inductances star-connected to the second three-phase system, a third group of three of the saturable inductances star-connected to the third three-phase system, a fourth group of three saturable inductances star-connected to the three midpoints of the first three groups, and a group of three capacitors energized from the three star midpoints of the first three groups, and a fourth capacitor energized with nine times the source frequency, output winding means on each of the saturable inductances of the fourth group, said winding means being connected in series and energizing the fourth capacitor, and an additional saturable stabilizing inductance connected in parallel with the fourth capacitor.

18. A plurality of frequency changers according to claim 2 adapted to be energized by nine-phase sources displaced in phase from each other and to supply a polyphase output of nine times the source frequency.

19. A plurality of frequency changers according to claim 4 adapted to be energized by nine-phase sources displaced in phase from each other and to supply a polyphase output of nine times the source frequency.

20. Two frequency changers according to claim 1, adapted to be energized from two nine-phase sources displaced in phase approximately ten degrees from each other, and adapted to supply two-phase output of nine times the source frequency.

21. Two frequency changers according to claim 1, adapted to be energized from two nine-phase sources displaced in phase approximately ten degrees from each other, with output windings on each of the saturable inductances of the fourth group of each frequency changer, the output windings of each frequency changer being connected in series to supply output voltage of nine times the source frequency, said output windings being Scott connected to provide a substantially symmetrical three phase output.

22. Two frequency changers according to claim 16, adapted to be energized from two nine-phase sources displaced in phase approximately ten degrees from each other, with output windings on each of the saturable inductances of the fourth group of each frequency changer, the output windings of each frequency changer being connected in series to supply output voltage of nine times the source frequency, said output windings being Scott connected to provide a substantially symmetrical three-phase output.

23. Two frequency changers according to claim 1, adapted to be energized from two nine-phase sources displaced in phase approximately ten degrees from each other, with output windings on each of the saturable inductances of the fourth group of each frequency changer, the output windings of each frequency changer being connected in series to supply output voltage of nine times the source frequency, said output windings being Scott connected to provide a substantially symmetrical three-phase output, a group of three capacitors and three saturable stabilizing inductances connected in parallel across the three phase output of nine times the source frequency.

24. In combination, first saturable inductance means adapted to be energized by a polyphase alternating current source of m times n phases and to generate n phases of the mth harmonic of the source frequency, second saturable inductance means adapted to be energized with the n phase mth harmonic generated by the first means and to generate the m times nth harmonic of the

source frequency, the second means cooperating with the first means in causing the first means to generate the *m* times *n*th harmonic thereby increasing the available power at this frequency, first capacitive means energized by the *m*th harmonic frequency and second capacitive means energized by the *m* times *n*th harmonic frequency, *m* and *n* being integers, biasing means adapted to produce unidirectional flux in at least one of the first and second saturable inductance means to augment the production of even harmonics when at least one of the integers *m* and *n* is an even number.

25. In combination, a saturable magnetic core structure comprising six core sections magnetically in series, each section comprising three primary core members and one secondary core member magnetically in parallel with each other, primary windings on said primary core members, the primary windings of each core section being star-connected to a substantially symmetrical three phase source, the primary windings on adjacent series core members being energized approximately ten electrical degrees out of phase with each other, secondary windings on the secondary core members, the secondary winding of each core section being energized from the star-midpoint of the primary windings of that section, the secondary windings being connected in two three-phase star-connected circuits, six capacitors energized from the six star-midpoints of the primary windings, output windings on the secondary core members, the output windings of alternate core sections being connected in series, balancing out the voltages of three times the source frequency and providing two output voltages of nine times the source frequency, with a phase displacement of substantially ninety degrees between them.

26. In combination, a saturable magnetic core structure comprising a plurality of core sections magnetically in series, each section comprising a plurality of primary core members and a plurality of secondary core members magnetically in parallel with each other, primary windings on the primary core members adapted to be energized from a polyphase source of alternating current and to induce in the secondary core members fluxes of a frequency which is a harmonic of the source frequency, a plurality of capacitors adapted to be energized with said harmonic frequency and to aid in its excitation, biasing means adapted to produce unidirectional flux through at least two of said secondary core members in each section, and a plurality of output windings on said secondary core members, the output windings being connected in series to cancel voltage of said harmonic frequency and to supply a load with voltage having a frequency which is an even-numbered multiple of the harmonic frequency.

27. A magnetic frequency multiplier comprising in combination a plurality of primary saturable inductances and a plurality of secondary saturable inductances, the primary inductances being adapted to be energized from a polyphase source and being both inductively and conductively connected to the secondary inductances to energize them with a harmonic of the source frequency, a plurality of capacitors adapted to be energized with said harmonic, and serially connected output windings on the secondary saturable inductances for supplying an output frequency which is a multiple of said harmonic.

28. A magnetic frequency multiplier comprising in combination a plurality of primary saturable inductances and a plurality of secondary saturable inductances, the primary inductances being adapted to be energized from a polyphase source and being both inductively and conductively connected to the secondary inductances to energize them with a harmonic of the source frequency, a plurality of capacitors adapted to be energized with said harmonic, and output circuit means for supplying an output frequency which is a multiple of said harmonic.

29. In combination, a saturable magnetic core structure comprising a plurality of core members in three sections arranged magnetically in series, each section having three primary core members in parallel with each other, and in parallel with a secondary core member, a primary winding on each of said primary core members adapted to be energized from a polyphase source of alternating current, the three primary windings in each section being star-connected to a substantially symmetrical three-phase system, the phase displacement between the induced voltage from adjacent primary core members magnetically in series with each other being substantially twenty electrical degrees, the phase displacement between the induced voltages from adjacent primary core members in parallel with each other being substantially 120 electrical degrees, a secondary winding on each secondary core member, the three secondary windings being adapted to have induced in them three-phase voltage of a frequency three times the frequency of the alternating current source, and three capacitors in series with the three secondary windings in a star-connected circuit connected to the three star-midpoints of the primary windings, output circuit means comprising substantially equal output windings on each of said secondary core members, the output windings being connected in series, and a fourth capacitor shunted by a saturable inductance energized from said output windings.

30. In combination with a frequency multiplier having saturable magnetic core means and secondary circuit means adapted to be energized with harmonic voltage from the saturable magnetic core means, output stabilizing means comprising parallel connected capacitive and saturable inductive means connected across the secondary circuit means.

31. In combination with a frequency multiplier having saturable magnetic core means and output circuit means adapted to be energized with harmonic voltage from the saturable magnetic core means, exciting means for producing stabilized harmonic voltage in the secondary circuit means, said exciting means comprising parallel connected capacitive and saturable inductive means connected across the output circuit means.

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