March 29, 1938. R. M. KALB 2,112,533

FREQUENCY CHANGER SYSTEM

Filed Sept. 23, 1936

FIG. 1

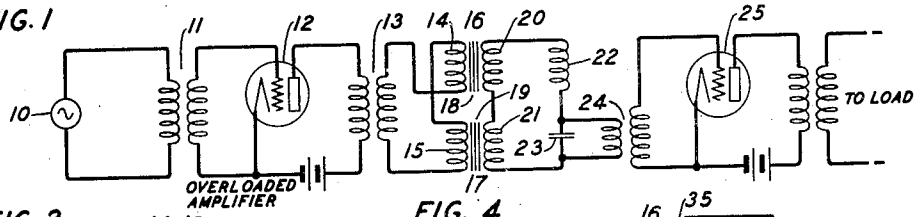


FIG. 2

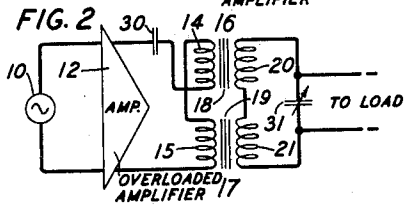


FIG. 4

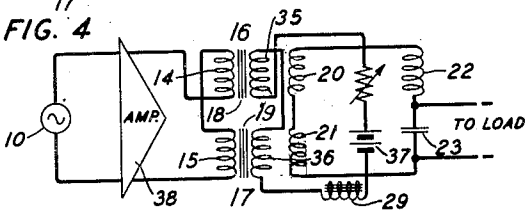


FIG. 3

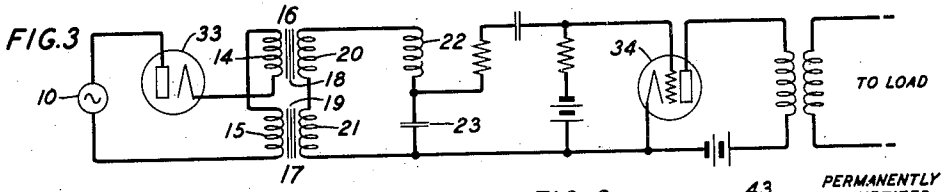


FIG. 5

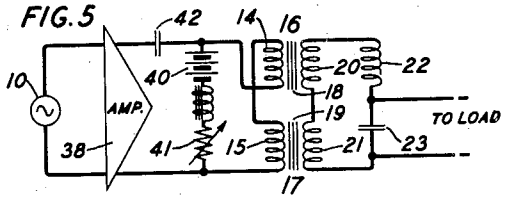


FIG. 6

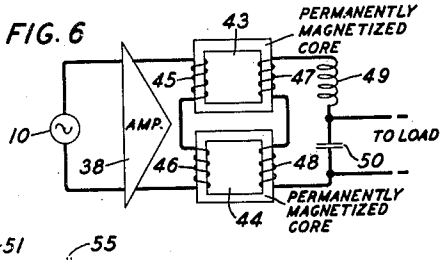


FIG. 7

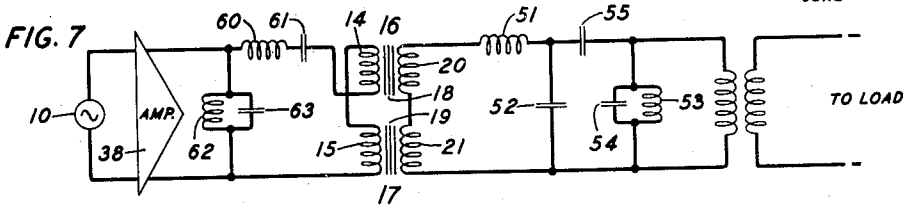


FIG. 9

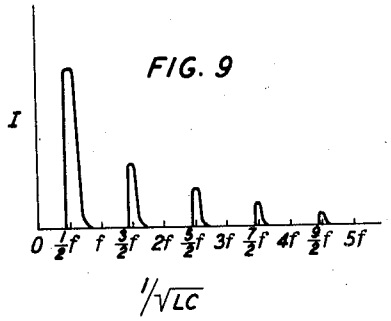
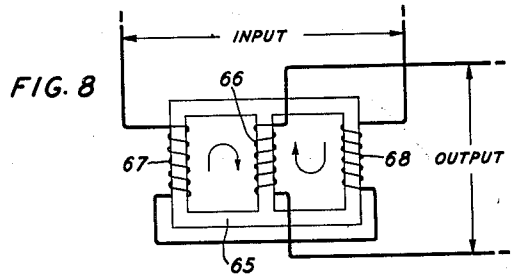


FIG. 8



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UNITED STATES PATENT OFFICE

2,112,533

FREQUENCY CHANGER SYSTEM

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Application September 23, 1936, Serial No. 102,114

11 Claims. (Cl. 172—281)

This invention relates to frequency changer systems where static frequency-transformers are employed for producing frequencies not present in the applied frequency.

An attribute of all non-linear ferromagnetic coils is their ability to produce frequencies other than those impressed. When an iron core coil under proper circuit conditions is subjected to a single frequency current it is known that harmonics of the impressed frequency will be generated. An object of the present invention is to provide a magnetic frequency converter whose output frequency is a rational fractional multiple of the input frequency. A more particular object is to provide such a converter in the secondary of which will be found no harmonics of the input frequency but only the odd harmonics of half of the input frequency whereby the frequencies generated for an input frequency f will be

$$\frac{f}{2}, \frac{3f}{2}, \frac{5f}{2}, \frac{7f}{2}, \text{ etc.}$$

In a preferred embodiment the frequency converter of this invention utilizes two magnetic core transformers having the two primary windings connected in series and the two secondary windings connected in series, the windings being poled as by a reverse connection of the two primaries to make the input and output branches conjugate. If it is desired to obtain one of the odd harmonics of half of the input frequency an asymmetrical flux wave of the periodicity of the input frequency is produced in each core, as by applying an asymmetrical wave of the input frequency across the two primary windings, and the desired fractional multiple frequency is selected by a tuned circuit across the two secondary windings. The applied asymmetrical wave may be obtained by overloading the grid circuit of a vacuum tube amplifier with a sinusoidal wave of the input frequency or by using the output of a half wave rectifier driven by a wave of the input frequency to be converted. Still other means for obtaining the desired asymmetry of the input wave may be utilized if desired.

Referring to the drawing,

Fig. 1 represents a magnetic frequency converter for obtaining a fractional multiple of the input frequency where an overloaded amplifier is employed for producing an asymmetrical wave which is applied to a magnetic frequency converter to produce an asymmetrical flux wave of the periodicity of the input frequency in its cores;

Fig. 2 is a modification of Fig. 1;

Fig. 3 is a magnetic frequency converter in which the desired asymmetrical wave of the input frequency is obtained by rectification of the input frequency;

Fig. 4 is a magnetic frequency converter in which the cores of the converter are polarized by a direct current flow through supplementary windings thereon;

Fig. 5 discloses a magnetic frequency converter provided with a direct current bias to give the desired asymmetrical wave of the input frequency;

Fig. 6 discloses a converter employing permanent magnets as cores;

Fig. 7 is an alternative form of the invention designed to make the selected output frequency substantially independent of small variations in the amplitude of the input frequency or the values of the circuit parameters;

Fig. 8 represents an alternative core construction that may be employed in Figs. 1 to 7; and

Fig. 9 is a curve illustrating the character of the frequency output of the converter of this invention.

In its preferred form this invention involves the use of transformer cores of a magnetic material such as permalloy which has a very high permeability at low magnetizing forces and which soon becomes saturated when these forces are increased, thereby reducing the permeability to a low value.

Referring to Fig. 1 an alternating current of a certain frequency f from source 10 is impressed through an input transformer 11 upon a vacuum tube amplifier 12 in sufficient amplitude to overload the grid circuit of the amplifier and drive the grid positive so that the output circuit of the amplifier includes current not only of the fundamental frequency f but harmonics thereof. The output from amplifier 12 is impressed through output transformer 13 upon the primary windings 14 and 15 of a pair of similar transformers 16 and 17 whose cores 18 and 19 may as previously stated be of permalloy or other high permeability material. Across the secondary windings 20, 21 is connected a series tuned circuit comprising an inductance 22 and a capacity 23 for tuning the secondary mesh of the transformers 16, 17 to the desired odd harmonic of half the fundamental frequency f of source 10.

Since the primary windings 14 and 15 are connected in series opposition the input and output branches of transformers 16 and 17 are conjugate. This arrangement tends to purify

the wave form in the output by preventing the setting up of a secondary current of the input frequency through transformer action. This conjugate relationship also prevents the impedance of the primary branch of the frequency converter from affecting the impedance of the secondary branch. Another advantage of the conjugate meshes is the discrimination by balance against extraneous currents in the input.

When the asymmetrical wave of frequency is impressed on coils 16 and 17 due to the overloaded amplifier 12 it has been found that if the series tuned circuit 22, 23 is adjusted to tune the secondary branch of the coils 16 and 17 to any one of the odd harmonics of half the input frequency there will be a current of relatively high amplitude of the fractional harmonic selected but if the secondary mesh is tuned to a substantially different frequency there will be substantially no current flow through the tuned circuit 22, 23.

For example, if the input frequency produced by source 10 is 4,000 cycles per second then by proper tuning of the secondary mesh 20 to 23 for the desired odd integral multiple of half the input frequency, one may readily obtain with relatively high amplitude current of one of the frequencies

$$2{,}000 \text{ cycles } \left(\frac{f}{2}\right),\ 6{,}000 \text{ cycles } \left(\frac{3f}{2}\right),\ 10{,}000 \text{ cycles } \left(\frac{5f}{2}\right),\ 14{,}000 \text{ cycles } \left(\frac{7f}{2}\right)$$

etc., but no current will be found in this secondary mesh if the secondary mesh is tuned to the frequency f or the harmonics thereof such as $2f$, $3f$, $4f$, etc.

The current of the desired frequency may be supplied to a load circuit in any suitable manner although direct application of large load would be objectionable as it would broaden the frequency response and either would tend to introduce extraneous frequencies or would suppress all oscillations. It is preferable to interpose an amplifier between the load and the frequency converter having the amplifier work from part of the voltage across one of the tuning elements or by having the amplifier connected to the secondary mesh of the frequency converter by a high ratio step-up transformer. In Fig. 1 the primary of a vacuum tube input transformer 24 is connected across condenser 23 so that the amplifier 25 prevents the load from reacting on the secondary mesh of the converter. Taking the load across condenser 23 serves to discriminate against higher extraneous frequencies in the output mesh; while taking the load across inductance 22 would discriminate against lower extraneous frequencies.

In a preferred embodiment each of the coils 16 and 17 may have a 1 to 1 winding ratio with their cores of laminated tape about 1 mil. thick made, for example, of 3.8 per cent chromium permalloy in accordance with the Elmen U. S. Patent No. 1,768,237. The unity ratio, however, is not essential and other kinds of magnetic materials of high permeability may be employed.

An important feature of the frequency converter of Fig. 1 is the ability of the output to maintain a fixed frequency relation with the input over a definite range of variation of the input amplitude or the circuit parameters.

Fig. 9 illustrates the relative amplitudes of the frequencies available in the secondary mesh of the frequency converter of Fig. 1. In Fig. 9 the current I in the secondary mesh of the converter 16, 17 is plotted against various values of

$$\frac{1}{\sqrt{LC}}$$

for the secondary mesh where L is the inductance and C the capacity of the secondary mesh. It will be noted that as the tuning of the secondary mesh is varied the odd harmonics of half the input frequency f appear but that the harmonics of the input frequency are absent. The greatest amplitude shown is for tuning to the frequency

$$\frac{f}{2}$$

followed by smaller amplitude peaks for tuning to a higher odd harmonic of half the fundamental frequency, but the relative amplitudes depend primarily upon the form of the input wave.

Since the asymmetrical input to the frequency converter in Fig. 1 is due mainly to the presence of even harmonics of the fundamental frequency produced by distorting amplifier 12 it will be apparent that other means may be readily substituted for amplifier 12 as a source of the even harmonics of the fundamental frequency f.

In order to accentuate the peaks in the output of the distorting amplifier 12 it may be desirable to place the condenser 30 in series with the primary windings of the frequency converter as shown in Fig. 2. The inductance 22 of Fig. 1 is not always necessary and has been omitted in Fig. 2. In Fig. 2 the condenser 31 serves to tune the invariable component of the inductance of the secondary windings 20, 21 to the desired fractional multiple of the fundamental frequency.

As previously stated, other means may be employed to produce the desired asymmetrical wave of the fundamental frequency. In Fig. 3 a half wave rectifier 33 is inserted in series with source 10 so that the rectifier output is supplied to the frequency converter 16, 17. The frequencies available in the secondary mesh of the converter of Fig. 2 are the same as for Fig. 1 and as shown in Fig. 9 comprise by proper tuning

$$\frac{f}{2} \text{ or } \frac{3f}{2} \text{ or } \frac{5f}{2}$$

etc., but no harmonics of the fundamental frequency will be present. In Fig. 3 a resistance capacity coupling of a well-known type is employed to impress the voltage across condenser 23 upon an amplifier 34 which serves to impress the selected fractional harmonic upon the load circuit.

Another way to obtain in the cores of the frequency converter the desired biasing magnetization is by polarizing the cores 18 and 19 as in Fig. 4 by placing additional windings 35 and 36 on the cores 18 and 19 and connecting these additional windings in series with a direct current source 37 and a choke coil 29. The frequency output available to the secondary mesh of the converter of Fig. 4 is the same as for Fig. 1 and is shown in Fig. 9. The amplifier 38 is a distortionless amplifier and not an overloaded amplifier as in the case of Fig. 1. Choke coil 29 in the direct current circuit prevents it from shunting the alternating current.

The desired biasing magnetization may also be obtained by a direct current component supplied

with the input wave of the fundamental frequency. This is shown in Fig. 5 where the primary windings **14**, **15** are traversed by direct current from source **40** connected across the windings in series with adjustable resistance **41**. If desired, battery **40** may be the space current source or B-battery of amplifier **38**. An isolating condenser **42** may be employed to direct the direct current through these primary windings, while a choke coil prevents the alternating current from being shunted through battery **40** and resistance **41**. The frequency output available from the converter to Fig. 5 is the same as that of Fig. 1 as shown in Fig. 9.

Still another way of securing the biasing magnetization for the frequency converter is to employ permanently magnetized cores. In Fig. 6 the two cores **43**, **44** are of a permanently magnetized material which saturates at relatively low magnetizing forces. Otherwise, the arrangement of Fig. 6 is similar to that of Fig. 1 with the primary windings **45**, **46** reversely poled to make the input and output branches conjugate, the secondary windings **47**, **48** being connected in series with a tuned circuit comprising an inductance **49** and a capacity **50**. As in Fig. 1 the values of inductance **49** and capacity **50** determine which odd harmonic of half the fundamental frequency is supplied to the load circuit. Some understanding of the operation of the circuits of the invention in changing the frequency may be gained from analysis of the output mesh. The voltage induced in a secondary winding of N_2 turns on one transformer core carrying a flux Φ is

$$e_i = N_2 \frac{d\phi}{dt}$$

The flux is a function of the magnetomotive force, k, produced by the combined action of three current components: i_0, the average value of the input current or the biasing direct-current; i_1, the alternating component of the input current, with a period $1/f$ where f is the frequency of the input current; and i_2, the secondary current, with a period yet to be ascertained. The magnetomotive force is proportional to the sum

$$N_0 i_0 + N_1 i_1 + N_2 i_2$$

where N_0 and N_1 represent turns traversed by the biasing and input currents, respectively. Thus the secondary voltage in the one core may be rewritten as

$$e_1 = N_2 \phi'(k)\left[N_2 \frac{di_2}{dt} + N_1 \frac{di_1}{dt}\right] \qquad (1)$$

where $\Phi'(k)$ denotes the derivative of the flux with respect to the magnetomotive force.

The two transformers of a pair are similar, so that the magnetomotive force producing flux in the core of the other transformer is proportional to

$$-N_0 i_0 - N_1 i_1 + N_2 i_2$$

The reversed signs are occasioned by the opposite poling of the windings, the only essential difference from the first transformer. In these devices as they operate, the magnetization of the cores is dominated by the input, with the result that the secondary current exerts minor influence on the magnetomotive force. Also, the slope of the magnetization curve depends on only the magnitude of the magnetomotive force and not its direction. The secondary voltage in the second transformer is therefore, to a close approximation

$$e_2 = N_2 \phi'(k)\left[N_2 \frac{di_2}{dt} - N_1 \frac{di_1}{dt}\right] \qquad (2)$$

The electromotive force in the two secondary windings connected in series is the sum of e_1 and e_2, and in this sum the normally transformed voltages induced by the primary current cancel, leaving only an electromotive force proportional to the rate of change of the secondary current and dependent upon the non-linear characteristics of the core material. In particular, the conjugate connection of the two transformers phases out of the secondary side all harmonic voltages generated by the core in the ordinary manner, as well as the fundamental and harmonic currents supplied to the primary windings by the driving source.

The secondary current flows through an inductance L, a resistance R, and a capacity C, in series with the secondary windings of the two transformers. The charge, q, on the condenser is connected with i_2 by the relation

$$i_2 = \frac{dq}{dt} \qquad (3)$$

and is given by the circuit equation

$$\left[L + N_2^2 \phi'(k)\right]\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = 0 \qquad (4)$$

This equation is obtained by adding the voltages around the mesh and equating their sum to zero in accordance with Kirchoff's law.

The coefficient of the second derivative in Equation (4) is periodic in time, a circumstance which accounts for the transfer of energy into the secondary mesh and endows the current in that mesh with its peculiar properties. The nature of the solutions of any linear differential equation with periodic coefficients has been known to mathematicians for some time through Floquet's theory. (G. Floquet—Sur les équations differentielles linéaires á coefficients périodiques. Ann. de. l'Ecole norm. sup. (2) vol. 12, (1883), pp. 47–88). This yields the result that periodic solutions of such equations may have twice the period of the coefficients. (E. L. Ince—Ordinary Differential Equations, London 1927, pp. 381 et seq.) Equation (4) thus specifies a charge with a fundamental frequency one half the fundamental frequency of $\Phi'(k)$.

The period of $\Phi'(k)$ is that of k and hence the same as the period of the primary magnetizing current when it includes direct current or even order harmonic components which cause the magnetization curve of the core material to be traversed asymmetrically. If the curve were traversed symmetrically a frequency doubling would occur in the cores; because $\Phi'(k)$ is an even function of the magnetomotive force it would vary at twice the frequency of this force. The fundamental frequency of the charge, being half that of $\Phi'(k)$, would then be the same as that of the primary current. It should also be noted that, unless the instantaneous flux components produced in both cores by the alternating current have the same relation to those produced by the direct current, phase displacement between the electromotive forces in the two secondary windings will result. This leads to a double-frequency component in $\Phi'(k)$ which produces an electromotive force of fundamental frequency in the secondary windings and a simultaneous reduction of the half-frequency electromotive force. Phase opposition produces complete frequency doubling and only the fundamental frequency and its harmonics then exist in the secondary current.

The above analysis proves that the waves ap-

pearing in the secondary mesh of the two transformers in the circuits of the invention as illustrated in the several figures of the drawing and described above, include waves of half the fundamental frequency applied to the primary mesh as well as harmonics of half the fundamental frequency.

One desirable characteristic of the circuits above described is that they lock in at the exact desired frequency ratio and so have the same frequency stability as the input frequency. The converter circuits of the invention constructed as shown in Figs. 1 to 7 make operation at unwanted frequencies impossible, thus preventing any chance frequency variation in driving source being transmitted through the converter. The circuits of this invention also have the advantage that the selected odd harmonic of half the fundamental frequency will be obtained even though small variations occur in the value of the circuit elements, the input amplitude, or the whole. This stability may be termed coherence—the ability of the output to maintain frequency relation with the input over a definite range of variation of the input amplitude or the circuit parameters. However, if the input of the fundamental frequency is subject to substantial variations in amplitude it may be desirable to feed the frequency converters 16, 17 from a constant current amplifier which in the case of Fig. 1 may be the overloaded amplifier employed to produce the asymmetrical wave input.

The increased frequency stability of the circuits of Figs. 1 to 7 is due to the fact that the secondary circuit of the saturable core transformers in each case comprises only one resonant mesh which is tuned to half the frequency applied to the primary circuit of the transformers, or to harmonics of that half frequency. The use of several resonant meshes tuned to different frequencies would provide several degrees of freedom tending to cause oscillations in unwanted modes, i. e., a lack of coherence, which would make the circuit hard to control.

Fig. 7 shows an alternative arrangement for obtaining an odd harmonic of half the fundamental frequency without the need of applying an asymmetrical wave to the input of the converter. The output from the two frequency converter coils 16, 17 comprises a network of two sections, the first section comprising a series inductance 51 and a shunt capacity 52, while the second section comprises an anti-resonant circuit comprising an inductance 53 and a capacity 54. These two sections may be coupled capacitatively if desired, by condenser 55. The tuned circuit 53, 54 should be made anti-resonant at the desired frequency output so that if the input to the frequency converters 16 and 17 from source 10 is 4,000 cycles and 10,000 cycles is desired, then the circuit 53, 54 should be tuned to 10,000 cycles. The series tuned circuit 51, 52 of the first section is employed to increase the stability of the circuit to insure that with a given input frequency the desired odd harmonic of half the input frequency will be obtained, under varying conditions of load and circuit parameters. Although inductance 51 and capacity 52 may also be tuned to the frequency to be selected to obtain this coherence, this identical tuning of the two sections is not essential. Since Fig. 7 does not have the asymmetrical flux wave input of the earlier figures, the arrangement of Fig. 7 is also capable of generating harmonics of the fundamental frequency by proper tuning of the secondary mesh.

With the adjustment explained above for Fig. 7 the voltage across the terminals of anti-resonant circuit 53, 54 will have a frequency of 10,000 cycles per second, which frequency may be led off to the load circuit in any suitable manner. The frequency converter of Fig. 7 is of particular importance when a relatively high ratio is desired between the selected output frequency and the input frequency.

In order to purify the output of amplifier 38 in Fig. 7 a series tuned circuit 60, 61 and an anti-resonant circuit 62, 63 may be connected in series and in shunt respectively, to the primary windings of the frequency converter, each tuned to the fundamental frequency of source 10. These tuned circuits 60, 61 and 62, 63 are not essential, however, to the operation of the converter and may be omitted if desired.

It should be noted that in general it is not necessary to employ two separate cores for the frequency converter as the primary and secondary windings may be placed on a two-mesh core 65 as shown in Fig. 8 where the common secondary winding 66 for the two primary windings 67, 68 is placed on the center leg with the two primary windings on the two outer legs of the core. The two primary windings are connected in series opposition so that the input and output circuits of the transformer of Fig. 8 are conjugate. The transformer 65 of Fig. 8 may be substituted for the coils 16 and 17 of any of the earlier figures. It may also be noted that, if desired, winding 66 may be included in the input mesh and windings 67, 68 in the output mesh of the frequency converter instead of the reverse connection indicated on the drawing.

In the frequency converters of Figs. 1 to 6 it is to be understood that the amount the flux wave supplied to the frequency converter cores is made asymmetrical depends upon circuit conditions and should be adjusted to produce the optimum amplitude of the frequency to which the secondary mesh of the converter is tuned.

It is to be understood that other embodiments of the invention are contemplated commensurate with the scope of the appended claims.

What is claimed is:

1. A circuit for obtaining rational fractional multiples or submultiples of a given fundamental frequency comprising two inductive windings, an input circuit comprising said two windings connected in series, magnetic core means for said windings, a secondary winding on at least a portion of said core means, an output circuit including said secondary winding, said input and output circuits being conjugate, a source of an alternating current wave of a given periodicity in said input circuit and means for producing in said core means an asymmetrical flux wave of a periodicity equal to that of said source and such that the electromotive forces in all parts of said secondary winding are substantially the same at any instant, said output circuit being tuned to the desired multiple or submultiple frequency.

2. A frequency converter in accordance with claim 1 in which the means for producing said asymmetrical flux wave comprises a vacuum tube amplifier coupling said source and said two serially connected windings, and means for making the amplitude of the wave supplied from said source to said amplifier such as to overload it whereby an asymmetrical wave is supplied to said two windings.

3. A frequency converter in accordance with claim 1 in which the means for producing said

asymmetrical flux wave comprises a rectifier connected between said source and said two serially connected windings.

4. A frequency converter in accordance with claim 1 in which the means for producing said asymmetrical flux wave comprises means for superposing on the alternating current wave supplied from said source to said two windings a direct current component of magnetization in such manner as to make the magnitudes of the instantaneous electromotive forces induced by the alternating component of the flux wave in equivalent portions of said secondary winding substantially equal.

5. A circuit for obtaining rational fractional multiples of a given fundamental frequency comprising a source of an asymmetrical wave of said given frequency, two magnetic core transformers each having a primary winding and a secondary winding, the two primary windings being reversely wound and connected in series across said source, and an output circuit connected across the two secondary windings in series, said output circuit being tuned to the desired multiple frequency.

6. The circuit of claim 5, in which said source of an asymmetrical wave of said given frequency comprises a vacuum tube amplifier having an input circuit and an output circuit, means to supply a sinusoidal wave of said given frequency to said input circuit in such manner as to overload said amplifier, said output circuit being connected across the reversely wound primary windings of said transformers.

7. A frequency converter for obtaining an odd harmonic of half a given fundamental frequency comprising two primary windings, an input circuit comprising said windings connected in series, magnetic core means for said windings, a secondary winding on at least a part of said core means, an output circuit including said secondary winding, said input and output circuits being conjugate, a source of a given frequency in said input circuit, and means for producing in said core means an asymmetrical flux wave of a periodicity equal to the frequency of said source, said output circuit being tuned to an odd harmonic of half the frequency of said source.

8. A frequency converter for obtaining an odd harmonic of half a given fundamental frequency comprising two magnetic core transformers each having a primary winding and a secondary winding, an input circuit comprising said primary windings connected in series, an output circuit comprising said secondary windings, said windings being so related that said input circuit and said output circuit are conjugate, and means for supplying to said input circuit an asymmetrical wave of said given frequency, said output circuit being tuned to the desired odd harmonic of half the frequency of said given frequency.

9. A frequency converter for obtaining an odd harmonic of half a given fundamental frequency comprising two magnetic core transformers each having a primary winding and a secondary winding, an input circuit comprising said two primary windings connected in series, an output circuit comprising said secondary windings, said windings being so related that said input circuit and said output circuit are conjugate, a source of a given frequency, means for producing in said cores an asymmetrical flux wave of a periodicity equal to the frequency of said source and such that the electromotive forces in all parts of said secondary winding are substantially the same at any instant, a resonant circuit in said output circuit tuned to the desired odd harmonic of half the frequency of said source, a load circuit to be supplied with a frequency equal to the frequency to which said resonant circuit is tuned, and a vacuum tube amplifier interposed between said resonant circuit and said load circuit.

10. A frequency changing device comprising input and output branches, an asymmetrical distorting device coupling said input and output branches in conjugate relation, means for impressing an alternating current wave of a given frequency on said input branch, and a single resonant mesh in said output branch tuned to frequencies other than harmonics of said given frequency.

11. A frequency changer comprising one or more pairs of oppositely poled transformers having primary and secondary windings and a saturable magnetic core, means to apply a pulsating existing current to the primary winding of each pair of transformers, and a single output mesh comprising reactive and resistance circuit elements connected in series with the secondary windings of each pair, said circuit elements being so proportioned that the current passing through them will have a periodicity different from that of the exciting current applied to the primary windings of the pair.

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