

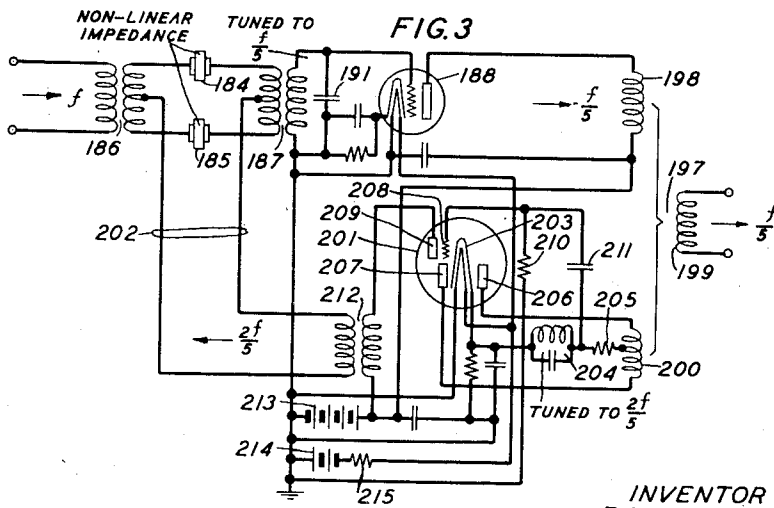
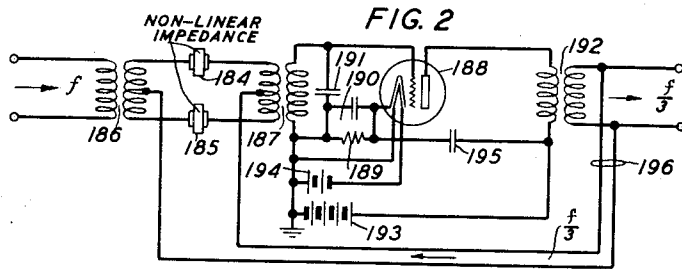
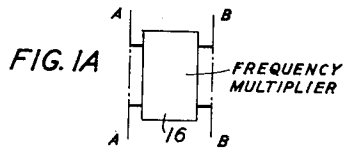
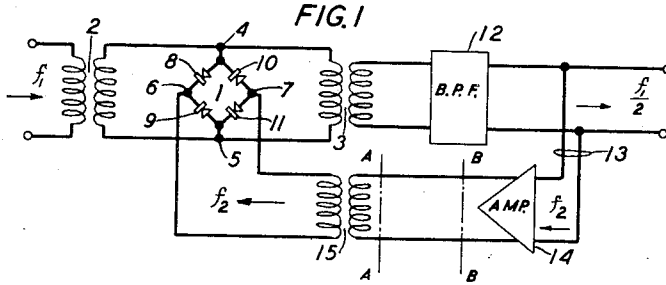
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2,159,597

FREQUENCY CONVERSION CIRCUITS

Original Filed July 31, 1937



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FREQUENCY CONVERSION CIRCUITS

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6 Claims. (Cl. 250—36)

This application is a division of my copending application, Serial No. 156,698, filed July 31, 1937.

The invention relates to the production of alternating current waves by frequency conversion methods.

An object of the invention is to convert alternating current waves of one frequency into alternating current waves of a different frequency.

A more specific object is to produce alternating current waves of desired frequencies which are accurate fractions of a given base frequency.

These objects are attained in accordance with the invention by frequency conversion circuits utilizing a process which may be termed regenerative modulation. Regenerative modulation is produced in general by feeding back the output of a balanced type modulator to the balanced or conjugate input thereof through a selective network, such as a filter, and an amplifier of fixed gain μ . Such a circuit is stable and of a non-oscillatory nature as long as the loss due to the balanced condition and the network or filter is greater than the gain μ of the amplifier.

The frequency conversion circuits of the invention employing this process, to be described hereinafter, may be used to produce electrical waves which are exact fractional ratios of a given frequency applied to the input, and which will follow amplitude and frequency variations in the applied waves over quite wide ranges, these circuits having exceptional frequency stability and efficiency in operation.

The various features and advantages of the circuits of the invention will be brought out in the following detailed description thereof when read in connection with the accompanying drawing of which:

Fig. 1 shows schematically a circuit which illustrates the basic principles of the invention;

Fig. 1A shows a modification of this basic circuit; and

Figs. 2 and 3 show schematically in greater detail frequency conversion circuits embodying different modifications of the invention.

The fundamental concept of regenerative modulation as applied to frequency conversion may be described by referring to Fig. 1.

The frequency converter circuit of Fig. 1 includes a balanced modulator 1 of the second order type, such as that disclosed in F. A. Cowan Patent No. 1,959,459, consisting of four copper-oxide rectifier units connected in a Wheatstone bridge formation, an input transformer 2 and an output transformer 3, the secondary winding of the input transformer and the primary winding

of the output transformer being connected in shunt with one diagonal 4, 5 of the bridge and a source of modulating current being connected to the other conjugate diagonal 6, 7 of the bridge. The copper-oxide rectifier units 8, 9 are poled so that each is conductive in the direction toward the common terminal 6, and the other rectifier units 10, 11 are poled so that each is conductive away from the common terminal 7. The primary winding of the input transformer 2 is connected to a source (not shown) of the base frequency f_1 to be converted, and a filter 12 is connected between the secondary winding of the output transformer 3 and the output terminal of the circuit. The source of modulating waves applied to the conjugate terminals 6, 7 of the modulator bridge is the regenerative circuit 13 comprising the filter network 12 and the one-way amplifier 14 of gain μ having its input connected across the output of filter 12 and its output connected across the conjugate terminals 6, 7 of the bridge 1 through the transformer 15. The gain μ of the amplifier 14 in the regenerative circuit is selected so as to provide the required stability. As indicated, a frequency multiplier 16, indicated by the box so labeled in Fig. 1A, would be included in the regenerative circuit 13 where it is desired to secure a fractional frequency having a denominator larger than 2.

Now if the input frequency f_1 is applied to the input of the second order modulator in the system of Fig. 1 and any frequency f_2 in the output thereof is selected by the filter 12 and fed back through the amplifier 14 and transformer 15 to the conjugate terminals 6, 7 of the modulator, the two frequencies f_1 and f_2 will combine in the modulator to produce the two side-band frequencies $f_1 \pm f_2$ which are at a certain loss with respect to f_2 . If the amplification μ is greater than the side-band loss plus the loss provided by the filter 12, the side-band frequencies will be fed back and will be applied to the conjugate terminals 8, 9 of the modulator 1 but at a greater amplitude. If the following arbitrary case is set up

$$f_1 \pm f_2 = f_2 \quad (1)$$

which is the case where f_2 will sustain itself, it will be found that

$$f_2 = \frac{f_1}{2}, 0 \quad (2)$$

so that the wave appearing in the output of the frequency conversion circuit is half the frequency

of the wave applied to the input thereof from the base frequency source, or

$$\frac{f_1}{2}$$

as indicated.

In the general case for this type of circuit depending upon the order of modulation used

$$nf_1 \pm mf_2 = f_2 \quad (3)$$

or

$$f_2 = \frac{n}{1 \pm m} f_1 \quad (4)$$

where n and m are integers depending upon the order of modulation. For the case of third order modulation, where a third order instead of a second order modulator is used,

$$n=1, m=2, \text{ or } n=2, m=1 \quad (5)$$

and

$$f_2 = \frac{1}{3} f_1, f_1 \quad (6)$$

In the case where the frequency multiplier 16 of Fig. 1A is used in the regenerative circuit 13, the following equations may be set up:

$$f_2 = nf_1 \pm mf_3 \quad (7)$$

$$f_3 = rf_2 \quad (8)$$

where f_3 is the frequency in the output of the multiplier and r is the factor by which the feedback frequency f_2 is multiplied.

Solving these two equations simultaneously gives

$$f_2 = \frac{n}{1 \pm mr} f_1 \quad (9)$$

$$f_3 = \frac{rn}{1 \pm mr} f_1 \quad (10)$$

If the input wave is represented by the equation

$$e_{f_1} = A \cos \omega t \quad (11)$$

and the frequency component f_2 at the input of the modulator is represented as

$$e_{f_2} = B \cos \left(\frac{\omega t}{2} + \Phi \right) \quad (12)$$

then the two side-band outputs which are obtained are given by

$$e_{S.B.} = KAB \left[\cos \left(\frac{\omega t}{2} - \Phi \right) + \cos \left(\frac{3\omega t}{2} + \Phi \right) \right] \quad (13)$$

In general, the frequency of interest is the frequency

$$\frac{\omega t}{2}$$

the other frequency being eliminated by the filter 12 in the regenerative circuit. Since the input to the modulator from the regenerative circuit is obtained from the side-band output in the case of a self-sustaining wave, then the condition for the phase relation of the regenerative component at the input and output of the modulator is

$$\cos \left(\frac{\omega t}{2} + \Phi \right) = \cos \left(\frac{\omega t}{2} - \Phi + \Theta \right) \quad (14)$$

where Θ is the phase shift which may be introduced by the filter 12 and the amplifier 14. From this is obtained

$$\Phi = \frac{\Theta}{2} \quad (15)$$

and it has been found that the frequency f_2 in the feedback circuit will automatically adjust its phase with respect to f_1 , so that its phase is right to reproduce itself, and its ability to pro-

duce a sustained frequency should be independent of any phase shift in the feedback circuit. This action has been verified experimentally.

An important consideration is the relation of the amplitude of a sub-harmonic component to that of the fundamental. Since the sub-harmonic is produced by a process of modulation its amplitude cannot exceed that of the fundamental. Thus, there can be no runaway condition as in an ordinary oscillation which is limited only by the overload capacity of the oscillator. The amplitude of the sub-harmonic will be such that the modulation loss is equal to the gain μ of the amplifier, less the loss of the filter network. In general, the amplitude of the sub-harmonic will be a function of the fundamental, although it may not be a linear relation.

Figs. 2 and 3 show frequency conversion circuits in accordance with the invention employing third order regenerative modulators instead of a second order modulator as in the circuit of the previous figure.

The circuit of Fig. 2 may be employed for reducing the base frequency f to the sub-multiple frequency

$$\frac{f}{3}$$

The modulator portion of the circuit comprises the two non-linear modulating elements 184 and 185 each comprising a plate of a material of the sort hereinafter described, held between a pair of terminal electrodes, serially connected between an input transformer 186 and an output transformer 187. The primary winding of the input transformer 186 is connected to the source of base frequency f (not shown) to be converted. The control grid-cathode circuit of a three-electrode space discharge amplifying tube 188 is connected across the secondary winding of the transformer 187 and includes in series with that winding the usual grid-biasing arrangement comprising a resistance 189 shunted by a condenser 190. A condenser 191 connected across the secondary winding of transformer 187 forms with the inductance thereof an anti-resonant circuit. The primary winding of a combined output and feedback transformer 192 is connected in the anode-cathode circuit of tube 188 in series with the plate battery 193. The heater type cathode of tube 188 is supplied with heating current from the battery 194 as shown. The usual condenser 195 for by-passing the a-c component of the output current from the plate battery is connected from the lower terminal of the primary winding of transformer 192 to the cathode of the tube 188.

The feedback circuit 196 has its input connected across the terminals of the secondary winding of transformer 192 and its output terminals connected across the mid-point of the secondary winding of the modulator input transformer 186 and the mid-point of the primary winding of the modulator output transformer 187. The terminals of the secondary winding of transformer 192 are also connected to a utilization circuit for the converted sub-multiple frequency

$$\frac{f}{3}$$

The plate of the non-linear modulating elements 184 and 185 in the modulator circuit of Fig. 2 preferably is of a material which comprises a mass of finely divided conductive or semi-conductive crystalline particles held to-

gether in random contact in a binding matrix of insulating substance. One example of a suitable material of this kind is a mixture of silicon carbide and carbon with clay or kaolin as a binder, as disclosed in the U. S. Patent 1,822,742 issued September 8, 1931 to K. B. McEachron.

In the operation of the system of Fig. 2, the base frequency f is impressed on the modulating elements 184 and 185 by the input transformer 186 of this third order modulator, and of the modulation products appearing in the output of the modulating elements the sub-multiple frequency

$$\frac{f}{3}$$

is selected by the anti-resonant circuit comprising the secondary winding of output transformer 187 and the shunt condenser 191, and will be amplified by the amplifying device 188. The amplified sub-multiple

$$\frac{f}{3}$$

appearing in the secondary winding of the transformer 192 will be fed back to the conjugate balanced input of the modulator by the feedback circuit 196 and will combine in the modulator with the base frequency f applied through input transformer 186 to produce, as indicated by Equation 6 above, the combination frequencies

$$\frac{f}{3}, f$$

The frequency f will be eliminated by the resonant circuit comprising the secondary winding of transformer 187 and the shunt condenser 191 and the sustained sub-multiple frequency

$$\frac{f}{3}$$

selected thereby will be amplified by the amplifier 188 and the amplified wave of the frequency

$$\frac{f}{3}$$

impressed by transformer 192 on the utilization circuit as indicated.

As in the other circuit described, the circuit constants of the tuned amplifier 188 should be adjusted to make the gain of the feedback circuit greater than the loss of the modulator and resonant network to give the required stability in operation.

The circuit of Fig. 3 is suitable for reducing a base frequency f to an exact sub-multiple

$$\frac{f}{5}$$

thereof. As shown, the modulator and the succeeding amplifier in the circuit of Fig. 3 are identical with the third order modulator and the amplifier used in the system of Fig. 2, as indicated by the use of the same characters for identifying their circuit elements. However, the transformer 197 connected to the output of the amplifying tube 188, in addition to a primary winding 198 in series in the cathode-anode circuit of the tube 188, and a secondary winding 199 connected to the utilization circuit, has a third winding 200 coupled to the winding 198, which is connected to the input of the double diode-triode tube 201.

The double diode rectifier portion of the tube 201 is utilized as a frequency multiplier, and the

triode portion of the tube 201 as an additional stage of amplification in the feedback circuit 202. The double diode portion of the tube 201 comprises a cathode 203 of the heater type, connected to the mid-point of the winding 200 of transformer 197 through the resonant circuit 204 and the resistance 205 in series, and the two rectifier anodes 206 and 207 respectively connected directly to the terminals of the winding 200.

The amplifier portion of the tube 201 comprises the cathode 203, the control grid 208 and the plate or anode 209. The control grid 208 of tube 201 is connected to the cathode 203 through the resistance 210, and to the mid-point of winding 200 of transformer 197 through the condenser 211 and resistance 205 in series.

The anode-cathode circuit of the amplifier portion of the tube 201 includes in series the primary winding of the feedback transformer 212, the secondary winding of which is connected across the mid-point of the secondary winding of the modulator input transformer 186 and the mid-point of the primary winding of the modulator output transformer 187, as indicated. Space current is supplied from plate battery 213 to the anode of amplifier tube 188 through the primary winding 198 of transformer 197, and to the anode of the amplifier portion of the tube 201 through the primary winding of feedback transformer 212. Heating current is supplied from battery 214 to the heaters for the cathodes of tubes 188 and 201 in series through series resistance 215.

The circuit of Fig. 3 operates as follows: The wave of the base frequency f is impressed upon the modulator circuit by the input transformer 186 and a desired sub-multiple frequency in the modulator output is selected by the anti-resonant circuit comprising the secondary winding of transformer 187 and shunt condenser 191. This sub-multiple frequency is amplified by the tube 188 and the amplified sub-multiple frequency appearing in the winding 198 of transformer 197 is induced in the winding 200 coupled thereto, forming the input coil for the double diode rectifier portion of the tube 201, acting as a frequency multiplier. The desired frequency multiple which is determined by the tuning of the resonant circuit 204 is impressed through condenser 211 upon the grid circuit of the amplifier portion of the tube 201 and is amplified thereby. The amplified multiple frequency is impressed by feedback transformer 212 on the conjugate balanced input of the modulator and modulates therein with the wave of base frequency f impressed on the input of the modulator through input transformer 186. The desired combination frequency in the output of the modulator is selected by the anti-resonant circuit comprising the secondary winding of transformer 187 and the shunt condenser 191. The selected component is amplified by the amplifier 188 and impressed through the coils 198 and 199 of transformer 197 on the utilization circuit.

The sub-multiple at which the frequency conversion circuit of Fig. 3 operates depends upon the tuning of the two amplifiers therein, that is, the amplifier 188 and the amplifier portion of the double diode-triode tube 201. The tuning of the first amplifier is determined by the resonant frequency of the anti-resonant circuit in the input thereof comprising secondary winding of transformer 187 and the shunt condenser 191, and the tuning of the second amplifier is determined by the resonant frequency of the resonant circuit

204. For the case in which it is desired to obtain the sub-multiple frequency

$$\frac{f}{5}$$

the first resonant circuit would be tuned to the frequency

$$\frac{f}{5}$$

and the resonant circuit 204 would be tuned to

$$\frac{2f}{5}$$

so that the harmonic

$$\frac{2f}{5}$$

will be fed back into the conjugate input of the modulator by feedback transformer 212. The frequency

$$\frac{2f}{5}$$

will combine in the modulator with the input frequency f to produce the combination frequencies

$$f \pm \frac{4f}{5} = \frac{9f}{5}, \frac{f}{5}$$

The former frequency will be eliminated in the tuned input of amplifier 188 and the latter frequency,

$$\frac{f}{5}$$

will be selected thereby, amplified by the amplifier 188 and impressed by transformer 197 on the utilization circuit connected to the winding 199 thereof.

Other types of non-linear elements which will provide third order modulation may be substituted for the particular modulating elements 184 and 185 described for the modulators in the systems of Figs. 2 and 3, for example, magnetic devices, such as saturable core coils or transformers well known in the art.

Other modifications of the circuits illustrated and described above within the spirit and scope of the invention will occur to persons skilled in the art.

What is claimed is:

1. A frequency converter comprising a balanced third order modulator having two conjugately connected inputs, means for impressing on one of said inputs a wave of a given frequency to be converted to a wave of another frequency which is a desired fraction of said given frequency, a circuit including a tuned amplifier coupling the output of said modulator to the other input thereof, designed to selectively feed back to said other input waves derived from the output of said modulator of such frequency and amplitude that when combined with waves of said given frequency in said modulator, a sustained component of said other frequency will appear in the output of said modulator, and means to select a wave of said other frequency from the output of said modulator.

2. A circuit for deriving from a wave of a base frequency f a wave of the sub-multiple frequency

$$\frac{f}{3}$$

comprising a balanced third order modulator having two conjugately connected inputs, means for impressing on one input of said modulator a

wave of the frequency f , a circuit including a tuned amplifier coupling the output of said modulator to the other input thereof, the tuning and gain of said amplifier being made such that the coupling circuit selectively feeds back to said other input a wave of the sub-multiple frequency

$$\frac{f}{3}$$

in sufficient amount so that the combination products in the output of said modulator include a sustained component of the frequency

$$\frac{f}{3}$$

and means to select from the output of said amplifier a wave of the frequency

$$\frac{f}{3}$$

3. A circuit for deriving from a wave of a base frequency f a wave of the sub-multiple frequency

$$\frac{f}{5}$$

comprising a balanced third order modulator having two conjugately connected inputs, means for impressing on one input of said modulator a wave of the base frequency f , a circuit connecting the output of said modulator to the other input thereof to feed back waves derived from said output, the feedback circuit comprising in order an amplifier connected to the output of said modulator tuned to selectively amplify the frequency

$$\frac{f}{5}$$

a frequency doubler for transforming the frequency

$$\frac{f}{5}$$

to the frequency

$$\frac{2f}{5}$$

and a second amplifier for selectively amplifying and impressing on said other input of the modulator the wave of the frequency

$$\frac{2f}{5}$$

to modulate therein with the impressed base frequency f , and means for picking off from the output of the first amplifier a sustained wave of the frequency

$$\frac{f}{5}$$

4. A circuit for producing accurate odd sub-multiples of a given frequency, comprising a balanced third order modulator having two conjugately connected input circuits and an output circuit, means to impress a wave of said given frequency on one of said input circuits, a regenerative circuit coupling said output circuit to the other input circuit, tuned to selectively feed back to said other input circuit waves of the desired odd sub-multiple frequency to combine with the waves of given frequency in said modulator, and means to pick off from said regenerative circuit sustained waves of said desired odd sub-multiple frequency.

5. A circuit for producing waves which are accurate odd sub-multiple ratios of a given frequency, comprising a balanced third order modulator having two conjugately connected input

circuits and an output circuit, means to impress a wave of said given frequency on one of said input circuits, a regenerative circuit coupling said output circuit to the other of said input circuits, means in said regenerative circuit for deriving from the waves impressed thereon from the output of said modulator, and transmitting to said other input circuit to modulate with the impressed wave of given frequency in said modulator, an amplified wave of double the frequency of the desired sub-multiple frequency, and means for picking off from said regenerative circuit a sustained wave of the desired odd sub-multiple frequency.

6. A circuit for producing accurate odd fractional sub-multiples of a given frequency comprising a balanced third order modulator having two conjugately connected input circuits and an output circuit, means for impressing a wave of said given frequency on one of said input cir-

cuits, a regenerative circuit coupling said output circuit with the other of said input circuits, said regenerative circuit comprising in order an amplifier connected to the output of said modulator tuned to selectively amplify waves of the desired sub-multiple frequency, a frequency multiplier for producing a multiple of the selected frequency and means for amplifying and impressing the multiplied frequency on said other input circuit of said modulator to modulate therein with the impressed wave of said given frequency, said multiple frequency produced by said multiplier and its amplification being selected to produce as one of the products of modulation a sustained component of the desired sub-multiple frequency, and means for picking off from the output of said tuned amplifier a sustained wave of said desired sub-multiple frequency.

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