May 23, 1939. R. L. MILLER 2,159,596

FREQUENCY CONVERSION CIRCUITS

Original Filed July 31, 1937

FIG. 1

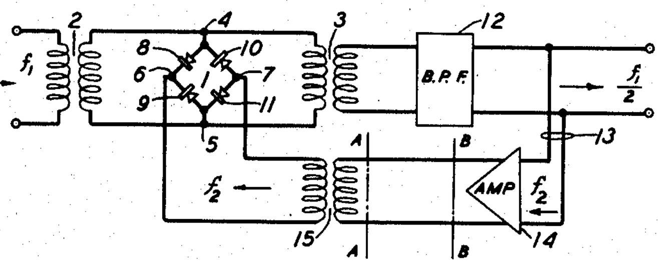


FIG. 1A

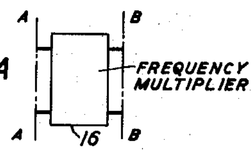


FIG. 2

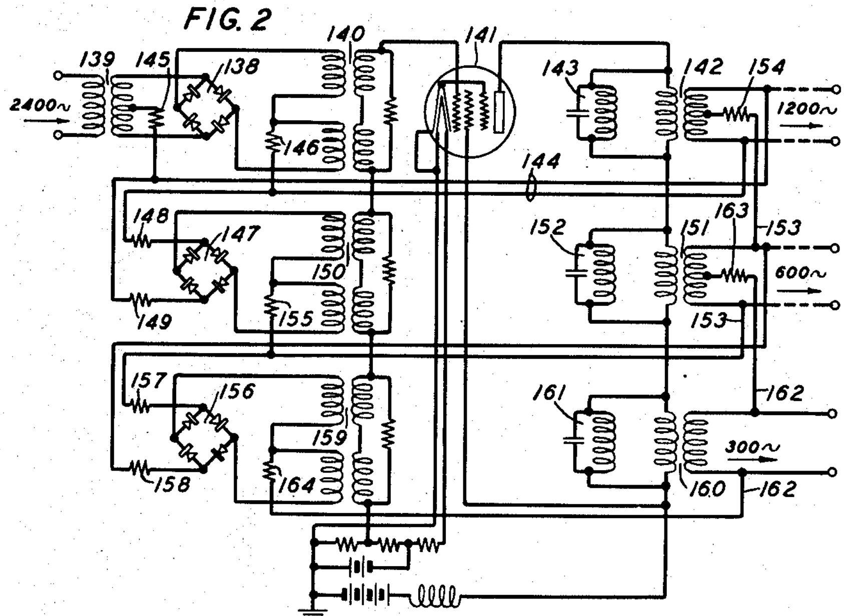
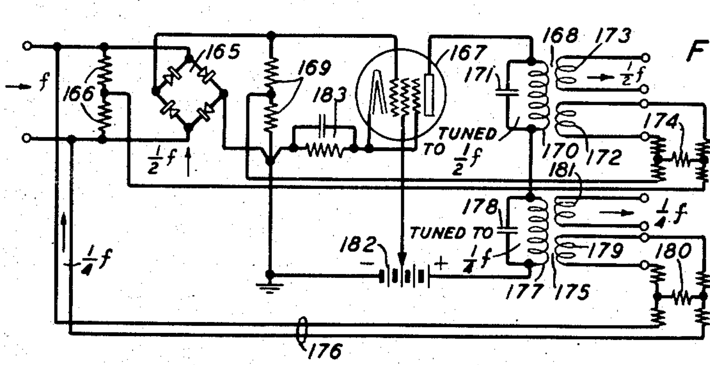


FIG. 3



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FREQUENCY CONVERSION CIRCUITS

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4 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 mu. 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 mu 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 mu 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 mu 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 mu 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

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

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

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

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 produce 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 mu 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.

In frequency conversion circuits employing regenerative modulation, the amplifier merely acts as a means of supplying the necessary gain in the feedback circuit and does not become overloaded unless an extremely large input is applied to the regenerative modulator. Because of this fact, it follows that if several regenerative modulator circuits are to be used at different frequency ranges, it should be possible to utilize the same amplifier for each of the circuits, using selective networks or other means to separate the frequencies on the inputs and outputs.

A special application of this principle is in the case where several regenerative modulators are to be used in cascade. In the case of the use of second order regenerative modulators, each stage will reduce the frequency applied thereto by a factor of two. By proper choice of the selective networks, the same amplifier may be used for several stages. Fig. 2 shows the circuit diagram of such an arrangement which was designed to convert a 2400 cycle frequency into 300 cycles and the intermediate frequencies 1200 and 600 cycles, which arrangement employs three stages of regenerative modulation and the same amplifier for each stage.

Referring to Fig. 2, it will be seen that the regenerative modulators in the three stages are of the double balanced type, such as is disclosed in Cowan Patent No. 2,025,158, each employing a copper-oxide rectifier bridge with all the copper-oxide rectifier elements poled in the same direction, and an input and an output transformer connected respectively across the two diagonals of the bridge. The first stage of the circuit comprises a modulator including the copper-oxide rectifier bridge 138, the input transformer 139 having its primary winding connected to the source of alternating current waves of the frequency (2400 cycles) to be converted and its secondary winding connected across one diagonal of the bridge, and the output transformer 140 having its primary winding connected across the other diagonal of the bridge 138, a single pentode amplifying vacuum tube 141 including in its control grid-cathode circuit the secondary winding of transformer 140, the combined output, feedback and interstage transformer 142 having its primary winding connected in the anode-cathode circuit of amplifier tube 141, the anti-resonant circuit 143 in shunt with that winding, and a feedback circuit 144 connecting the secondary winding of the transformer 142 across the mid-point of the secondary winding of the modulator input transformer 139 and the mid-point of the primary winding of the modulator output transformer 140, through the series resistances 145 and 146, as indicated.

The second stage of the circuit of Fig. 2 comprises a modulator including the copper-oxide rectifier bridge 147, similar to the bridge 138, the transformer 142 having its secondary winding connected across one diagonal of the bridge 147 through the circuit 144 and the series resistances 148 and 149 and the modulator output transformer 150 having its primary winding connected across the other diagonal of bridge 147, the amplifying vacuum tube 141 including in its control grid-cathode circuit the secondary winding of transformer 150 in series with the secondary winding of the transformer 140, the combined output, interstage and feedback transformer 151 having its primary winding connected in the anode-cathode circuit of the amplifier tube 141 in series with the primary winding of transformer 142, the anti-resonant circuit 152 shunting that winding and the feedback circuit 153 connecting the secondary winding of transformer 151 across the mid-point of the secondary winding of transformer 142 and the mid-point of the primary winding of transformer 150 through the series resistances 154 and 155.

The third stage of the frequency conversion circuit of Fig. 2 comprises the modulator including the copper-oxide rectifier bridge 156, similar to the bridges 138 and 147, the transformer 151 having its secondary winding connected across one diagonal of bridge 156, through the series resistances 157 and 158, the transformer 159 having its primary winding connected across the other diagonal of the bridge 156, the amplifying vacuum tube 141 including in its control grid-cathode circuit the secondary winding of transformer 159 in series with the secondary windings of transformers 150 and 140, the combined output and feedback transformer 160 having its primary winding connected in the anode-cathode circuit of amplifier tube 141 in series with the primary windings of the transformers 151 and 142, the anti-resonant circuit 161 shunting that winding, and the feedback circuit 162 connecting the secondary winding of transformer 160 across the mid-point of the secondary winding of transformer 151 and the midpoint of the primary winding of transformer 159, through the series resistances 163 and 164.

The anti-resonant circuits 143, 152 and 161 are respectively tuned to the successively lower sub-multiple frequencies to be fed back to the conjugate terminals of the modulator in each stage through the feedback circuits 144, 153 and 162, respectively, to reduce the input frequency applied to the primary winding of the modulator input transformer in the succeeding stages by a factor of two in each case.

In the case illustrated, where the wave applied to the input of the frequency conversion circuit has a frequency of 2400 cycles, the anti-resonant circuit 143 will be tuned to select the frequency 1200 cycles from the waves in the output of amplifier 141, and this frequency will be fed back to the conjugate terminals of the modulator in the first stage through transformer 142 and circuit 144, and will be applied also through resistances 148, 149 to the input of the modulator in the next stage.

The anti-resonant circuit 152 is tuned to select the frequency 600 cycles from the combination waves in the output of amplifier 141, which frequency will be fed back to the conjugate input of the modulator in the second stage through transformer 151 and circuit 153 and will be applied also through resistances 157 and 158 applied to the input of the modulator in the third stage.

The resonant circuit 161 in the third stage is tuned to select the frequency 300 cycles which frequency will be fed back through transformer 160 and circuit 162 to the conjugate input of the modulator in the third stage. The amplifier tube 141 will operate in each of the three stages to amplify first the applied frequencies and then the combination frequencies produced by the modulator by regeneration in each stage.

Outgoing circuits are connected to the secondary winding of transformers 142, 151 and 160 for respectively taking off the sub-multiple frequencies produced in these windings for each stage of sub-multiplication, 1200 cycles, 600 cycles and 300 cycles, as indicated.

In the circuit of Fig. 2 the balance of the modulator unit alone is utilized to prevent oscillation, whereas in each of the succeeding stages the balance of the modulator unit plus the loss of the resonant circuit in the output of the amplifier in each regenerative path is depended on to prevent oscillations in these paths. The tendency to oscillate increases as the number of stages increases. A lesser degree of balance will be required if a resonant circuit or filter tuned to the same frequency as the resonant circuit in the output of the amplifier in each stage is included in the input circuit of the amplifier for each stage. If filters in the input circuits of the amplifier are employed, the only limit to the number of stages which can be used depends on the load carrying capacity of the amplifier and its ability to furnish the proper gain for each frequency.

In Fig. 3 is shown a frequency conversion circuit employing a single amplifier for a plurality of stages of regenerative modulation as in the system of Fig. 2, and the same modulator for the several stages and other simplifications which will be pointed out below.

The first regenerative stage in the conversion circuit of Fig. 3 comprising a modulator of the double-balanced type similar to those used in the system of Fig. 2, comprising the copper-oxide rectifier bridge 165 having one diagonal connected across the source of alternating current of the base frequency f to be converted (not shown) through the potentiometer 166, a regenerative circuit comprising the single amplifying pentode vacuum tube 167 and the combination tuned feedback and output transformer 168. The control grid-cathode circuit of the amplifier 167 is connected across the output diagonal of the modulator bridge 165 through the potentiometer 169. The anode-cathode circuit of the amplifying tube 167 includes the primary winding 170 of transformer 168, this winding being shunted by the tuning condenser 171. A secondary (feedback) winding 172 of transformer 168 connects the output of the regenerative circuit across the mid-points of the potentiometers 166 and 169 connected respectively across the input and output diagonals of rectifier bridge 165, in conjugate relation to the incoming circuit and the input of amplifier 167 in the input of the regenerative circuit. The transformer 168 has a third (output) winding 173 for taking off the converted frequency in the output of the first regenerative modulator stage. A resistance pad 174 is inserted in the regenerative circuit between the feedback winding 172 of transformer 168 and the conjugate terminals of the modulator bridge 165, to adjust the loss in the feedback circuit to a suitable value.

The second stage of the conversion circuit of Fig. 3 comprising the same modulator rectifier bridge 165 and associated potentiometers 166, 169, and the same amplifier 167 as used in the first stage, but a separate combined interstage, output and feedback transformer 175 and a separate feedback circuit 176.

The primary winding 177 of transformer 175, shunted by a tuning condenser 178, is connected in the anode-cathode circuit of the amplifying vacuum tube 167 in series with the primary winding 170 of the first stage transformer 168, shunted by condenser 171. The feedback circuit 176 of the second stage has its input connected to a second (feedback) winding 179 of transformer 175 and its output connected across the base frequency supply circuit in front of potentiometer 166. The circuit 176 includes a resistance pad 180, similar to the pad 174 in the first stage regenerative circuit, for providing a desired amount of loss in the feedback circuit 176. A third (output) winding 181 in transformer 175 is provided for taking off the converted frequency from the second stage.

Plate current is supplied to the plate of the amplifying tube 167 from battery 182 through winding 177 and 170 of transformer 175 and 168, in series, a positive bias potential for the screen grid of tube 167 is also obtained from plate battery 182, and a suitable negative bias on the control grid of tube 167 is obtained by the usual parallel resistance-condenser biasing combination 183 in the control grid-cathode circuit of tube 167 through the potentiometer 169. Heating current for the cathode of tube 167 may be supplied from any suitable source, not shown.

The anti-resonant circuit comprising winding 170 and parallel condenser 171 in the output of tube 167 is tuned to the sub-multiple frequency

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

and the anti-resonant circuit comprising winding 177 and parallel condenser 178 is tuned to the sub-multiple frequency

$$\frac{f}{4}$$

In a manner similar to that described in the circuit of Fig. 2, the first stage of regenerative modulation comprising modulator 165, amplifier 167 and the regenerative circuit will operate to produce a sustained wave of the frequency

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

which will be applied to the second stage of regenerative modulation comprising the same modulator 165, the same amplifier 167, and the regenerative circuit 176 to produce a sustained wave of the frequency

$$\frac{f}{4}$$

which will be induced in the output winding 181 of transformer 175 connected to the load circuit, and a sustained wave of the sub-multiple frequency

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

will be induced in the other load circuit connected to the winding 173 of transformer 168.

The pad 174 in the feedback circuit of the first regenerative modulator stage will be selected to provide the proper loss to make the operation of the first stage stable, and the pad 180 is likewise adjusted to make the second regenerative modulator stage stable.

If a larger amount of power in the produced waves of sub-multiple frequencies is required in the circuit of Figs. 2 and 3, two amplifying vacuum tubes may be used therein in place of the single tube illustrated, for example, in the circuit of Fig. 2, the first two stages might be arranged to make use of one of these amplifying vacuum tubes and the last stage of the other vacuum tube. Although only three stages of submultiplication have been illustrated in Fig. 2, and two in Fig. 3, it is apparent that a greater number of stages connected in similar manner may be employed where it is desired to produce a greater step-down in frequency. The circuits of Figs. 2 and 3 as illustrated and described employ regenerative modulators of a simple second order type, but it is apparent that the same principles hold if other types of regenerative modulators are used.

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 conversion circuit comprising a plurality of stages of regenerative modulation each consisting of a balanced modulator having two inputs conjugately connected, and a regenerative circuit including an amplifier for feeding back to one of the conjugate inputs of said modulator a wave derived from the output thereof to modulate in the modulator with waves supplied to the other input thereof, the same amplifier being employed in all of said stages, means for impressing a wave of a given frequency on the other input of the modulator in the first stage, a plurality of selective networks in series in the output of said amplifier each tuned to a different frequency bearing a definite relation to said given frequency, the regenerative circuit in each stage including a different one of said networks, the other input of the modulator in each stage after the first being taken from the selective network in the preceding stage, and a utilization circuit for picking off a converted frequency, connected to the output of one or more stages.

2. A frequency conversion circuit comprising a plurality of stages of regenerative modulation each consisting of a balanced modulator having two conjugately connected inputs, and a feedback circuit including an amplifier, connecting the output of the modulator with one input thereof, the same amplifier being employed in the feedback circuit of all the stages, means for impressing a wave of a given base frequency on the other input of the modulator in the first stage, a plurality of selective networks connected in the output of the amplifier each tuned to select a different frequency which is a desired fraction of said given frequency, a different one of said networks being included in the feedback circuit of each stage, the input to the modulator in each stage after the first being taken off from the selective network in the preceding stage, and a utilization circuit coupled to the selective network in one of the stages for taking off a sustained wave of the selected frequency.

3. A frequency conversion circuit comprising a plurality of stages of regenerative modulation each consisting of a balanced modulator having

two conjugately connected inputs, and a circuit including an amplifier for feeding back to one of the conjugate inputs of the modulator a wave derived from the output thereof, the same modulator and the same amplifier being employed in all the stages, means for impressing a wave of a given frequency on the other input of the modulator in the first stage, and a plurality of selective networks in series in the output of said amplifier, each tuned to a different frequency bearing a definite relation to said given frequency, the feedback circuit in each stage including a different one of said networks, the input of the modulator for each stage of regeneration after the first being taken from the selective network in the preceding stage, and a utilization circuit for picking off a converted frequency from the selective network in at least one of said stages.

4. The frequency conversion circuit of claim 3, in which said balanced modulator comprises a plurality of non-linear modulating elements connected in a balanced bridge circuit, and two resistances respectively connected across the two diagonals of said bridge circuit, said wave of given frequency being impressed on one diagonal of said bridge circuit across one of said resistances, the other diagonal of said bridge circuit being connected to the input of said amplifier across the other resistance, the output of the feedback circuit in successive stages being connected across the mid-points of the two resistances and across said one resistance, respectively.

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