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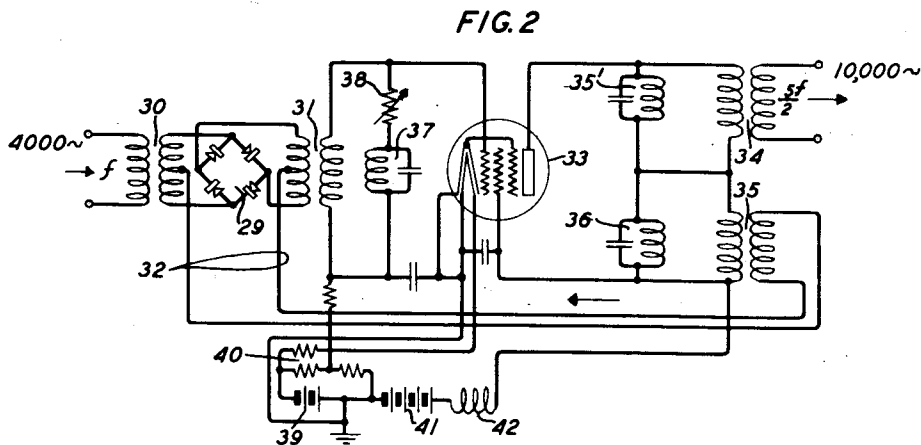
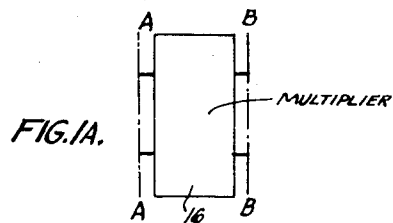
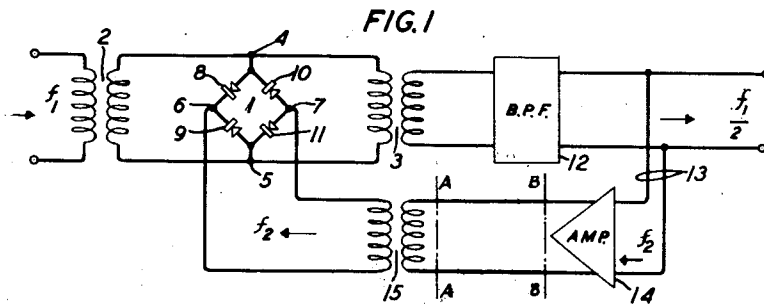
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2,159,595

FREQUENCY CONVERSION CIRCUITS

Filed July 31, 1937

4 Sheets-Sheet 1



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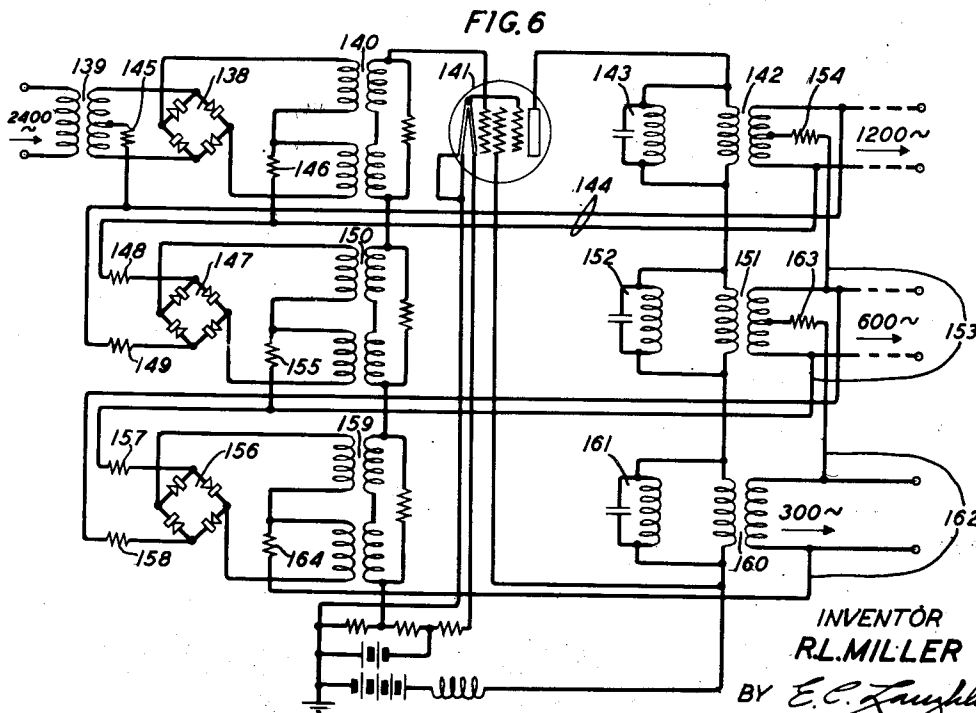
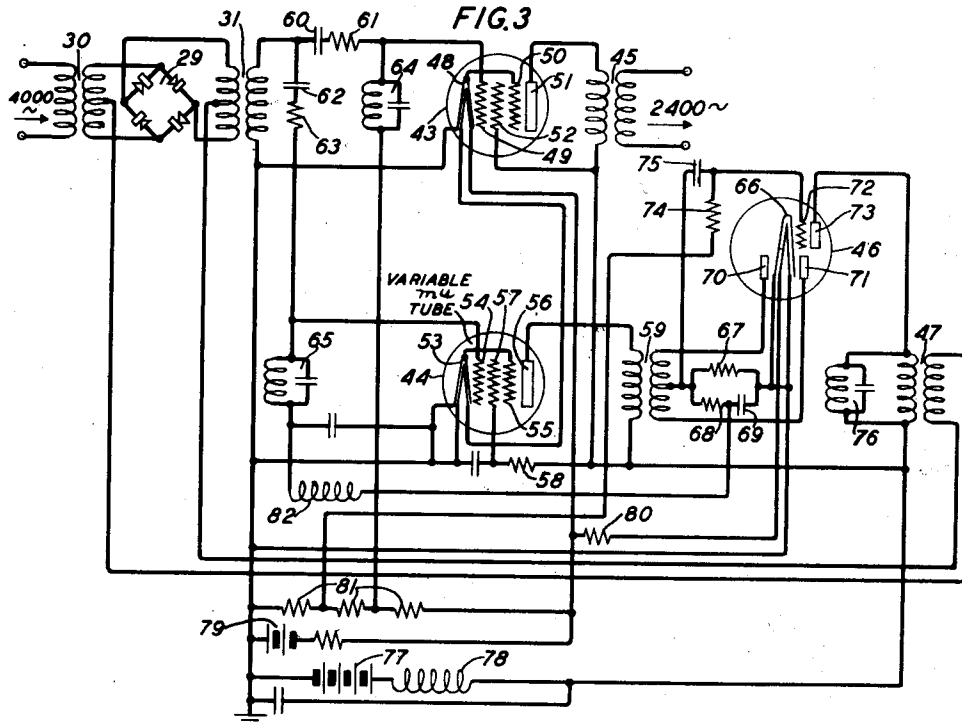
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FREQUENCY CONVERSION CIRCUITS

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4 Sheets-Sheet 2



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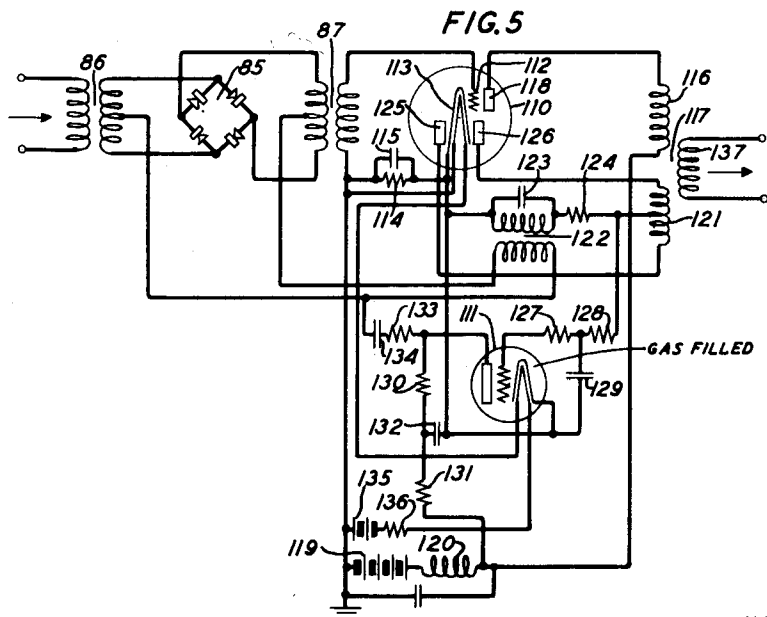
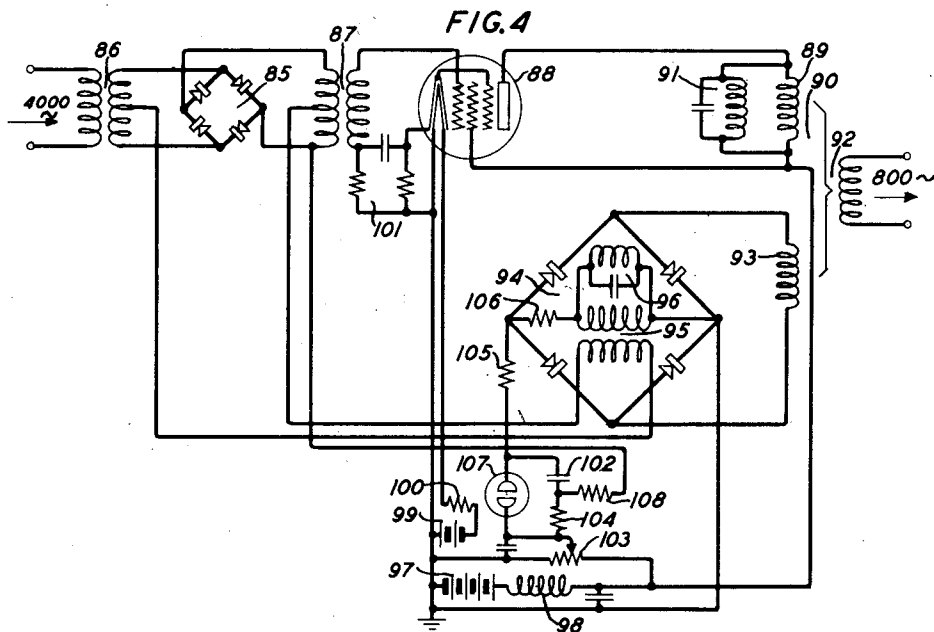
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FREQUENCY CONVERSION CIRCUITS

Filed July 31, 1937

4 Sheets-Sheet 3



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2,159,595

FREQUENCY CONVERSION CIRCUITS

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Application July 31, 1937, Serial No. 156,698

11 Claims. (Cl. 250—36)

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 drawings 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 to 9 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 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

$$nf_1 \pm mf_2 = f_3 \quad (3)$$

or

$$f_3 = \frac{n}{1 \pm m} f_1 \quad (4)$$

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

$$f_3 = \frac{1}{3} f_1, f_1 \quad (6)$$

15

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;

$$f_3 = nf_1 \pm mf_2 \quad (7)$$

20

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

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

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

30

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

If the input wave is represented by the equation

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

35

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

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

40

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

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

45

In general, the frequency of interest is the frequency

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

50

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

60

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

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

65

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

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 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.

In Fig. 2 is shown a frequency converter circuit in accordance with the invention which may be used to produce accurate fractions, both proper and improper of a given fundamental frequency f , for example, for transforming a 4000-cycle frequency wave to a 10,000-cycle frequency wave, but may be used for obtaining other fractional ratios, for example,

$$\frac{3f}{2}, \frac{5f}{2}, \frac{7f}{2},$$

20

etc.

In the circuit of Fig. 2, the modulator is of the double balanced type disclosed in Cowan Patent No. 2,025,158, comprising a four-element copper-oxide rectifier bridge 29 with the individual elements poled in the same direction, an input transformer 30 and an output transformer 31. The secondary winding of the input transformer 30 and the primary winding of the output transformer 31 are connected respectively across the two diagonals of the bridge; and the output of the regenerative circuit 32 is connected across the mid-points of these two windings, so as to be connected to the modulator 29 in conjugate relationship with the incoming circuit through transformer 30 and the input of the amplifier connected to the output of the modulator.

The amplifier portion of the regenerative circuit 32 comprises a single amplifying vacuum tube 33 of the pentode type, having its control grid-cathode circuit connected across the secondary winding of the modulator output transformer 31.

The anode-cathode circuit of tube 33 includes in series the primary winding of an output transformer 34 and the primary winding of the feedback transformer 35, the former primary winding being shunted by an anti-resonant circuit 35' and the latter primary winding being shunted by an anti-resonant circuit 36.

The secondary winding of the feedback transformer 35 in the regenerative circuit 32 is connected across the mid-points of the secondary winding of the modulator input transformer 30 and of the primary winding of the modulator output transformer 31. An output circuit for taking off the converted frequency

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

60

(10,000 cycles) is connected to the secondary winding of output transformer 34.

Suitable heating current is supplied to the heater type cathode of the amplifying tube 33 and suitable biasing current is supplied to the control grid thereof from battery 39 through resistances of the resistance network 40 in well-known manner. Plate current is supplied to the anode of tube 33 from plate battery 41 through the retard coil 42 and the primary windings in series of the feedback transformer 35 and output transformer 34, as indicated.

In the usual regenerative modulator of the

75

type illustrated in Fig. 2, the sub-multiple frequency

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

(where f is the input frequency) is filtered out in the amplifier and fed back to the conjugate input of the modulator. Under these circumstances there will be produced in the output of the modulator the combination frequencies

$$f + \frac{f}{2} = \frac{3f}{2} \quad (16)$$

$$f - \frac{f}{2} = \frac{f}{2} \quad (17)$$

Usually

$$\frac{3f}{2}$$

is eliminated by selective circuits; however, in the present circuit, it is desired that a certain amount of

$$\frac{3f}{2}$$

be applied to the modulator to combine with f to produce

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

The products given by this secondary process are

$$f + \frac{3f}{2} = \frac{5f}{2} \quad (18)$$

$$f - \frac{3f}{2} = -\frac{f}{2} \quad (19)$$

The negative sign which appears in Equation (19) indicates that if the two frequencies,

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

and

$$\frac{3f}{2}$$

are modulated against f with the same phase angles, two

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

components will be produced which are 180 degrees out of phase with each other. As long as the component indicated by Equation (19) is small compared to that of Equation (17), no appreciable interaction will be obtained. However, it is desirable to make the product which appears in Equation (19) as large as possible since the desired product

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

is obtained as the other side-band.

In the circuit of Fig. 2, where it is desired to convert a frequency f of 4,000 cycles to 10,000 cycles

$$\left(\frac{5f}{2}\right)$$

the anti-resonant circuit 35' shunting the primary winding of output transformer 34 is tuned to 10,000 cycles

$$\left(\frac{5f}{2}\right)$$

and the anti-resonant circuit 36 shunting the regenerative or feedback circuit 32 will be tuned

to approximately 2,600 cycles so that the two frequencies to be fed back, 2,000 cycles

$$\left(\frac{f}{2}\right)$$

and 6,000 cycles

$$\left(\frac{3f}{2}\right)$$

will appear on opposite sides of the resonant curve, which will give a phase displacement approaching 180 degrees.

The anti-resonant circuit 37 in series with the resistance 38 across the control grid-cathode circuit of the amplifier tube 33, is provided to prevent the amplifier from being over-loaded by the 2,000 cycle and 6,000 cycle waves. To accomplish this, the anti-resonant circuit 37 is preferably tuned to 10,000 cycles. The discrimination of the grid circuit against 2,000 cycles and 6,000 cycles may be varied by changing the value of the resistance 38. This resistance is also convenient for adjusting the gain of the regenerative section of the amplifier at 2,000 cycles.

Some of the advantages which have been obtained with an experimental circuit substantially as shown in Fig. 2 over other known types of frequency converters are as follows: the circuit employing a single vacuum tube gave a conversion gain of approximately 20 decibels; practically the full output power of the vacuum tube is available at 10,000 cycles; the converter will not give other than the correct frequency ratio; it will remain inactive when the input is removed; and by proper design, the output may be made to vary linearly with input over a considerable range.

The circuit shown in Fig. 2 may be simplified by using a single tuned transformer to take the place of each transformer and anti-resonant circuit shown, and by using a vacuum tube of greater power capacity greater output powers may be obtained.

Fig. 3 shows a frequency converter circuit in accordance with the invention which may be used for producing accurate fractional ratios of a given frequency, for example, a

$$\frac{3}{5}$$

ratio (such as 4,000 to 2,400 cycles) or a

$$\frac{1}{5}$$

ratio (such as 300 cycles to 60 cycles).

The circuit of Fig. 3 comprises a double balanced type of copper-oxide modulator 29, 30, 31, identical with that in the system of Fig. 2 as indicated by the use of the same identifying characters, an amplifier comprising the two amplifying vacuum tubes 43, 44, of the pentode type, an output transformer 45 for the tube 43, and a regenerative circuit comprising the duplex diode-triode unit 46 and the tuned feedback transformer 47 for feeding back the output of the amplifying tube 44 to the conjugate balanced input of the modulator.

The amplifying vacuum tube 43 comprises the heater type cathode or filament 48, the control grid 49, the suppressor grid 51 connected directly to the cathode 48, the anode or plate 50 and the screen grid 52 connected to the anode 51 through the primary winding of output transformer 45. The amplifying vacuum tube 44, which is of the variable mu type, comprises the heater type cathode 53, the control grid 54, the suppressor grid 55 connected directly to the cathode 53, the plate or anode 56 and the screen

grid 57 connected to the anode 56 through the resistance 58 and the primary winding of the transformer 59.

The control grid-cathode circuits of the amplifying vacuum tubes 43 and 44 are connected in parallel across the secondary winding of the modulator output transformer 31, the former circuit including in series the condenser 60 and resistance 61 and the latter circuit including in series the condenser 62 and the resistance 63. An anti-resonant circuit 64 is connected across the control grid-cathode circuit of an amplifying vacuum tube 43 and an anti-resonant circuit 65 is connected across the control grid-cathode circuit of tube 44.

The double diode or full-wave rectifier portion of the unit 46 is used to obtain a frequency multiplier whose output is nearly linear with input, and the triode part is used as an amplifier at the desired harmonic frequency to be fed back to the conjugate input of the modulator 29, 30, 31.

The full-wave rectifier portion of the tube 46 comprises the cathode 66 of the heater type connected to the mid-point of the secondary winding of transformer 59 through a resistance 67 shunted by a resistance 68 in series with a condenser 69, and two rectifier anodes 70, 71 connected respectively to the two terminals of the secondary winding of transformer 59. The amplifier portion of the tube 32 comprises the cathode 66, the control grid 72 and the anode 73. The control grid 72 is connected to the mid-point of the secondary winding of transformer 59 through the condenser 75. The cathode-anode circuit of the amplifier portion of tube 46 includes the primary winding of the feedback transformer 47, which winding is shunted by the anti-resonant circuit 76.

Space current is supplied from plate battery 77 through choke coil 78 to the plates of the amplifier tubes 43 and 44 through the primary windings of transformers 45 and 59, respectively, and to the plate of the amplifier portion of tube 46 through the primary winding of the feedback transformer 47. Appropriate heater potentials are applied from the battery 79 to the cathode heaters of tubes 43, 44 and to the cathode heater of tube 46 through the resistance 80, and suitable fixed biasing potentials are applied to the grids of these tubes from that battery through the resistance network 81, and the resistance 74, as indicated.

The secondary winding of the feedback transformer 47 is connected across the mid-point of the secondary winding of the modulator input transformer 30 and the mid-point of the primary winding of the modulator output transformer 31 so that the feedback circuit is in conjugate relation with the incoming circuit through the input transformer 30 and with the inputs of amplifiers 43 and 44.

The cathode-control grid circuit of the variable mu amplifier tube 44 is connected to a point between the resistance 68 and condenser 69 in the common branch of the full-wave rectifier portion of tube 46, through the retard coil 82 so that the D. C. component of the rectifier provides a variable grid bias to automatically control the gain of the variable mu tube. When an input to the variable mu tube 44 is first applied through the modulator output transformer 31, this tube has very small control grid bias and thus a high gain for starting the regenerative action; as the regenerative component builds up to the steady state condition, the voltage drop produced by the

D. C. component in the resistances 67 and 68 of the common branch of the full-wave rectifier portion of tube 46 coupled to the output circuit of the amplifier tube 44 by transformer 59 will increase the bias applied to the control grid circuit of the latter tube causing its gain to be automatically decreased.

In the circuit of Fig. 3, if the output frequency of the modulator is represented as f_1 , then the frequency out of the multiplier (output of tube 46) is $r \times f_1$ where r is the harmonic used. Denoting f as the input frequency to the modulator, the relation between the two frequencies is:

$$f \pm r f_1 = f_1 \quad (20)$$

$$f_1 = f \left(\frac{1}{1 \pm r} \right) \quad (21)$$

In the operation of the circuit of Fig. 3, the numerator of the fractional frequency obtained in the output transformer 45 will depend upon the tuning of the resonant circuit 64 in the input of amplifier 43, the denominator being determined by the submultiple frequency f_1 which is present in the regenerative circuit. If a fractional ratio of

$$\frac{3}{5}$$

for example, a conversion of 4,000 cycles to 2,400 cycles, is desired, the amplifier 43 will be tuned by resonant circuit 64 to

$$\frac{3f}{5}$$

(2400 cycles), the first stage of amplification in the regenerative circuit (amplifier 44) would be operated at

$$\frac{1}{5}$$

of the input frequency (800 cycles) by tuning the resonant circuit 65 in the control grid circuit of that amplifier to that frequency, and by operating the second amplifier stage in the regenerative circuit (amplifier of tube 46) at

$$\frac{4}{5}$$

of the input frequency (3200 cycles) by tuning the resonant circuit 76 in shunt with the feedback transformer 47 to that frequency.

There will be a considerable amount of

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

(1600 cycles) present in the output of the duplex diode unit 32, as well as

$$\frac{4f}{5}$$

(3200 cycles) which is necessary for regeneration, and the former will modulate against f (4000 cycles) in the modulator 29, 30, 31 to produce

$$\frac{3f}{5}$$

(2400 cycles) at the output of the modulator. This will be filtered out by means of the highly selective resonant circuit 64 tuned to

$$\frac{3f}{5}$$

(2400 cycles), and will be amplified by amplifier 43 and impressed in amplified form on the output circuit through output transformer 45.

Other fractional ratios, for example,

$$\frac{1}{5}, \frac{3}{5}, \frac{7}{5}, \dots$$

may be obtained by a suitable tuning of the resonant circuit 84.

If the condenser 80 is connected to the mid-point of transformer 59, instead of to transformer 31, fractional ratios of

$$\frac{2}{5}, \frac{4}{5}, \frac{6}{5}, \dots$$

can be obtained.

Other sub-multiple ratios may be obtained by suitable tuning of the two amplifiers in the regenerative circuit. That is, if a sub-multiple ratio

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

is desired, the first amplifier in the regenerative circuit will be tuned to

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

and the second amplifier therein to

$$\frac{2f}{3}$$

and the amplifier associated with the output circuit to

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

In similar manner fractions of

$$\frac{1}{3}, \frac{2}{3}, \frac{4}{3}, \frac{5}{3}, \dots$$

can be obtained. By removing the connection to either of the diode plates 70 or 71, odd harmonics can be obtained in the multiplier circuit thus making it possible to secure sub-multiple ratios of

$$\frac{1}{4}, \frac{1}{6}, \dots$$

If the duplex diode triode unit 46 is omitted, the circuit will give

$$\frac{1}{2}$$

the input frequency, provided the amplifier in the feedback circuit is tuned approximately to

$$\frac{1}{2}$$

of the input frequency.

Any other type of rectifier which is nearly linear over a considerable range may be used in place of the duplex diode triode.

The general conditions for stable operation of the type of circuit shown in Fig. 3 can be stated as follows:

(1) The total gain in the feedback circuit must be less than unity or of a non-oscillatory nature when considered as on a single frequency basis; and (2) the gain of the feedback circuit when considered on a basis of the magnitude of f_1 at the output of the modulator to that of rf_1 into the modulator, should be greater than the loss of the modulator.

There are numerous advantages of the type of sub-multiple generator shown in Fig. 3 over sub-multiple generators of the prior art. Probably the most important of these is the fact that the circuit cannot go out of step with the input frequency. Another important advantage is that if the input becomes too low, the circuit will not go out of step, but will simply become inoperative.

Another important advantage of the circuit of Fig. 3 is that the upper limit in frequency is determined only by the ability of the circuit to modulate and amplify the frequencies in question. This limit may extend into the ultra-high frequency range.

It may be demonstrated that regenerative modulators which employ frequency multipliers in their feedback circuits, such as illustrated in Fig. 3, usually require a finite value of the sub-multiple frequency present in the feedback circuit before they will build up to a steady-state condition. The magnitude of the sub-multiple frequency and the length of time which it must be present for purposes of starting will depend upon the amount of amplification of the amplifier and the characteristics of the frequency multiplier. Without an auxiliary starting circuit, it is necessary to make the gain of the modulator so high that it might be self-starting due to amplifier noise and circuit unbalances, and to make use of a rectifier unit which will maintain its sensitivity down to very low levels.

These requirements are dispensed with in the circuits of Figs. 4 and 5 by providing auxiliary means for supplying the small amount of sub-multiple frequency necessary for starting purposes, so that equivalent results are obtained with much simpler circuit arrangements. The general method employed in these circuits is to supply a sharp pulse of low amplitude to one of the resonant circuits, which pulse creates a damped oscillation which will at some time during its decay satisfy the conditions for starting.

The circuit of Fig. 4 employs a modulator of the double balanced type similar to that used in the circuits of Figs. 2 and 3, consisting of a copper-oxide rectifier bridge 85, an input transformer 86 having its primary winding connected to the alternating current source of the frequency (e. g., 4000 cycles) to be converted and its secondary winding connected across one diagonal of the bridge, and an output transformer 87 having its primary winding connected across the other diagonal of the rectifier bridge. The control grid-cathode circuit of a pentode type amplifying vacuum tube 88, similar to those illustrated in the systems of Figs. 2 and 3, is connected across the secondary winding of transformer 87. The anode-cathode circuit of tube 88 includes the primary winding 89 of the transformer 90, this winding being shunted by the resonant circuit 91 tuned to the desired sub-multiple (800 cycles) of the input frequency (4000 cycles). A second winding 92 of transformer 90 coupled to the winding 89 is provided for taking off the former frequency. A third winding 93 of the transformer 90, coupled to the winding 89, is connected across one diagonal of the balanced four-element copper-oxide rectifier bridge 94 acting as a frequency multiplier, the other diagonal of the bridge being coupled by the feedback transformer 95 tuned by the resonant circuit 96 connected across its primary winding to the necessary multiple (3200 cycles) of the applied frequency (800 cycles), which when modulated in the modulator with the original input frequency (4000 cycles) will produce as one component the desired sub-multiple frequency. The secondary winding of the feedback transformer 95 is connected across the mid-point of the secondary winding of the modulator input transformer 86 and the mid-point of the primary winding of the modulator output transformer 87, as shown.

Plate current is supplied to the plate of the am-

plying vacuum tube 88 from the plate battery 97 through the retardation coil 98 and the winding 89 of transformer 90 in series. The battery 97 through the retardation coil 98 supplies a suitable bias to the screen grid of tube 88. Heating current is supplied to the heater for the cathode of tube 88 from battery 99 through the series resistance 100, and a fixed bias is supplied to the control grid of the tube 88 from that battery through the resistance-condenser network 101 and the secondary winding of the modulator output transformer 87, as shown.

The arrangement now to be described is used for producing a sharp pulse of low amplitude and applying it to the regenerative circuit to start regeneration if, for any reason, it is stopped.

The condenser 102 is arranged to be charged to the potential of the plate battery 97 through the potentiometer 103 shunting that battery and choke coil 98, the resistance 104 connected thereto, the resistances 105 and 106 associated with the frequency multiplier unit 94, and the primary winding of feedback transformer 95. If the regenerative modulator is not operating, the condenser 102 will charge up to the breakdown potential of the neon lamp 107 connected across it in series with resistance 104. The breakdown of the neon lamp 107 discharges the condenser 102 through the resistance 104, a small part of this discharge being applied to the modulator regenerative circuit through the resistance 108 connected between a point intermediate condenser 102 and resistance 104, and one terminal of the primary winding of transformer 87 in the input of that circuit. When the charge on the condenser 102 falls below the ionizing potential of the neon tube 107, it will be again charged up from battery 97 over the path previously traced.

This cycle of operations will be repeated at regular intervals to apply a series of pulses to the regenerative circuit until the regenerative modulator starts. As the regenerative modulator builds up, the amplified modulator output voltage applied from the output of amplifier 88 through transformer 90 to the rectifier bridge 94 produces a D. C. voltage drop in the resistance 106 in series with the primary winding of the feedback transformer 95 in the output of the bridge, which voltage opposes the battery voltage applied from the plate battery 97 and, by suitable choice of the circuit constants, is made sufficient to prevent the breakdown of the neon lamp 107. Thus, when the regenerative modulator circuit is working normally, the neon lamp 107 remains inactive, but as soon as the regenerative modulator stops operating the neon lamp will attempt to start it as described.

When the circuit is operating normally, the multiple frequency (3200 cycles) appearing in the output of the frequency multiplier unit 94 is fed by the tuned feedback transformer 95 to the conjugate terminals of the balanced modulator and modulates therein with the base frequency (4000 cycles) impressed thereon through the primary winding of the modulator input transformer 86, to produce combination frequencies in the output of the modulator which are amplified by the amplifier 88. The desired fraction of the input frequency (800 cycles) is selected by the resonant circuit 91 in the output of amplifier 88 and is impressed by transformer 90 on the utilization circuit connected to the winding 92 of that transformer, and also on the multiplier 94 through winding 93.

The circuit of Fig. 5 shows a similar starting

circuit applied to a frequency converter of the regenerative modulator type in which a duplex diode-triode unit 110, such as was described in connection with the system of Fig. 3, is used for the amplifier and multiplier in the regenerative circuit in place of the amplifier 88 and copper-oxide rectifier bridge 94 employed as the frequency multiplier in the system of Fig. 4.

The starting circuit in the system of Fig. 5 also differs from that shown in Fig. 4 in the use of a three-element, hot-cathode, gas-filled discharge tube 111 in place of the cold cathode neon tube 107 used in the system of the previous figure, because in the case of a duplex diode only a negative voltage can be obtained with respect to the cathode which is usually at or near ground potential. By using a three-electrode, gas-filled vacuum tube instead of the cold cathode discharge tube, the same action may be obtained except that the voltage which is developed by the multiplier is used to control the grid of the three-electrode, gas-filled tube.

In the system of Fig. 5, the control grid 112 and the cathode 113 of the amplifier portion of the duplex tube 110 are connected across the secondary winding of the modulator output transformer 87, the control grid-cathode circuit including the usual grid bias combination resistance 114 shunted by condenser 115, and the winding 116 of a transformer 117 is connected between the amplifier anode 118 and the cathode 113 of tube 110, in series with the plate battery 119 and the choke coil 120.

The full-wave rectifier portion of the tube 110 operating as a frequency multiplier, comprises the cathode 113 connected to the mid-point of the winding 121 of the transformer 117, through the primary winding of the feed-back transformer 122, which is shunted by the tuning condenser 123, and the resistance 124 in series, and the two rectifier anodes 125, 126 connected respectively to the two terminals of the winding 121 of the transformer 117. The secondary winding of the feed-back transformer 122 is connected across the mid-point of the secondary winding of the modulator input transformer 86 and the mid-point of the primary winding of the modulator output transformer 87.

The control grid of the gas-filled discharge tube 111 is connected to the mid-point of winding 121 of transformer 117 through series resistances 127 and 128 so as to receive a variable direct current bias due to the voltage drop in the resistance 124 in the rectifier output of the tube 110, and a condenser 129 is connected between the cathode of tube 111 and a point between the resistances 127 and 128. The resistances 130 and 131 are connected in the anode-cathode circuit of tube 111 in series with the plate battery 119 and choke coil 120, and the condenser 132 is connected from a point between resistances 130 and 131 to the cathode of tube 111. The plate of tube 111 is connected through resistance 133 and condenser 134 in series to a point in the regenerative circuit connecting the secondary winding of feedback transformer 122 across the mid-point of the secondary winding of the modulator input transformer 86 and the mid-point of the primary winding of the modulator output transformer 87.

The heaters for the cathodes of the tubes 110 and 111 are supplied in series with heating current from the battery 135 through series resistance 136.

The starting circuit in the system of Fig. 5

operates as follows: The condenser 132 is charged to the potential of the plate battery 119 through the choke coil 120 and the resistance 131. If the regenerative modulator is not operating, the condenser 132 will charge to the breakdown potential of the gas-filled tube 111, the plate-cathode circuit of which is connected across condenser 132 in series with resistance 130. The breakdown of the gas-filled tube discharges the condenser 132 through the resistance 130, a small part of the discharge being applied to the modulator regenerative circuit through resistance 133 and condenser 134 in series. When the charge on condenser 132 falls below the ionization potential of the tube 111, that condenser will again be charged from plate battery 119 over the path previously traced.

This cycle of operations will be repeated at regular intervals to apply a series of sharp pulses to the regenerative circuit of the modulator until the regenerative modulator starts. As the regenerative modulator builds up, the amplified voltage in the output of the amplifier portion of tube 110 is applied through transformer 117 to the output circuit of the converter, and to the double diode portion (rectifier) of tube 110 and produces a D. C. voltage drop in the resistance 124 which will cause the grid voltage of the gas tube 111 to become sufficiently negative to prevent the gas-filled tube 111 from breaking down. It will be seen, therefore, that the gas-filled tube will remain unoperated unless and until this negative voltage is built up to the point to make that tube inoperative as will occur only when the regenerative modulator circuit is operating properly, and when this voltage is not built up the gas-filled tube is operated in the manner described to attempt to start regenerative modulation.

When the regenerative modulator is working properly, a wave of a frequency which is the desired multiple of the frequency applied to the input of the double diode rectifier unit 110 (multiplier) is selected by the tuned feedback transformer 122 and is applied to the conjugate terminals of the modulator to modulate therein with the base frequency wave applied to the primary winding of the input transformer 86, to produce the desired fraction of the base frequency in the output of the modulator. This frequency is amplified by the triode portion of the tube 110 and is impressed by transformer 117 on the utilization circuit connected to the winding 137 thereof.

Only one starting unit of the type described in connection with Fig. 4 or 5 should be necessary for any cascaded series of regenerative modulators. That is, where several regenerative modulators are used in series, the starting unit would be controlled by the last one and the starting pulses would be applied to each regenerative modulator stage in the manner previously described for the single regenerative modulator in the previous figures. As each individual stage builds up, it will continue to operate regardless of the small impulses received from the starting circuit. As soon as the last unit builds up, the starting circuit will cease operating.

Although the starting circuit will supply a short pulse to the output of the frequency conversion circuit, this will not be objectionable since it has been found that this pulse will be approximately 20 decibels below the normal output level, and by proper adjustment of the circuit may be made to occur not oftener than once a second. If no input is applied to the frequency conversion circuit, the amplitude of the impulse in the output will be

even lower because of the greater loss of the modulator. This pulse may be even made use of, if desired, to give an indication at a distant point of trouble in some preceding part of the system. For example, the operator at the distant point could by a simple test on the line determine whether the trouble was in the transmission line or in the regenerative modulator, according to whether the pulse was or was not heard. The lighting of the neon lamp in the case of the starting circuit of Fig. 4 would also give an indication of trouble at the point where it is located.

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. 6 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. 6, it will be seen that the regenerative modulators in the three stages are of the double balanced type, such as used in the systems of Figs. 2 to 5, 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. 6 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 142 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 145, 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. 6 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 mid-point of the primary winding of transformer 159, through the series resistances 163 and 164.

Space current for the common amplifying vacuum tube, heating current for the heater type cathode and biasing voltages for the other electrodes thereof are supplied in a manner similar to that described for the similar tubes in the circuits of Figs. 2 to 5.

The anti-resonant circuits 144, 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 144 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. 6 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. 7 is shown a frequency conversion circuit employing a single amplifier for a plurality of stages of regenerative modulation as in the system of Fig. 6, 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. 7 comprising a modulator of the double-balanced type similar to those used in the system of Figs. 2 to 6, 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 of 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. 7 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 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 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. 6, 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, 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 will be selected to provide the proper loss to make the

operation of the first stage stable, and the pad 180 is likewise adjusted.

If a larger amount of power in the produced waves of sub-multiple frequencies is required in the circuit of Figs. 6 and 7, two amplifying vacuum tubes may be used therein in place of the single tube illustrated, for example, in the circuit of Fig. 6, 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 sub-multiplication have been illustrated in Fig. 6, and two in Fig. 7, 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. 6 and 7 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, such as the ones illustrated in Figs. 3, 4 and 5 in which case each feedback circuit would include a suitable multiplier, for example, of the double diode-triode vacuum tube type, as of the copper-oxide bridge type, as illustrated in those figures.

Figs. 8 and 9 show frequency conversion circuits in accordance with the invention employing third order regenerative modulators instead of second order modulators as in the circuits of the previous figures.

The circuit of Fig. 8 may be employed for reducing the base frequency of 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 util-

zation circuit for the converted sub-multiple frequency

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

5 The plate of the non-linear modulating elements 184 and 185 in the modulator circuit of Fig. 9 preferably is of a material which comprises a mass of finely divided conductive or semi-conductive crystalline particles held together 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. E. McEachron.

10 In the operation of the system of Fig. 8, 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

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

25 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

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

35 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

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

40 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

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

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

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

55 impressed by transformer 192 on the utilization circuit as indicated.

As in the other circuits 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. 9 is suitable for reducing a base frequency f to an exact sub-multiple

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

70 thereof. As shown, the modulator and the succeeding amplifier in the circuit of Fig. 9 are identical with the third order modulator and the amplifier used in the system of Fig. 8, 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 cir-

cuit 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, similar to the corresponding tubes used in the systems of Figs. 3 and 5 in the feedback circuit 202.

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 205 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 205.

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. 9 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. 9 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. 8 and 9, 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.

The terms "balanced modulator" and "modulator of the balanced type" as used in the claims are meant to define that type of modulator which will suppress substantially the frequency of one of the modulating waves applied to the modulator while transmitting other components of modulation, and the terms "double balanced modulator" and "modulator of the double balanced type" as used in the claims are meant to define that type of modulator which will suppress substantially the frequencies of both of the modulating waves applied to the modulator while transmitting other components of modulation.

What is claimed is:

1. A frequency converting circuit for producing accurate fractions of a given base frequency comprising a modulator consisting of a plurality of solid non-linear modulating elements con-

nected in a balanced arrangement, means for impressing a wave of said given base frequency on the input of said modulator, a feedback circuit including an amplifier and one or more selective networks, connecting the output of said modulator to said input, in conjugate relation with the input of said amplifier, said amplifier comprising an electron space discharge device having a gain which is greater than the loss of said modulator and said networks, said selective networks being so tuned that the amplified waves fed back into the input of said modulator are of such frequency that when combined therein with the impressed wave of base frequency, sustained waves of combination frequencies including the desired frequency are produced, and means for selecting a wave of said desired frequency from the output of said amplifier.

2. A frequency converter for producing a wave of a desired frequency which is a fractional ratio of a given base frequency comprising a balanced second order modulator having one input supplied with a wave of said base frequency and a second input in conjugate relation with the first input, an amplifier having an input circuit coupled to the output of said modulator, and two output circuits, a regenerative circuit coupling one of said output circuits to the second input of said modulator, including means to selectively feed back to said second input waves derived from the modulator output of selected frequencies and amplitudes, which when modulated with the wave of base frequency in said modulator will produce combination waves including a sustained component of said desired frequency, and means enabling a sustained wave of said desired frequency to be selected from the other output of said amplifier.

3. The frequency converter of claim 2 in which said one output circuit is tuned so that the waves fed back to said second input of said modulator include two different frequencies of such values and amplitudes that when modulated with the supplied wave of base frequency in said modulator, a sustained side-band component of said desired frequency is produced, and said other output circuit is tuned to select said desired frequency.

4. A frequency multiplier for deriving from a wave of a base frequency f a wave of the frequency

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

comprising a balanced modulator having one input circuit supplied with said wave of base frequency and a second input circuit in conjugate relation with said one input circuit, a feedback circuit including an amplifier coupling the output of said modulator to said second input circuit thereof, including means to selectively feed back to said second input circuit in sufficient amount to produce regeneration waves of the frequencies

$$\frac{f}{2} \text{ and } \frac{3f}{2}$$

to modulate in said modulator with the wave of frequency f , and means for selecting from the resulting sustained modulation components in the output of said modulator a sustained wave of the desired frequency

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

5. A circuit for producing a wave of a frequency which is a desired fractional ratio of a given base

