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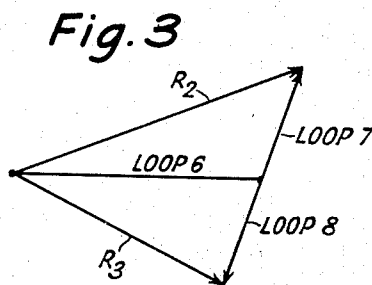
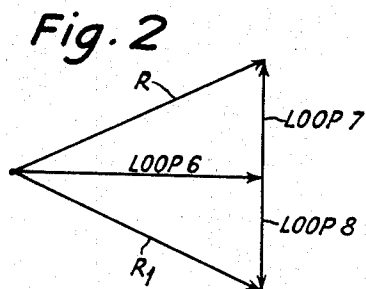
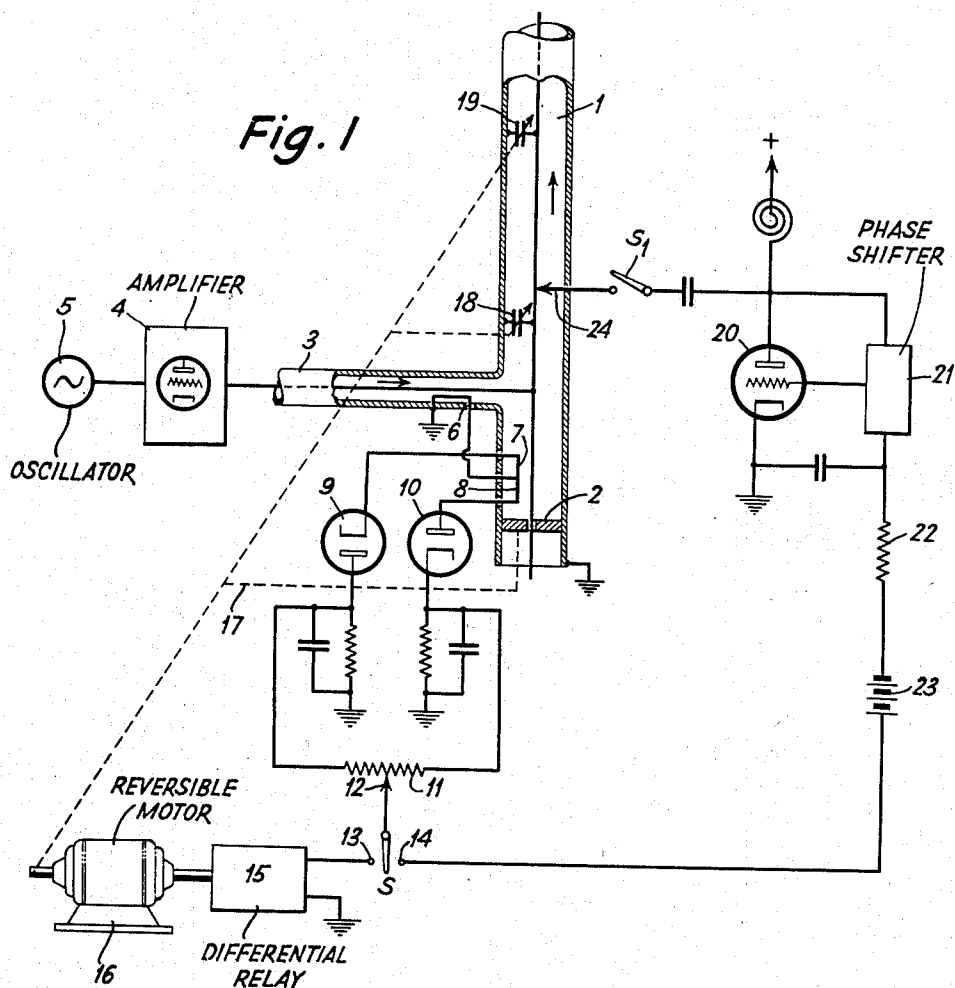
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2,304,377

AUTOMATIC FREQUENCY CONTROL SYSTEM

Filed Feb. 11, 1941

2 Sheets-Sheet 1



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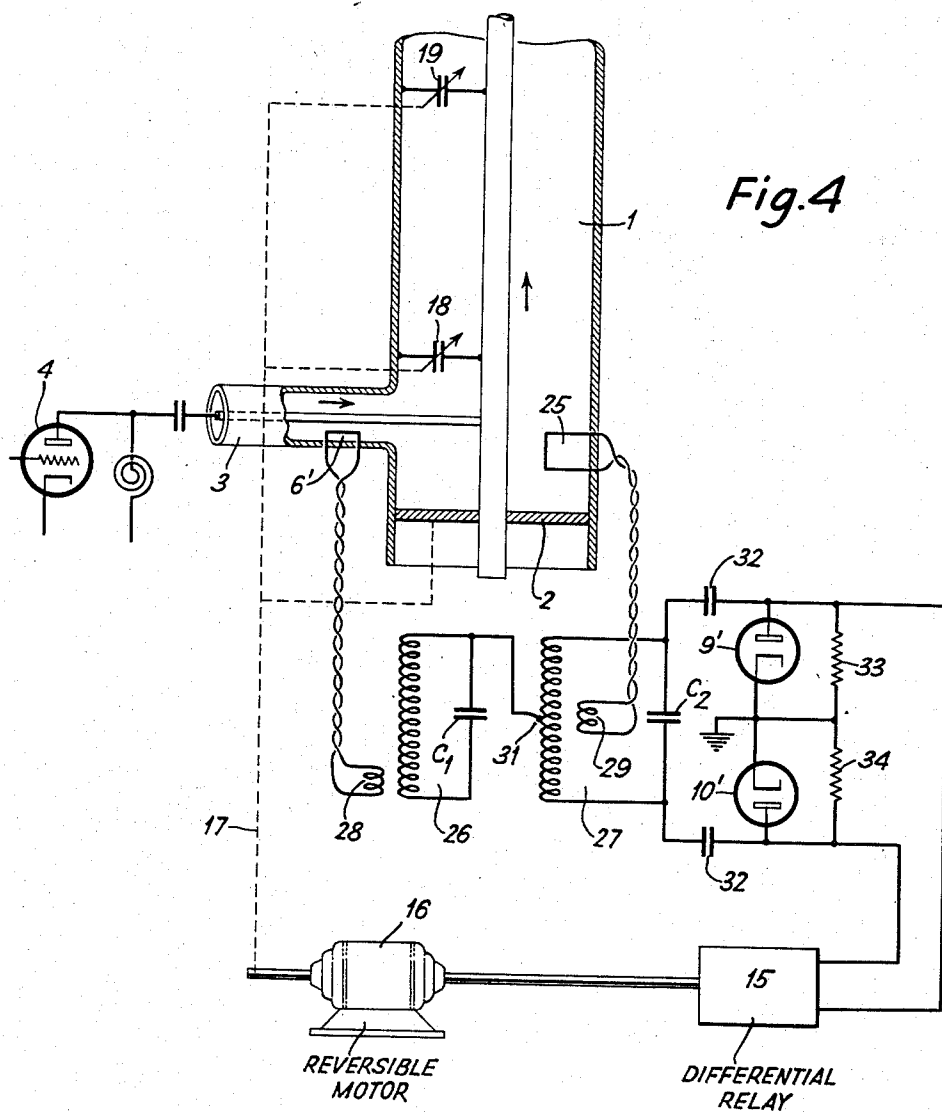
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AUTOMATIC FREQUENCY CONTROL SYSTEM

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2 Sheets-Sheet 2



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2,304,377

AUTOMATIC FREQUENCY CONTROL
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Application February 11, 1941, Serial No. 378,374

10 Claims. (Cl. 178-44)

The present invention concerns means for automatically maintaining the syntony between the natural frequency of a tuned circuit and the frequency of an applied current by varying the effective constants of the tuned circuit.

It is required in many circuit arrangements that the natural frequency of a tuned circuit be identical with the frequency of the driving source coupled to the tuned circuit, irrespective of whether the driving source is a constant frequency oscillator or a varying frequency oscillator. One trouble heretofore experienced in the art has been due to the change in natural frequency of the tuned circuit, caused by a change in temperature during operation, which is responsible for a departure from syntony between the frequency of the tuned circuit and the frequency of the applied current.

The primary object of the present invention is to provide a circuit arrangement which automatically maintains the syntony between the natural frequency of the tuned circuit and the frequency of the driving source, and to achieve this syntony or synchronization, so to speak, irrespective of whether the frequency of the driving source changes, or whether there is a tendency for the tuned circuit to change its natural frequency due to a change in dimensions caused by heat, or any other reason.

A more specific object is to maintain syntony between the natural frequency of a concentric line resonator and the constant frequency of a driving source of high frequency waves coupled to said resonator.

The foregoing objects, among others, are achieved in accordance with the invention by means of a circuit arrangement which is sensitive to the phase difference between the driving (applied) currents and the currents in the tuned circuit, in order to control the tuning of the tuned circuit.

A more detailed description of the invention follows in conjunction with drawings wherein Figs. 1 and 4 illustrate two embodiments of the present invention, and Figs. 2 and 3 are vector diagrams given to illustrate the principles of operation of the invention.

Referring to Fig. 1, there is shown a concentric line resonator 1 comprising a section of coaxial line whose conductors are connected together at one end by a metallic end plate 2. The inner conductor of the resonant line is shown coupled to a transmission line 3, which extends to a suitable driving high frequency source, here shown by way of example only as an electron discharge

device amplifier 4, in turn having its input coupled to a constant frequency oscillator 5. The oscillator 5 may be a piezo electric controlled affair, if desired, while amplifier 4 may be the final amplifier of a suitable circuit arrangement.

The outer conductors of the section of transmission line 3 and the resonator 1 are shown connected to ground and to each other. The transmission line 3 is preferably coupled to the resonator 1 at a suitable point to obtain a match between the impedances of the two elements. In order to maintain syntony, or identity of frequency between the natural frequency of the resonator 1 and the frequency of the current applied to the resonator by the constant frequency oscillator 5, there are provided a loop 6 located in the interior of the transmission line 3, a pair of loops 7 and 8 located in the interior of the resonator 1, a pair of diode rectifiers 9 and 10 coupled to the foregoing loops, and suitable means, described later, for changing the tuning of the resonator 1. Loop 6 is so arranged in the feed line 3 as to derive energy from the currents flowing over the line, while loops 7 and 8 are arranged in the interior of the resonator to derive energy from the currents flowing in the resonator. Loops 7 and 8 are arranged reversely with respect to one another so as to derive voltages of opposite polarity and of equal magnitude from the resonator. One terminal of the loop 6, it should be noted, is coupled to an intermediate point, such as the mid point, of the connection between the two loops 7 and 8, while the other terminals of the loops 7 and 8 are connected to the cathode of rectifier 9 and the anode of rectifier 10, as shown. The anode of rectifier 9 and the cathode of rectifier 10 are connected together through a resistance potentiometer arrangement 11 to an intermediate point on which, preferably the mid point, there is provided a tap 12 coupled to the knife blade of a suitable switch S having contacts 13 and 14. The tap is so arranged that when the rectifiers 9 and 10 draw equal currents, there will be equal direct current voltages of opposite polarity developed across both sides of the potentiometer 11, in which case there will be no voltage at the tap 12. In view of the fact that the current in the transmission line 3 is in quadrature with respect to the current in the resonator 1 when the resonator 1 is tuned to have a frequency identical with the frequency of the currents supplied by the oscillator 5, the voltage induced in loop 6 will be in quadrature with the voltages induced in loops 7 and 8. The voltages in loops 7 and 8 are reversed in polarity with

respect to each other, although approximately equal in magnitude. The loops 6, 7 and 8 are so designed, however, that the voltages are preferably of the same order of magnitude and, if desired, equal to one another.

At resonance (that is, when the frequency of the resonator 1 is in sympathy with the frequency of the oscillator 5), the vector diagram of the various voltages of the loops is represented in Fig. 2. By referring to Fig. 2, it will be seen that the resultant voltage R of the vectors representing the voltages in loops 6 and 7, applied to diode 9, is equal in magnitude to the resultant R_1 of the vectors representing the voltages in loops 6 and 8, applied to the diode 10.

Should the natural frequency of the resonator 1 change because of a change in dimensions due to temperature fluctuations or for any other reason, the phase of the current in the resonator 1 will change relative to the current in the transmission line 3, with the result that the resultant voltages R and R_1 on the diodes 9 and 10 are different in magnitude. Fig. 3 is representative of what occurs with a change in the tuning of the resonator 1. It will be noted that the vector representing the voltage in loop 6 is no longer in quadrature with the vectors representing the voltages in loops 7 and 8, although the voltages in loops 7 and 8 are still reversed in polarity relative to each other. The resultant R of Fig. 2 now becomes the resultant R_2 of Fig. 3, while the resultant R_1 of Fig. 2 now becomes the resultant R_3 of Fig. 3. It should be noted that the resultants R_2 and R_3 representing the voltages applied to the diodes 9 and 10, are now quite different in magnitude. The application of different voltages to the diodes 9 and 10 represented by resultants R_2 and R_3 will cause different values of currents to flow through the diodes and both sides of the resistor potentiometer 11, and thus set up a potential at tap 12 and the blade of switch S , of a sign depending upon which resultant R_2 or R_3 predominates.

It will thus be obvious that the tap 12 becomes positive or negative as the tuning of the resonator 1 changes in one sense or the other, thus providing an available control voltage whose value is in proportion to the amount of the detuning of the resonator 1, provided, of course, that the departure of frequency of the resonator 1 from its normal frequency is not great enough to cause any very large reduction in the current flowing in the resonator.

The sign of the controllable voltage appearing on tap 12 can, of course, be reversed for any given direction of detuning of the resonator merely by interchanging the connections of the anode and cathode electrodes of each diode.

Fig. 1 illustrates two different ways of restoring the natural frequency of the resonator 1 to its desired value when the resonator becomes detuned. One means for accomplishing this result comprises a differential relay 15 whose input is connected to the contact 13 of the switch S and whose output is coupled to a reversible motor 16. The shaft of the motor 16 may be linked either to the end plate 2 (as shown by dotted line 17) or to variable condensers 18 and 19 (shown bridged across the inner and outer conductors of the resonator). It should be understood that condensers 18 and 19 may be employed alternatively for tuning (it is not necessary to use both), and that if either of these variable condensers is employed, then the link between the end plate 2 and the reversible motor need not be employed;

while if the link to the end plate is used, then the condensers 18 and 19 need not be employed. In other words, there have been shown three different elements; namely, end plate 2, and condensers 18 and 19, any of which can be employed for automatically tuning the resonator to restore the frequency thereof to the desired value. Where end plate 2 is used for this purpose, this end plate should be made to be movable over the outer surface of the inner conductor and the inner surface of the outer conductor, over a desired tuning range, and should be arranged to make good electrical contact with the surfaces of these conductors over its range of movement.

Another way of changing the tuning of the resonator to restore its frequency to the assigned value comprises a reactance simulating electron discharge device 20 to whose anode and grid and cathode elements is connected a phase shifter 21 comprising preferably a condenser and a resistor in series, the grid being connected to the junction point. The grid of the reactance device is shown coupled through a resistor 22 and a battery 23 to a contact 14, on switch S , while the anode of tube 20 is shown coupled through a condenser to the blade of a switch S_1 which, when closed, connects with a lead 24 suitably tapped on the inner conductor of the resonator 1. The reactance device 20 is designed to provide either an inductance or capacity effect, depending upon which is desired, of such sign as to compensate for the change in capacity or inductance of the resonator 1 causing the detuning.

In the operation of Fig. 1, assuming that it is desired to use the differential relay 15 and reversible motor 16 as the automatic frequency restoring means for the resonator 1, switch S will be thrown to engage contact 13, and switch S_1 opened. Any change in the natural frequency of the resonator 1 from the assigned value will produce a difference in the magnitudes of the voltages applied to the rectifiers 9 and 10, thus causing the blade of the switch S to assume a potential positive or negative, depending upon whether the resonator 1 is detuned in one sense or the other. Since the blade of switch S engages contact 13, the voltage on the blade of this switch will cause the differential relay to affect the reversible motor in such direction as to move end plate 2, if this is used, or either of the capacities 18 and 19 in such direction as to compensate for the change in tuning of the resonator 1. If, for example, the resonator 1, due to an increased temperature caused by operating or other conditions increases its length, there will be a decrease in the natural frequency of the resonator. To compensate for the longer resonator and its decreased frequency, it will be necessary to decrease the capacity or decrease the inductance of the resonator. Similarly, where there is a decreased temperature the resonator will become shorter with a consequent increase in natural frequency. To offset this increase in frequency, there is required an increased capacity across the resonator or an increased inductance for the resonator. The desired compensation can be achieved by moving the end plate 2, or, in the event either the condenser 18 or the condenser 19 is employed, to change the capacity of the variable condenser in the proper sense.

In case it is desired to employ the reactance electron discharge device 20 to maintain the fre-

quency of the tuned circuit 1 constant, the blade of the switch S will be thrown to engage contact 14 and the switch S₁ will be closed to make connection with the lead 24. The device 20 acts as a reactance across part of the resonator 1 and the effective reactance of this device is altered by the controllable voltage developed as a result of mistuning of the resonator 1, and applied to the grid in such sense as to correct the tuning of the resonator. With a sufficiently large control voltage developed by a very small amount of detuning of the resonator, the detuning of the resonator may be held to negligible amounts. Such a sufficiently large controllable voltage may be developed by proportioning the loops 6, 7 and 8 to pick up large voltages or, if desired, by amplifying the control voltage before it is impressed upon the reactance device 20. If desired, the reactance device control circuit may be made to be very fast in operation by making small the time constant of the circuit connecting the control voltage to the grid of the device 20. It should be understood that the automatic frequency control arrangement employing the reactance device 20 is quicker in operation than the method employing the reversible motor.

Although Fig. 1 has been particularly described with reference to a change in the tuning of the resonator, it should be understood that the principles of the invention apply equally well if the resonator 1 is not mistuned by temperature fluctuations or for other reasons, and if the frequency of the driving source changes. In this last case, assuming that the frequency of the driving source 5 changes, then again there will be a phase change between the driving currents and the currents in the resonator circuit which will produce a difference in magnitude of the resultants representing the vector sum of the loop voltages which are applied to the detectors. This change in the resultants applied to the detectors will produce a controlling voltage of such sign as to change the tuning of the resonator to have its frequency conform with the changing frequency of the driving source in the same manner as described above. It will thus be seen that the invention provides an automatic circuit for conforming the frequency of the tuned circuit to the frequency of the driving source, irrespective of whether the tuned circuit becomes mistuned, or the driving source is variable in frequency, or both.

Fig. 4 shows another embodiment of the invention, which differs from Fig. 1 only in the manner in which currents are derived from the transmission line 3 and from the resonator 1 and applied to a type of discriminator circuit. The same reference numerals appearing in Figs. 1 and 4 refer to the same parts throughout the two figures. The frequency controlling circuit of Fig. 4 includes a pair of tuned circuits 26 and 27, both of which are tuned to the same assigned frequency. Energy at the frequency of the driving source is obtained by loop 6' in the interior of the transmission line 3 and applied via a link circuit and a coil 28 to the tuned circuit 26. Energy is also derived from the resonator 1 by loop 25 in the interior of the resonator 1 and applied to the tuned circuit 27 via coil 29 so as to apply equal currents of opposite polarities to the anodes of the two rectifiers 9' and 10'. The high potential point 30 of the tuned circuit 26 is connected to the mid point 31 of the coil of the tuned circuit 27. A pair of rectifiers 9' and 10' are connected through blocking condensers 32 to op-

posed terminals of the tuned circuit 27. The cathodes of the diodes 9' and 10' are connected together and to the junction point of a pair of series arranged resistors 33 and 34 of equal magnitude. The outputs from the diode rectifiers are coupled to a differential relay 15 which controls the reversible motor 16, in turn coupled to the shaft 17 in a manner similar to the arrangement described in Fig. 1. If the frequency of the tuned circuit 1 is identical with that of the frequency of the applied currents, supplied through transmission line 3, the circulating current in the resonator 1 will be substantially 90° out of phase with the feed current in the transmission line 3, and the voltages in the tuned circuits 26 and 27 will also be in quadrature, in which case there will be equal voltages on the diodes and equal and opposed voltages applied to the resistors 33 and 34. For such a condition, the differential relay will be in its normal central position and will not operate. For any small detuning of the resonator 1 caused by temperature change or for other reasons, the phase of the circulating current in the resonator will shift relative to the currents in the transmission line 3, thus causing a difference in the magnitudes of the voltages applied to the diodes with a consequent difference of currents in the resistors 33 and 34 to cause the differential relay 15 to operate in such direction as to affect the reversible motor 16 to compensate for the change in tuning of the resonator. The compensation in tuning brought about by the reversible motor 16 will restore syntony between the frequency of the resonator and the frequency of the applied currents. The discriminator circuit shown in Fig. 4 constituting the tuned circuits 26 and 27 and the coupling circuits associated therewith, is well known in the art, the principles thereof being described generally in Seeley Patent 2,121,103, granted June 21, 1938, to which reference is made. Of course, here again a reactance electron discharge device frequency control arrangement may be provided as an alternative to the discriminator in the same manner as is shown in Fig. 1 and described in connection therewith.

The invention may find particular application in the operation of a cyclotron circuit, in which case each of the D's of the cyclotron would be connected to the open end of a concentric line resonator 1. The heating effects produced by the operation of the cyclotron tend to change the tuning of each resonator associated with a D. By using the principles of the present invention, the natural frequency of the resonator 1 will be made to conform at all times with the frequency of the driving source, despite changes in dimensions of the concentric line resonator caused by the heating. In using the invention with a cyclotron arrangement, the driving source would be a push-pull transmitter connected to the two feeder lines associated with the concentric resonators for the two D's, and the concentric resonators, as well as the D's of the cyclotron, would operate in an imperfect vacuum. Since the condenser 19, if this were used in the cyclotron, would be located at a high potential end of each concentric resonator, and in a very strong magnetic field, its plate spacing may be less than if such condenser were used in a resonator not associated with a cyclotron. This is because the magnetic field tends to prevent spark-over, or break-down, of the space between the plates of the condenser.

What is claimed is:

1. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, means for deriving a voltage from said feed line, means for deriving opposed voltages of equal magnitude from said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifiers, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom.

2. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, means for deriving a voltage from said feed line, means for deriving opposed voltages of equal magnitude from said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifiers, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom, said last means including a differential relay coupled to said rectifier structures, a reversible motor coupled to said relay, and a tuning element for altering the constants of said resonator linked to the shaft of said motor.

3. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, means for deriving a voltage from said feed line, means for deriving opposed voltages of equal magnitude from said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifiers, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom, said last means including a reactance electron discharge device coupled to said rectifier structures and connected across a part of said resonator.

4. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, means for deriving a voltage from

said feed line, means for deriving opposed voltages of equal magnitude from said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifiers, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom, said last means including a differential relay coupled to said rectifier structures, a reversible motor coupled to said relay, and a variable condenser linked to the shaft of said motor and connected across the conductors of said resonator.

5. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, means for deriving a voltage from said feed line, means for deriving opposed voltages of equal magnitude from said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifiers, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom, said last means including a differential relay coupled to said rectifier structures, a reversible motor coupled to said relay, and a movable plate linked to the shaft of said motor and coupled between the conductors of said resonator near one end thereof.

6. Apparatus in accordance with claim 1, characterized in this that said circuit for combining each of said opposed voltages with the voltage derived from said feed line includes a pair of parallel tuned circuits tuned to the same frequency, one of tuned circuits being inductively coupled to said feed line and the other of said tuned circuits being inductively coupled to said resonator, there being a connection from the high potential end of said first tuned circuit to the electrical center of said other tuned circuit.

7. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator comprising a feed line coupled to the inner conductor of said resonator at a point intermediate the ends thereof, a loop in the interior of said feed line for deriving a voltage therefrom, a pair of loops in the interior of said resonator for deriving therefrom opposed voltages of equal magnitude, a rectifier circuit, means for combining each of said opposed voltages with the voltage derived from said feed line and for applying the resultants to said rectifier circuit, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom.

8. A system for maintaining the natural fre-

quency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator, despite temperature fluctuations of said resonator, comprising a coaxial feed line extending between said source and a point on the inner conductor of said resonator intermediate its ends, a loop in the interior of said feed line for deriving voltage therefrom, a loop in the interior of said resonator for deriving voltage from said resonator, a pair of rectifier tubes, and a circuit for applying the voltage derived from said coaxial line cophasally to certain electrodes of said rectifier tubes and for applying equal parts of the voltage derived from said resonator to said same electrodes but in an out-of-phase relation, means coupled to other electrodes of said rectifier tubes for comparing the rectified outputs of said tubes and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom.

9. A system for maintaining the natural frequency of a tunable concentric line resonator substantially synchronous with the frequency of a source of oscillations exciting said resonator, despite temperature fluctuations of said resonator, comprising a coaxial feed line extending between said source and a point on the inner conductor of said resonator intermediate its end, connections between ground and the outer conductors of said coaxial feed line and concentric resonator, a loop in the interior of said coaxial line for deriving energy therefrom, a connection

between the outer conductor of said feed line and one terminal of said loop, a loop in the interior of said resonator, a connection from the other terminal of said first loop to the electrical center of said second loop, a pair of rectifier tubes each having a cathode and an anode, connections from the cathode of one rectifier tube and the anode of the other rectifier tube to opposite terminals of said second loop, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to restore the aforesaid relation between the frequency of said resonator and the frequency of said source upon departure therefrom.

10. A system for maintaining the natural frequency of a tunable resonator substantially synchronous with and subject to the exclusive control of the frequency of a fixed source of oscillations exciting said resonator, comprising a connection coupled to said resonator for supplying alternating currents thereto from said source, means for deriving a voltage from the currents in said connection, means for deriving opposed voltages from the oscillatory current in said resonator, a pair of rectifier structures, a circuit for combining each of said opposed voltages with the voltage derived from said connection and for applying the resultants to said rectifier, and means for comparing the rectified outputs and for controlling the tuning of said resonator in accordance with the difference in said outputs in such direction as to bring said first named and second named voltages into quadrature phase.

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