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REGENERATIVE AMPLIFIER

Filed May 1, 1930

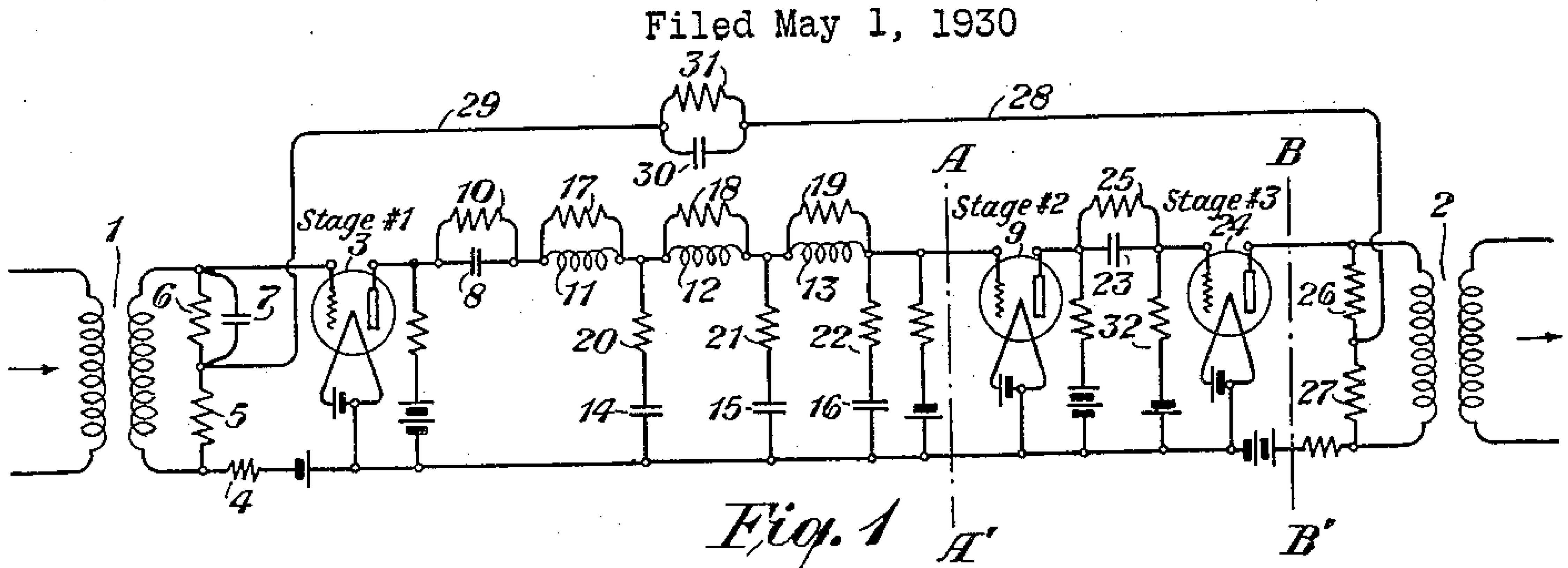
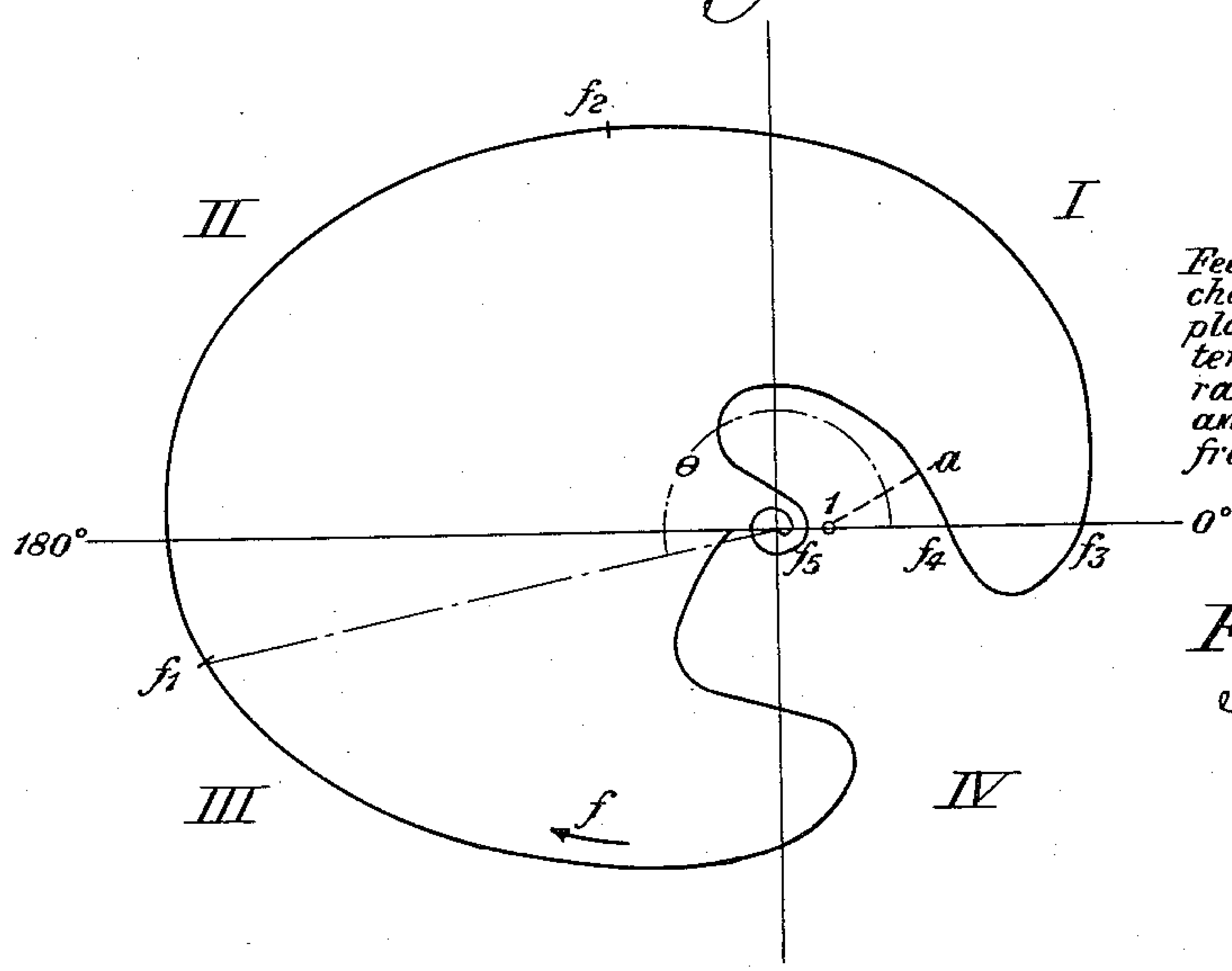


Fig. 1



Feed-back characteristic plotted in terms of feed-back ratio and phase angle for frequencies from 0 to +∞.

Fig. 2

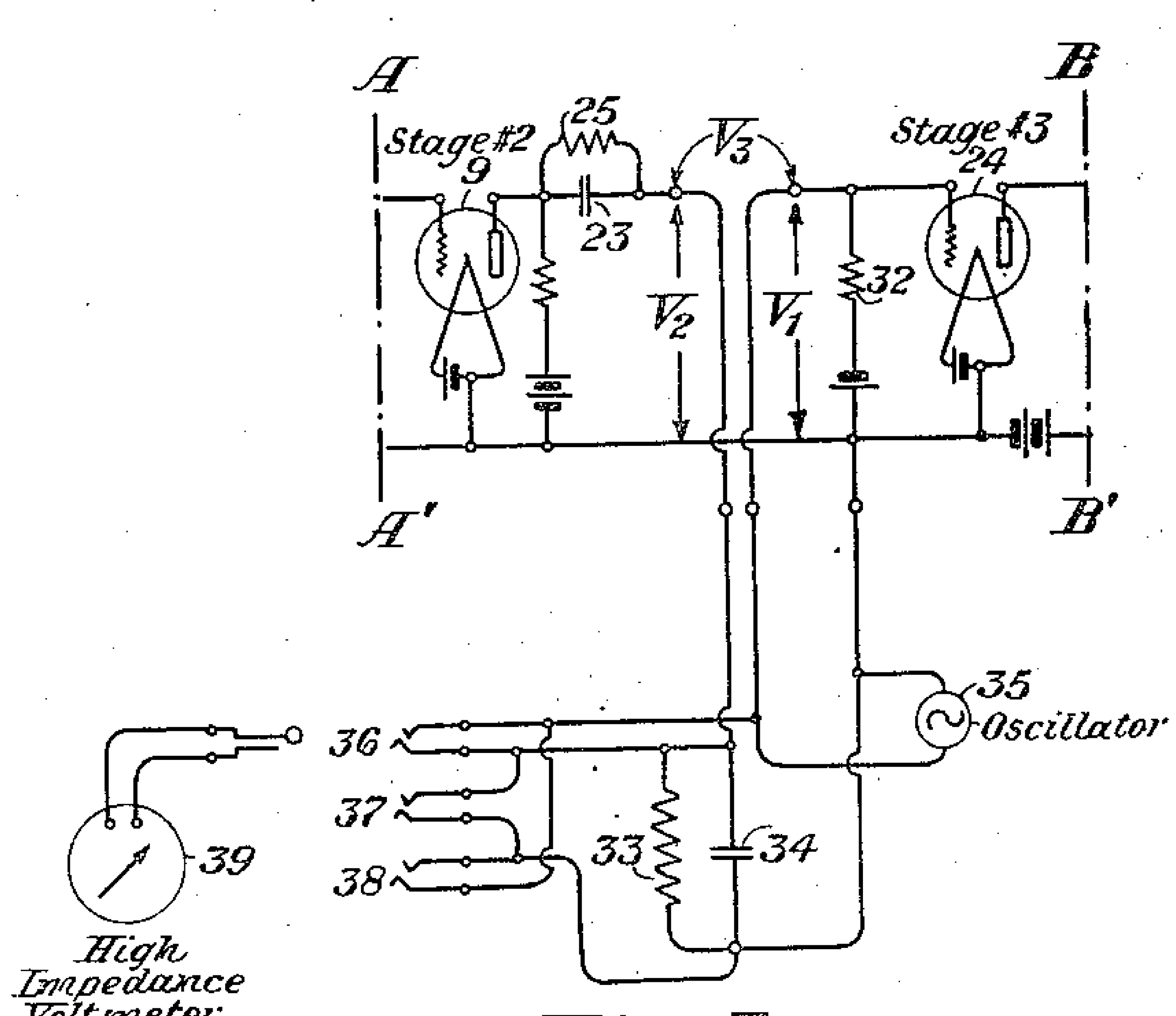


Fig. 3

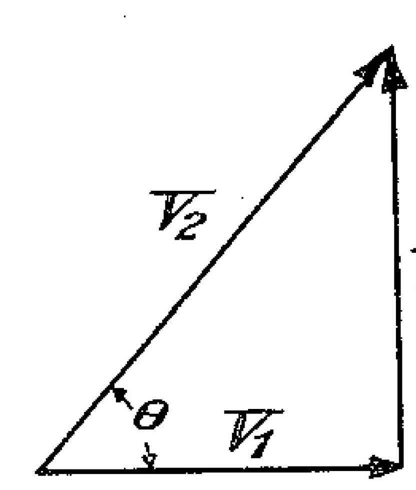


Fig. 4

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UNITED STATES PATENT OFFICE

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REGENERATIVE AMPLIFIER

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This invention relates to regenerative amplifiers and particularly to an amplifier that will remain stable even though the feed-back ratio is greater than unity and the current fed back is in phase at one or more frequencies.

In certain forms of electrical circuits employing vacuum tubes a portion of the output current is fed back to the input either unintentionally or by design. Such a device may be looked upon as an amplifier whose output is connected to the input through a transducer. When thus connected the resulting combination may be either stable or unstable. The circuit is said to be stable when an impressed small disturbance which itself dies out, results in a response which dies out. It is said to be unstable when such disturbance results in a response which goes on indefinitely, either staying at a relatively small value or increasing until it is limited by the nonlinearity of the amplifier. Heretofore it has been understood if a regenerative circuit had a feed-back ratio greater than unity and the current fed back was in phase with the input current, that such regenerative circuit was unstable. I have recently discovered that it is possible to have a stable regenerative circuit even though the feed-back ratio is greater than unity and the current fed back is in phase at one or more frequencies with the input current.

My invention resides in a method for determining the stability of a regenerative amplifier, and also resides in a regenerative amplifier that is stable even though the feed-back ratio is greater than unity and in spite of the fact that the current fed back at one or more frequencies may be in phase with the input current.

This invention will be understood from the following description when read in connection with the attached drawing of which Figure 1 shows schematically a regenerative amplifier embodying my invention, Fig. 2 illustrates graphically the method employed in determining the stability of such amplifiers, Fig. 3 illustrates a simple method for obtaining the feed-back ratio, and Fig. 4 is a vector diagram used in the description of Fig. 3.

In Fig. 1 the input current is impressed upon the amplifier by the transformer 1 and the output current is impressed by the transformer 2 upon the output circuit. The secondary of the transformer 1 is connected across the input of the vacuum tube 3 of the first stage of the amplifier. The input circuit of tube 3 includes also the resistances 4, 5 and 6, the latter being shunted by the condenser 7. The output circuit of tube 3 is coupled by the condenser 8 with the input circuit of the tube 9 constituting the second stage of the amplifier. The condenser 8 is shunted by a resistance 10, the purpose of which will be made clear hereinafter. Connected between the condenser 8 and the grid of the tube 9 are the inductances 11, 12 and 13, which together with the condensers 14, 15 and 16, connected in shunt across the input circuit, constitute a low-pass filter. Each of the inductances is shunted by one of the resistances 17, 18 and 19, and each of the condensers has connected in series therewith one of the resistances 20, 21 and 22. The purpose of the resistances is to prevent undesired phase shifts at certain frequencies, the manner of doing which will later be described. The output of tube 9 is coupled by condenser 23 with the input of tube 24, constituting the third stage of the amplifier. Condenser 23 is shunted by a resistance 25 which is similar to resistance 10. Connected across the output of tube 24 are the resistances 26 and 27. A feed-back circuit comprising the conductors 28 and 9, the condenser 30 and resistance 31, extends from the junction point of the resistances 26 and 27 in the output circuit of the tube 24 to the junction point of the resistances 5 and 6 in the input circuit of the tube 3. Each of the tubes has associated therewith sources of current or potential to energize the filament and to supply the requisite plate and grid voltages to insure the proper functioning of the amplifier.

The invention relates to the type of amplifiers in which the current is fed back in phase opposition. This results in improved repeater characteristics, particularly in freedom from modulation. The general aim is to feed back as much current as possible within the working range of frequencies, without producing an unstable condition outside of the working range where the phase relations may be more unfavorable than within the working range. In the design of a regenerative amplifier without transformers in the regenerative portion of the circuit it is necessary to employ an odd number of vacuum tubes for the reason that a vacuum tube has the property of changing the phase of the current passing therethrough. An odd number of tubes will therefore tend to insure that the current fed back will be in phase opposition to the input current. Owing to the presence in the circuit of a certain amount of reactance the current fed back will not be in phase opposition at all frequencies to the input current.

Fig. 2 shows the manner in which the feed-back varies with frequency both as to magnitude and phase angle. The curve shown in that figure represents the locus of the points corresponding to the feed-back ratio and phase angle for successive values of frequency from zero to infinity. The distance from any point on the curve to the origin represents the feed-back ratio and the angle that that line makes with the positive axis represents the phase shift. The relative magnitude of the feed-back ratio may be determined by comparison with the distance from the origin of the point 1 upon the positive axis which point represents unity feed-back ratio of zero angle. The feed-back ratio is usually a complex quantity. It denotes the ratio by which the current or voltage is attenuated by one round trip through the circuit, including the phase shift. A simple method for obtaining the feed-back ratio is illustrated by Fig. 3 which is a modification of that part of Fig. 1 between AA′ and BB′. The circuit of Fig. 1 is opened at some convenient place, such as next to the grid resistance 32 of the third stage. A voltage V_1 is applied to this resistance by an oscillator 35 and its magnitude measured by the meter 39 by connecting to the jacks 38. The elements 33 and 34 are adjusted to simulate the impedance of the resistance 32 in parallel with the grid of the tube 24, so that the voltage V_2 which is next measured on jacks 37 shall not be affected by improper termination. The voltage V_3 is measured on jacks 36. A triangle may be constructed having the magnitudes V_1, V_2, V_3 as its sides, as in Fig. 4, in order to determine the angular displacement, θ, between V_1 and V_2. This angle and the ratio V_2/V_1 give the complex feed-back ratio. Such measurements afford the basis for deriving the data which when plotted will produce the feed-back characteristic of the amplifier. Now let a straight line be drawn from the point numbered 1 to point "a" on the feed-back characteristic. Let "a" be moved along the curve while the line 1—a changes length and rotates about point 1 as a pivot. I have discovered that when the line 1—a rotates through a total of zero degrees as "a" follows the course of the feed-back characteristic from $f=0$ to $f=\infty$, the circuit upon which that characteristic curve is based will be stable even though the feed-back ratio is greater than unity, and has zero angle at certain frequencies. For example, in the curve shown in Fig. 2, the point designated f_3 represents a feed-back ratio in which the current fed back is not only in phase with the input current, but the ratio is slightly under 7. Following the curve further toward increasing frequency, we find another point f_4 where the same conditions prevail. Subsequently, there is another point designated f_5 where the current fed back is in phase with the input current, but the ratio of output to input is less than unity. Since the line 1—a rotates through a total of zero degrees as "a" follows the entire curve representing the feed-back characteristic of the circuit shown in Fig. 1, the circuit will be stable in spite of the fact that at the frequencies f_3 and f_4 the ratio is greater than unity, and the output currents are in phase with the input currents. It is desirable to point out, however, that since the point f_5 lies close to the point 1 representing unity feed-back, the curve might be caused to extend to the right so that f_5 lies to the right of the point 1 if the gain of the amplifier should be greatly increase above that represented by the curve of Fig. 2. In this case the line 1—a would rotate through 360° as "a" follows the curve from $f=0$ to $f=\infty$ and the circuit would be unstable.

In the curve shown in Fig. 2 the working range of frequencies is represented by that portion lying between f_1 and f_2. The remaining portions of the curve below f_1 and f_2 must be considered from the standpoint of the possibility of feed-back at frequencies above or below the working range. In order to maintain stability of the regenerative amplifier its characteristic curve must be kept away from the point representing unity feed-back. It will be seen from Fig. 2 that that portion of the curve representing frequencies below f_1 approaches the positive axis from the third quadrant (the quadrants being designated I, II, III and IV) which tends to insure that the curve will not enclose the point of unity feed-back. The performance of the curve below f_1 is due to the presence in the circuit of the series condensers 8, 23 and 30, the latter being in the feed-back connection. Those condensers tend to cause a phase shift of 90 degrees at very low frequencies but that tendency is overcome by the shunting of each condenser by one of the resistances 10, 25 and 31, and the tendency of the curve to extend into the first quadrant and to enclose the point 1 is prevented.

The behavior of the curve in the range from f_2 to f_4 and for some distance beyond, is caused by the presence of the network that is located between the first and second stages of the amplifier which network resembles a low-pass filter. If the filter structure comprised merely the inductances 11, 12 and 13, and the condensers 14, 15 and 16, there would be a continuous variation in the phase angle with frequency, so that each element of the filter would produce a phase shift approaching 90 degrees at very high frequencies. That would cause the curve to surround the point 1 and produce a condition of instability. By connecting the resistances 17, 18 and 19 in shunt with their corresponding inductances, and also by connecting the resistances 20, 21 and 22 in series with their corresponding condensers 14, 15 and 16, the phase shift at very high frequencies is zero, and consequently, there results a condition such as is shown in Fig. 2 in the neighborhood of f_4. The performance of the curves at frequencies around f_5 and at higher frequencies is caused principally by distributed capacity. This effect cannot be eliminated by devices used in connection with the low-pass filter, and therefore for those very high frequencies the curve will surround the origin. It is desirable to point out that it is inevitable to have the condition shown at f_5 which may result in singing if the gain is increased sufficiently. However, a low-pass filter having the characteristics hereinbefore described, introduces great losses at the frequency f_5 and therefore postpones the condition of instability until the gain of the amplifier is made very large. It is to be understood, however, that the number of sections of the filter may be increased indefinitely.

It is usually considered preferable, in regenerative amplifiers of this sort, to make the resistances in the plate circuit of the last tube form a Wheatstone bridge with the plate impedance so that the feed-back will not be affected by changes in the impedance connected to the output transformer. The elements 5, 6 and 7 form part of a similar bridge at the input.

While this invention has been disclosed as embodied in a certain arrangement, it is to be understood that such arrangement is purely schematic and that the invention is capable of embodiment in other and different forms without departing from the spirit and scope of the appended claims.

What is claimed is:

1. A regenerative amplifier comprising a network including reactances made up of series and shunt elements, the series reactance elements having resistances in shunt therewith and the shunt reactance elements having resistances in series therewith, an amplifying element connected to said network, and a feed-back connection between said amplifying element and said network.

2. A regenerative amplifier comprising a low-pass filter including coils and condensers in series and in shunt respectively, the series elements having resistances in shunt therewith and the shunt elements having resistances in series therewith, and amplifying element connected to said filter, and a feed-back connection between said amplifying element and said filter.

3. A regenerative amplifier comprising a plurality of amplifying elements, a condenser shunted by a resistance connected in series between adjacent amplifying elements, a low-pass filter including series inductance coils and shunt condensers connected between two of said amplifying elements, each of said coils having a resistance in shunt therewith, and each shunt condenser having a resistance in series therewith, and a feed-back connection between the output of the last amplifying element and the input of the first amplifying element.

4. A circuit as defined by claim 1 in which the parts are so proportioned that the locus of the points representing magnitude and phase angle of the feed-back ratio for frequencies between zero and infinity shall be a curve such that a straight line drawn from any point on this curve to the point representing unity feed-back ratio and zero angle shall generate a total angle of zero as the straight line rotates about the said unity point as a pivot with its other end following the curve from zero to infinite frequency.

5. A regenerative amplifier comprising an odd number of vacuum tubes, a condenser shunted by a resistance in series between adjacent tubes, a low-pass filter including series inductances and shunt condensers connected between two of said tubes, each of said inductances having a resistance in shunt therewith, and each shunt condenser having a resistance in series therewith, and a feed-back connection including a condenser shunted by a resistance between the output of the last vacuum tube and the input of the first vacuum tube.

6. A regenerative amplifier comprising an odd number greater than unity of vacuum tubes, means coupling the output of each tube to the input of the next succeeding tube, a feed-back circuit connecting the output of the last tube to the input of the first tube, the said coupling means between the amplifier stages including means to control the shifting of the phase of frequencies lower than those in the working range of frequencies, and also including means to control the shifting of the phase of the frequencies higher than those in the said working range.

7. A regenerative amplifier comprising a plurality of vacuum tubes, means coupling

the output of each tube to the input of the next succeeding tube, a feed-back circuit connecting the output of the last tube to the input of the first tube, the said coupling means between the amplifier stages including means to control shifting of the phase of frequencies lower than those in the working range of frequencies, and also including means to control the shifting of the phase of frequencies higher than those in the said working range, in such manner that stability of operation is attained with a feed-back ratio that for some frequencies is greater than unity with zero phase shift.

8. The method of stabilizing a regenerative amplifier which consists in adjusting the constants of said amplifier for a given frequency and measuring the feed-back ratio and the phase angle for that frequency, then adjusting said amplifier for another frequency and continuing through a sufficient range of frequencies so that a curve can be drawn from zero to infinity, plotting the resulting measurements, and then adjusting the constants of the amplifier until the locus of the measurements is a closed curve that excludes the point corresponding to unity feed-back ratio and zero angle.

9. The method of stabilizing a regenerative amplifier which consists in opening the circuit at some point, measuring the input and output currents or voltages and their phase difference, plotting the points representing the magnitude and phase angle of the feed-back ratio and drawing the resulting locus of said points from zero to infinite frequency, and adjusting the constants of the regenerative amplifier until the resulting locus of said points constitutes a curve such that a straight line of variable length, rotating with one end as a pivot on the point corresponding to unity feed-back of zero angle, with the other end of the line tracing the said locus curve from zero to infinite frequency shall rotate through a total angle equal to zero.

10. The method of stabilizing a regenerative amplifier which consists in measuring and plotting the feed-back ratio and phase angle for a sufficient range of frequencies, and drawing their locus from zero to infinite frequency, adjusting the constants of the amplifier until the locus has such a path that a point traveling over the locus from zero to infinite frequency, and always joined by a straight line to the point of unity feed-back ratio and zero angle as a pivot, will cause said line to turn through a total of zero.

In testimony whereof, I have signed my name to this specification this 30th day of April, 1930.

HARRY NYQUIST.