

June 16, 1942.

W. VAN B. ROBERTS

2,286,377

FREQUENCY MODULATION RECEIVER

Filed Aug. 31, 1940

2 Sheets-Sheet 1

Fig. 1.

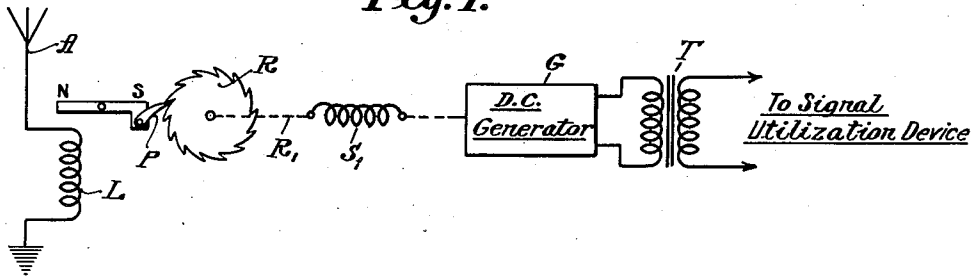


Fig. 2.

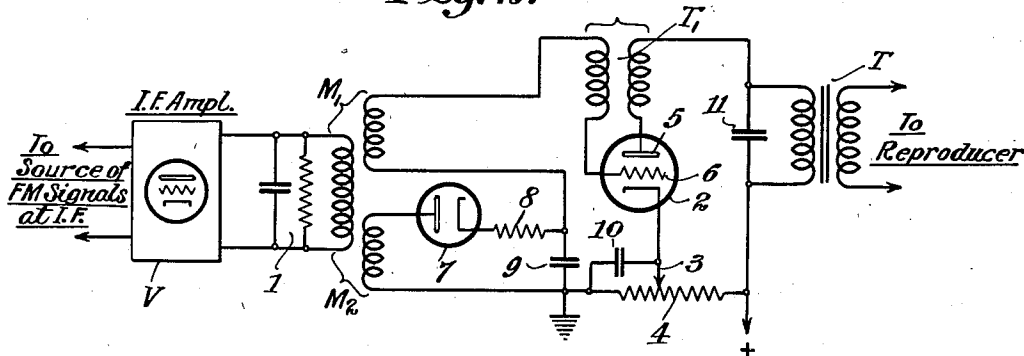
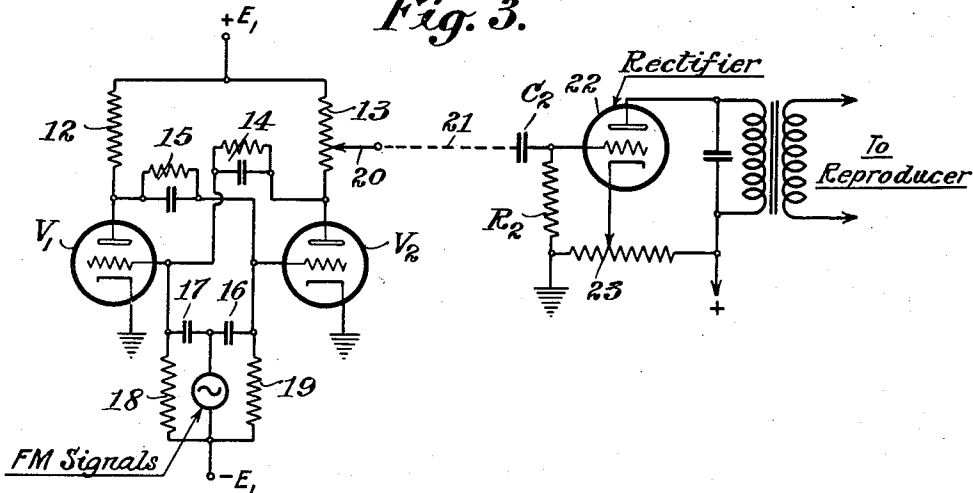


Fig. 3.



INVENTOR
Walter van B. Roberts
BY *H. S. Grover*
ATTORNEY

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2 Sheets-Sheet 2

Fig. 4.

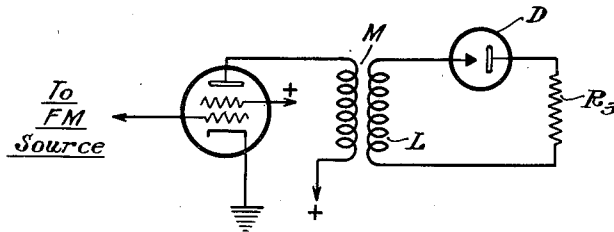


Fig. 5.

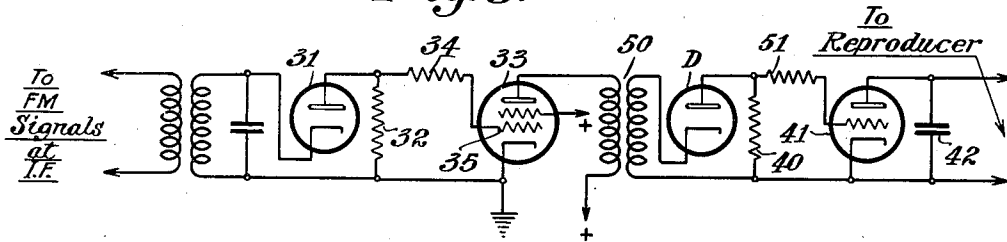
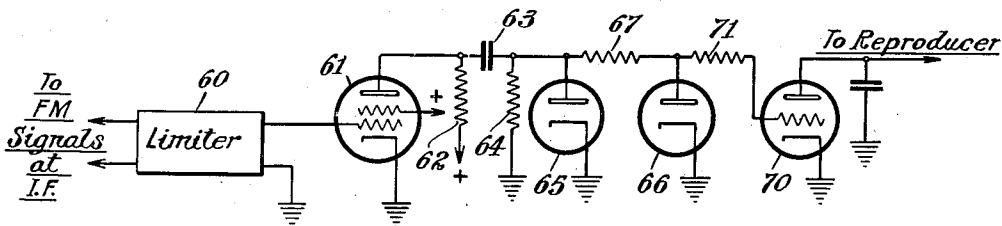


Fig. 6.



INVENTOR
Walter van B. Roberts
BY
H. S. Snow
ATTORNEY

UNITED STATES PATENT OFFICE

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FREQUENCY MODULATION RECEIVER

Walter van B. Roberts, Princeton, N. J., assignor
to Radio Corporation of America, a corporation
of Delaware

Application August 31, 1940, Serial No. 354,982

3 Claims. (Cl. 250—27)

My present invention relates to reception of frequency modulated waves (FM), and more particularly to novel FM detectors.

The method used heretofore for the demodulation of FM signals has been to pass the signals through a limiter device to eliminate so far as possible any variations of amplitude, and then to impress the varying frequency-constant amplitude signals upon a frequency discriminator network whose output voltage varies in amplitude in accordance with the instantaneous frequency of the signal, and finally to detect the resulting amplitude modulated signal in the usual fashion and with whatever non-linear distortion inheres in the particular amplitude modulation detector employed. In addition to this detector distortion the said method is subject to distortion which may result from any lack of linearity in the relation between the frequency modulation of the original signal and the amplitude modulation produced by the discriminator network. Furthermore, exact tuning of the system is more difficult, especially when the modulation is low, than in the case of amplitude modulated signals, and limiter devices as used in FM receivers up to the present time are less than ideal in their operation so that the effects of undesired amplitude modulation on the original signals are not entirely eliminated.

The present invention provides means for demodulating FM signals without any of the aforesaid drawbacks, and is based on the concept of releasing a fixed amount of electrical charge for each signal wave regardless of its amplitude, the successively released quanta of charge constituting an average flow of current which is necessarily and exactly directly proportional to the wave frequency. Hence the alternating component of this current is an exact reproduction of the frequency modulation of the signal.

It may be stated that it is one of the main objects of the present invention to provide a method of, and means for, demodulating frequency modulated signals which comprises producing from each wave thereof a fixed quantum of charge which is substantially independent of the wave amplitude for waves above a threshold value of amplitude, combining said quanta to form a current having an average value proportional to wave frequency, and utilizing the alternating component of said average value.

The novel features which I believe to be characteristic of my invention are set forth in particularity in the appended claims; the invention itself, however, as to both its organization and

method of operation will best be understood by reference to the following description taken in connection with the drawings in which I have indicated diagrammatically several circuit organizations whereby my invention may be carried into effect.

In the drawings:

Fig. 1 is an explanatory diagram to illustrate the basic operation of the invention,

Fig. 2 shows an embodiment of the invention,

Fig. 3 illustrates a modification,

Fig. 4 shows a further modification,

Fig. 5 is a circuit diagram of an embodiment based on Fig. 4,

Fig. 6 illustrates a modification of the arrangement in Fig. 5.

Before disclosing means for carrying out the method of the present invention in actual practice, it may be helpful to explain the basic nature of the invention in more detail by reference to Fig. 1 wherein is shown a simplified and idealized arrangement. The latter, however, is not suitable in the form shown for the demodulation of signals involving frequencies as high as ordinarily used in radio signalling. It is merely explanatory in nature. Fig. 1 shows a signal wave pick-up device, such as a grounded antenna A from which signal waves are passed through a coil L whose magnetic field attracts or repels the north pole N of a permanent magnet M according as the current through L is passing in one direction or the other at the instant in question. Thus, the end N of the magnet M will be pulled down once during each half wave of signal picked up by A, and pushed back up by the reverse half of the signal wave. Magnet M is centrally pivoted so that each time its north end is pulled down, its south end rises and by means of pawl P moves a ratchet wheel R one tooth. It will be seen that provided the amplitude of the incoming signal wave is greater than the threshold value required to operate the ratchet, the wheel R is moved one notch and only one per arriving signal wave, regardless of the amplitude of the wave. Thus, the average speed of rotation of wheel R is strictly proportional to the frequency of the incoming signal wave. Wheel R in turn drives a direct current generator G through a mechanical coupling device R₁, shown in dotted lines, which absorbs the intermittency of the motion of wheel R so that the speed of rotation of generator G is the average speed of wheel R. The coupling R₁ includes a spring S₁ and may be of any well known construction.

Spring S is stiff enough so that relatively slow variations of the average speed of R, which constitute the frequency modulation of the arriving signal wave, are not absorbed. The generator G may be imagined as of the magneto type whose output current is directly and accurately proportional to its speed, so that the output current varies strictly linearly with the frequency modulation of the signal wave. As the signal frequency varies about a mean value, the generator output similarly varies about a corresponding mean value. Hence, the output current may be passed through the primary of a transformer T so that a signal utilization device receives from the secondary winding of T only the alternating component of the varying direct current. The latter component corresponds to the frequency modulation of the signal.

In order to carry out the method illustrated by Fig. 1 in a manner adapted to high frequency signalling the escapement mechanism, including M, P and R, of Fig. 1 is replaced by an electron discharge device circuit adapted to generate a quantum of electric charge for each arriving wave. Spring S₁ is replaced by a low pass filter designed to absorb wave frequency variations from the current constituted by the successive pulses of charge, while not absorbing the relatively slow variations of average current which constitute the demodulated signal. No counterpart for generator G is then required as the varying current produced by the signal is adapted to energize a loudspeaker, or amplifier, without being converted to a different form of energy.

Fig. 2 illustrates an embodiment of the invention wherein a form of relaxation oscillator is used as the escapement mechanism. In Fig. 2 it is assumed that frequency modulated waves of high frequency have been converted to FM waves of much lower frequency by the usual superheterodyne converter network followed by intermediate frequency (I. F.) amplification. It is also assumed that automatic volume control (AVC), and preferably some limiter action in one of the amplifier tubes, is also employed, although this limiter action is not absolutely necessary. Thus, the tube V may be considered for the present purposes as a source of FM signals of relatively low frequency and of fairly constant amplitude. Tube V may be the final I. F. amplifier. These signals are impressed by way of a broadly tuned circuit 1 upon a relaxation oscillator including a back-coupled tube 2.

Tube 2 has its plate 5 reactively coupled, as at T₁, to its control grid 6. The tuned circuit 1 is reactively coupled, as at M₁, to grid 6. The reactive coupling M₂ applies signal energy to diode 7. The cathode of diode 7 is connected to its anode by a path including resistor 8, condenser 9 and the secondary winding of coupling M₂. Condenser 9 is in series with the secondary winding of M₁. The tap 3 is by-passed to ground by condenser 10. The plate 5 of oscillator tube 2 is connected to the positive terminal of potentiometer 4 through the primary winding of transformer T, the winding being by-passed by condenser 11. The secondary winding of the transformer may feed any desired type of reproducer, one or more amplifiers being employed between them if desired. Tube 2 is biased well beyond cut-off by proper adjustment of tap 3 on the potentiometer.

When a sufficiently strong signal wave emanates from V to drive the grid 6 in the positive direction far enough to start any small flow of

plate current, this increasing plate current reacts by way of transformer T₁ upon the grid to make it still more positive. This process builds up until the plate current reaches saturation. Then, since it is no longer increasing there is nothing to maintain the highly positive grid voltage required to maintain the saturated plate current condition, so the plate current begins to fall. The process of feedback is then reversed, and the sudden cutting off of plate current drives the grid to a high negative potential leaving the plate current entirely cut off. It might be thought that since the above described cycle of events is completed in a very short time, the positive voltage impressed through M₁ would still be effective to start another similar cycle. This, however, is avoided by the insertion of condenser 9 which traps the large negative charge drawn by the grid during the time the grid was driven to the aforesaid high positive potential.

Thus, after the cycle is completed the grid returns not to its original potential, but to a potential so much beyond the cut-off value that no signal voltage permitted by the assumed AVC and/or limiter action is sufficient to "trip" the oscillator again until the excessive bias has been removed. This excess bias may be removed by a simple leak across the condenser 9, the leak being so adjusted that the bias does not leak off rapidly enough to permit the same positive wave applied to the grid to trip the oscillator more than once, yet letting the bias leak off in time to permit the succeeding positive wave (or the second or third etc., succeeding wave) to trip the oscillator. However, in accordance with one feature of the invention, an improvement over the aforesaid simple leak across condenser 9 is achieved by connecting diode 7 in series with leak 8. The diode is so poled as to permit the leakage current to pass, and the applied signal wave voltage is of such polarity as to oppose the said leakage during the half wave period during which the signal voltage impressed on the grid is positive. This leakage controlling voltage is introduced by way of mutual inductance M₂. On the one hand it insures that the excess bias produced by the first cycle of the oscillator, which is started by a positive half wave of signal voltage on its grid, will not leak off during the remaining portion of this half cycle. On the other hand, it accelerates the leakage of this excess bias during the half cycle of signal wave during which the grid is driven in the negative sense, and thus insures that the oscillator will be properly "cocked" in readiness to be triggered by the next positive impulse in its grid.

To recapitulate, the net result of the arrangement is that once, and only once, per cycle of signal voltage, the oscillator plate current rises from zero to saturation and falls to zero again as a function of time. This function is determined by the circuit constants, and is substantially not affected by the relatively very small magnitude of the voltage pulse which triggers off the relaxation cycle. Thus, at each cycle a definite constant amount of negative charge is caused to pass to the plate from the space within the tube, and the succession of such quanta of charge constitutes a plate current whose average value is directly proportional to the prevailing signal wave frequency. This current is passed through the primary of transformer T, across which the small condenser 11 is connected to absorb the wave frequency variation. Hence, the audio utilization device, such as a telephone receiver or other re-

producer, is acted upon only by the alternating component of the plate current which corresponds to the frequency modulation of the incoming signals. At this point it may be noted that in the present system it is advantageous to employ a low value of mean I. F. since for a given frequency swing the variation of the direct current produced by the liberation of one charge quantum per wave will have an alternating component which bears the same relation to the direct current component as the frequency swing does to the mean frequency. However, the I. F. should be chosen high enough so that the minimum instantaneous frequency is high compared to the maximum modulation frequency.

Other forms of relaxation oscillators may equally well be employed. Fig. 3 shows an arrangement employing an oscillator known in counters for cosmic rays and the like. This known circuit is that portion of the figure to the left of the dotted line. The two tubes V_1 and V_2 have the plates thereof connected through resistors 12 and 13 respectively to a common terminal to which the direct current potential E_1 is applied. The grid of V_1 is connected to the plate of V_2 by a parallel condenser-resistor network 14. The grid of tube V_2 is connected by condenser-resistor network 15 to the plate of tube V_1 . The FM signals are applied to the grids through condensers 16 and 17. The grids of tubes V_1 and V_2 are connected to the negative terminal of E_1 . The signal source is connected between the junction of condensers 17 and 16 and the $-E_1$ terminal. The cathodes of the tubes are at ground potential. Potential developed across resistor 13 is tapped off by a slidable tap 20, and after transmission through any desired transmission line 21 (shown as a dotted line) is applied to rectifier tube 22 across network C_2-R_2 . The rectifier tube is energized from a direct current voltage potentiometer 23. The cathode of tube 22 may be adjusted to a point on potentiometer 23 such that the grid of tube 22 is biased to cut-off.

In this circuit, the constants being suitably chosen, there are two stable conditions; one being with plate current entirely cut off in one of the tubes V_1-V_2 and the current in the other tube's plate resistor being substantially the maximum that can be caused to flow by the impressed voltage E_1 . The other stable condition is similar, but with the tubes interchanged. It has been found that an input alternating voltage will cause a switchover, from one of these two stable conditions to the other, once and only once per cycle of input voltage. As a result, the potential at the plate of V_2 , for example, varies in a somewhat square wave fashion between limits determined almost solely by circuit constants and with a frequency integrally related to that of the input voltage. In accordance with the invention, the potential at the plate of V_2 may be impressed by way of line 21 upon the series combination of C_2 and R_2 .

Now, if the duration of the constant potential portions of the square wave of potential at the plate of V_2 is sufficient to permit conditions to reach a steady state, a charge equal to the capacity of C_2 multiplied by the potential change at the plate of V_2 will flow through resistor R_2 at each half cycle of said change. Thus, the time integral of current through R_2 per cycle of input voltage is constant. The rectifier 22 is associated with R_2 to eliminate the effects of voltages in one direction. The rectifier is a tube biased to cut-off so that voltage drops in one direction

cause pulses of plate current while drops in the other direction do not. Thus, the average plate current is directly proportional to the prevailing frequency of the FM input signals. For the purpose of FM detection the input voltage is, of course, the amplified, and preferably limited, I. F. signals assumed in connection with the circuit of Fig. 2.

It is, of course, possible to connect another circuit, similar to that to the right of the dotted line of Fig. 3, to the plate resistor 12 of V_1 , and to combine the outputs of the two rectifiers for the purpose of obtaining increased output. Also, since the circuit to the left of the dotted line 21 happens to be one designed to give plate potential alternations in either one of the tubes at half the frequency of the input voltage, it is possible to utilize the potential variations of either plate to operate another similar system, and so on, so as to permit operating the detector portions of the system at as low a frequency as desired.

Still another type of relaxation circuit suitable for use in my invention is disclosed in my pending application Serial No. 310,115, filed December 20, 1939. This arrangement need not be discussed in detail as it will be obvious to those skilled in the art how it may be substituted for the arrangement shown in Fig. 2. In like manner it will be sufficient merely to mention that a switching back and forth between two stable conditions, as employed in Fig. 3, may be achieved in a dynatron circuit wherein the presence of more than a critical value of dynode resistance the dynode potential may be swung from a high stable value to a low stable value, or vice versa, in a "snap switch" manner by the application of a signal voltage greater than a necessary threshold value in the dynode circuit.

In the arrangements hitherto discussed, the signal voltage has functioned merely to trigger off some device which then acts independently of the signal to generate a fixed quantum of charge at each cycle of operation. In what is to follow, on the other hand, the signal wave itself generates the necessary fixed quantum of charge per cycle by virtue of a limiting action in combination with circuit means for deriving a fixed quantum of charge from a flat-topped wave. It should be emphasized at the outset that a limiter may be entirely satisfactory for the present purpose, and yet not be entirely satisfactory for previous methods of FM reception. For example, if a "perfect" limiter, (that is, one which chops the peaks off of waves so that the peaks of the output waves of the limiter are all of equal magnitude regardless of input so long as the input is above a threshold value) is used to feed a resonant system, the voltage developed in the resonant system will not be independent of the amplitude of the limiter input. This is true because the fundamental frequency component of the limited wave is a function not only of its peak value, but, also, of its wave form and hence of its amplitude prior to being limited. In contrast to this unfortunate result it will now be demonstrated that a quantum of charge may be developed from a flat-topped, limited wave, which quantum is independent of the wave form provided certain precautions are taken.

Fig. 4 shows a screen grid tube arranged to transmit a limited wave of current to the output circuit; that is, a current whose value is limited to a fixed magnitude i_1 for a portion of its cycle, then changes in an arbitrary fashion to a second fixed value i_2 which is held constant for an-

other portion of its cycle, then changes back again in an unknown fashion to the first limiting value i_1 . Let us see what happens when the current changes from i_1 to i_2 . Neglecting for the moment the presence of the rectifier D the circuit equation is:

$$R\dot{q} + L\ddot{q} = M\frac{di}{dt} \quad (1)$$

where i is the primary current, $\dot{q}$ is the secondary current, and $\ddot{q}$ is the time derivative of $\dot{q}$. Integrating we have:

$$\int_{t_1}^{t_2} \ddot{q} dt = \frac{M}{R}(i_2 - i_1) - \frac{L}{R}[\dot{q}]_{t_1}^{t_2} \quad (2)$$

where

t_1 is an instant at which $i = i_1$ and

t_2 is an instant at which $i = i_2$

Now, if t_1 is taken as an instant prior to which i has been constant and equal to i_1 sufficiently long so that $\dot{q}$ is substantially zero at t_1 , and if t_2 is similarly so chosen that $\dot{q}$ is substantially zero at t_2 , the last term of the integrated equation vanishes. The left hand term is the displacement of charge around the secondary circuit in the interval between t_1 and t_2 . Hence, we have the result that a quantum of charge equal to

$$\frac{M}{R}(i_2 - i_1)$$

is moved in the secondary circuit, and this quantum is determined solely by the limiting value of the limited current wave and not by the wave form according to which the current passes from one limiting value to the other.

Of course, this result is based on the assumptions stated, which may be described from a more physical point of view by stating that the time constant L/R must be sufficiently small so that the system attains a steady state condition during the time the primary current i remains constant at each limiting value. It is now pointed out that rectifier D will prevent any backwards displacement of charge in the secondary circuit, so that each cycle of the limited voltage will cause a fixed charge displacement in the same direction through R_3 . Thus, the average current through R_3 is

$$F\frac{M}{R}(i_2 - i_1)$$

and the average voltage across R_3 , is, therefore, $FM(i_2 - i_1)$ which is directly proportional to the frequency F of the limited current wave. This voltage may then be amplified by a vacuum tube, and the alternating component of average plate circuit impressed on a loudspeaker.

Fig. 5 shows a complete circuit of the type analyzed in connection with Fig. 4. Signal voltage at I. F. is impressed on a diode 31 which permits only negative half waves of voltage to occur across resistor 32, i. e., with a polarity such as to drive the screen grid tube 33 toward cut-off. Resistor 34 helps prevent the grid 35 being driven positive by any capacity across the diode 31. Thus, the plate current of this tube has a constant normal value throughout one half cycle, while it is zero for a time which is variable but is a considerable portion of the other half cycle for all amplitudes of signal wave above a certain threshold level. The output of the combination of diode 31 and screen grid tube 33, which constitutes the limiter shown here as illustrative, is impressed on the circuit described in

connection with Fig. 4. The average voltage across resistor 40 is FMi_0 , where i_0 is the normal plate current of the screen grid tube. This voltage across resistor 40 is impressed on a following amplifier tube 41, preferably with negative polarity, so as to make any other bias unnecessary, and the output is utilized to operate a reproducer. A small condenser 42 may be shunted across the reproducer to absorb wave frequency variation of the amplifier plate current. The plate circuit of tube 33 is coupled as at 50, to the rectifier D. The anode of the latter is connected by resistor 51 to the grid of amplifier 41.

It will be understood that any other form of limiter may be substituted for the one shown, provided that its output current is approximately "square wave" in nature. Also, an auto-transformer may be used in place of the transformer shown in the limiter output circuit, and the required rectification of the alternating quantum of charge displacement may be effected in various ways, including the use of a grid-biased detector. Finally, it should be pointed out that any arrangement operating in the manner of the system shown at the right of the dotted line of Fig. 3 may, also, be employed to follow a limiting device supplying a limited voltage wave as well as in connection with the generator of square voltage waves shown at the left of Fig. 3.

In Fig. 6 there is shown such a combination. Here the limiter 60, schematically represented, feeds the limited FM signals to the input electrodes of screen grid amplifier tube 61. The plate circuit of tube 61 includes a resistor 62. The plate end of resistor 62 is coupled by condenser 63 to the upper end of resistor 64. The diode 65 is connected between the upper end of resistor 64 and its grounded end. A second diode 66 has its anode connected to the anode of diode 65 through resistor 67, while the anode of diode 66 is further connected to the input grid of amplifier tube 70 through resistor 71. The cathodes of diode 66 and tube 70 are at ground potential. The plate circuit of amplifier tube 70, properly by-passed, may feed the detected audio voltage to any desired type of reproducer.

The plate resistor 62 develops a square wave of voltage, while condenser 63 has pass through it a definite quantum of charge at each half cycle of the square wave voltage. The resistor 64 develops a voltage from the passage of the aforesaid charge in one direction, and amplifier tube 70 is energized by this voltage. The pair of diodes 65-66 are arranged in combination with resistors 67-71 to form a "polarity filter" to permit the transfer of negative potential pulses from resistor 64 to the amplifier, but to suppress positive potential pulses. The amplifier output is similar to that shown in Fig. 4. In Fig. 6 the constants are again so chosen as to permit the system to assume steady state conditions within the time during which the flat-topped plate potential wave stays constant at a limiting value. If E is the maximum potential change across 62, and F the frequency of the limited wave, then the charge displacement per cycle is CE (where C is the capacity of 63), and the average current through resistor 64 is FCE . The average voltage impressed on the final amplifier grid is $FCER$, where R is the resistance of element 64. The rectifying arrangement shown in Fig. 6 has been made different from that shown in Fig. 3 for the sake of variety, as it is well to emphasize that various types of rectifying circuits may be employed.

While I have indicated and described several systems for carrying my invention into effect, it will be apparent to one skilled in the art that my invention is by no means limited to the particular organizations shown and described, but that many modifications may be made without departing from the scope of my invention, as set forth in the appended claims.

What I claim is:

1. In a receiver of the type wherein high frequency waves modulated in frequency to a wide frequency deviation in accordance with audio frequency modulating voltage are converted to intermediate frequency waves of frequency which is low compared to said high frequency, but higher than the maximum deviation of frequency of said high frequency waves, means, including a high vacuum electron discharge device characterized by continuous control of its output current by its input voltage, for producing, from such of said intermediate frequency waves as exceed a predetermined amplitude, amplitude limited waves, each of the limited waves having a substantially fixed difference between maximum and minimum values of intensity and each having at least one extremum of intensity which remains substantially constant throughout a large portion of the half-period of said limited wave, a resistance element, a reactance coupling element for impressing said limited waves upon said resistance element, the time constant of the combination of said resistance and reactance elements being substantially less than the duration of said constant intensity portion of said limited wave, means for smoothing out current pulses in said resistance produced by changes in intensity of said limited waves to said extremum of intensity from the opposite extremum, indicating means for said smoothed out pulses, and rectifying

means for preventing current pulses in said resistance, produced by changes in intensity of said limited waves from said extremum of intensity to the opposite extremum, from affecting said indicating means.

2. In a demodulator for frequency modulated waves, means to produce in a first circuit, from said frequency modulated waves, limited current waves each having a substantially constant current portion whose duration is a large portion of the half-period of said waves, a second circuit including in series an inductance and a resistance, the time constant of said second circuit being less than said duration, mutual inductance means coupling said first and second circuits, a rectifier arranged to be responsive to current in said second circuit, low frequency amplifying means for amplifying the output of said rectifier, and an indicating means for the output of said amplifier.

3. A demodulator for frequency modulated waves comprising an amplifier, a high vacuum electron discharge limiting device characterized by an output which is a continuous function of the input thereto, connections for impressing said frequency modulated waves on said amplifier, means for impressing the output of said amplifier upon the input of said limiter device, a first resistance arranged to be traversed by the limited wave output of said limiter, a condenser and a second resistance connected in series with each other, the series combination being connected in shunt to said first resistance, the time constant of said condenser and second resistance being substantially less than the half-period of said limited waves, rectifier means associated with said second resistance and amplifying and indicating means connected to the output of said rectifier.

WALTER VAN B. ROBERTS.