SECTION 21

CONTROL CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

AGC (AVC) CIRCUITS.

Automatic gain control, AGC, frequently referred to as **automatic volume control**, AVC, is a control circuit that automatically changes the over-all gain of a receiving system in a manner which is inversely related to the strength of the received carrier signal. The terms **AGC** and **AVC** have been used interchangeably for several years, and some confusion has resulted from this practice. The exact use of one or the other term is determined principally by the type of circuit(s) being controlled or by the type of useful output obtained from the controlled system.

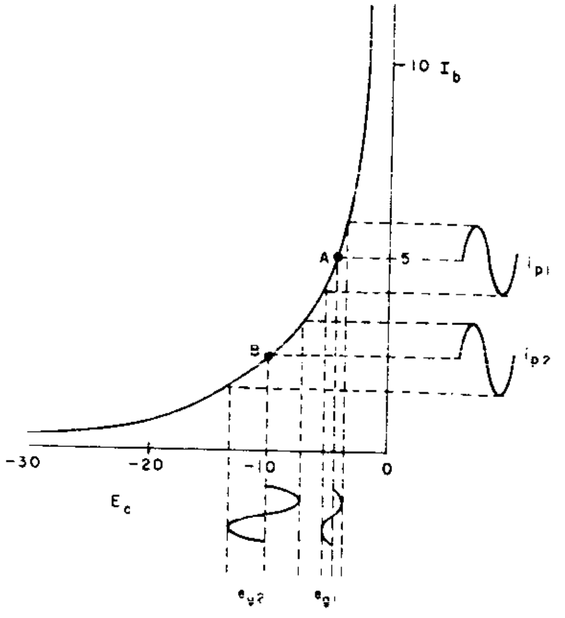
Originally, the circuit was used extensively in radio and communications equipments where the useful output obtained was an audible signal heard in headphones or from a loud speaker; the circuit was therefore called **automatic volume control**. However, basically the same circuit has also been employed to provide automatic control of amplification, or gain, in other electronic equipments. Since these similiarly controlled equipments produce a useful output that does not necessarily result in an audible output signal, the term **volume** does not apply; in this case the term **gain** is technically correct. For example, if the basic circuit is used to control the amplification (gain) of the r-f and i-f amplifier stages in a communications or broadcast receiver, it is frequently still referred to as an **AVC circuit**; on the other hand, if it is used to control the amplification (gain) of the i-f amplifier stages in a radar receiver, or the r-f and i-f stages in a television receiver, it is called an **AGC circuit.** In either example the electronic function is the same--to control an output signal in accordance with the strength of the input carrier signal.

In the paragraphs to follow and throughout this section, the distinction between AGC and AVC will not be made. The term **AGC** (automatic gain control) will be used to designate the circuit that controls useful output, regardless of whether it is in the form of a visual (video) display or similar indication, or an audible signal.

The basic AGC circuit is intended to maintain the output of a receiving system nearly constant within relatively narrow limits, and must do so as the input carrier signal level varies over a considerable range. AGC action is normally accomplished by developing a d-c control voltage which is proportional to the amplitude of the received carrier signal, and then applying this voltage in the form of bias to regulate the gain of one or more remote cutoff amplifier stages within the receiving system.

Remote Cutoff Amplifier Characteristics. Before discussing the operation of a typical AGC circuit, a brief review of the action of a typical remote-cutoff pentode amplifier tube will be given. This review should provide a better understanding of the effect obtained by changing the applied grid bias in accordance with the strength of the received carrier signal.

The accompanying illustration shows the E_c/I_b characteristic curve for a typical remote-cutoff pentode used as an r-f or i-f amplifier, and the effect on plate-current variation caused by a change in control grid bias. When the signal input to the receiver is small (e_{g1}), the developed AGC voltage is low and the plate current variation (i_{p1}) is centered about point A on the illustration. When the signal input to the receiver is large (e_{g2}), the developed AGC voltage increases and the plate current variation (i_{p2}) is centered about point B on the illustration. The plate current variation, i_{p1}, resulting from a small signal input (e_{g1}) to the receiver and the plate current variation, i_{p2}, resulting from a large signal input (e_{g2}) are approximately equal and, in theory, should produce output signals of approximately the same amplitude. Although the relationships given in the illustration are idealized, they serve to show the effect of applying a negative control voltage to an amplifier stage. In actual practice, it is necessary to supply the AGC voltage to several remote cutoff amplifier stages simultaneously in order that the cumulative effect will produce a satisfactory control of signal amplification by the controlled stages.

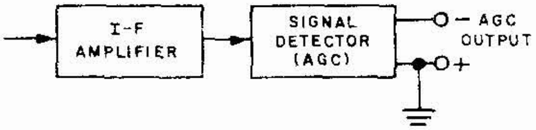


E_c/I_b Characteristic Curve for Typical Remote Cutoff Pentode Amplifier

TYPES OF AGC CIRCUITS.

Automatic gain control circuits vary somewhat because of the over-all gain characteristics required of the receiving system. However, most AGC circuit configurations fall into one of three general classifications: simple AGC, delayed AGC, and amplified and delayed AGC. These three classifications of AGC circuits are described briefly in the paragraphs which follow.

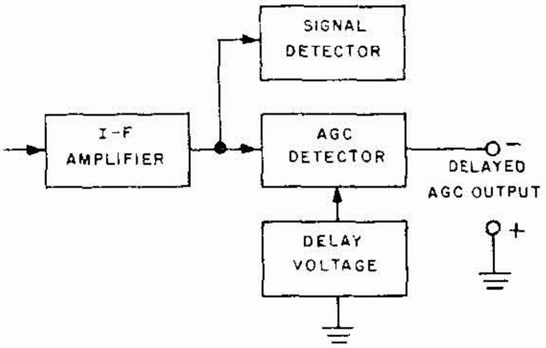
Simple AGC. A simple AGC circuit and a diode-detector circuit (described in Section 11) are very similar in many respects. For this reason, the AGC circuit and the signal detector circuit of a receiving system are frequently combined within a single stage. The accompanying block diagram illustrates a simple AGC system; this AGC system makes use of a negative d-c control voltage obtained directly from the signal detector output, since the rectified voltage produced by the detector is proportional to the amplitude of the received carrier.



Simple AGC System

The resulting d-c voltage obtained from the detector circuit is filtered by an R-C circuit to remove any amplitude modulation components present in the detector output, and is then applied as bias to the control grid of each stage to be controlled in the receiving system. The time constant of the R-C filter is long enough to remove the lowest modulation frequencies from the d-c voltage, but short enough that a change in d-c bias level will respond to moderately rapid changes in received signal strength due to signal fluctuations, fading, etc. The simple AGC circuit is employed in many typical AM superheterodyne receivers which use a diode-type detector; it is also employed in some FM receivers which use a ratio-type detector.

Delayed AGC. The term **delayed AGC** is used to denote a voltage delay, and should not be confused with a time delay. The simple AGC system just described is effective on all received signals, from the weakest to the strongest. It has the disadvantage of developing an AGC voltage even for very weak received signals and, as a result, the sensitivity of the receiver to weak signals is reduced considerably. Therefore, in order to increase sensitivity and enable the receiver to respond to weak signals, it is desirable to provide a means of delaying the application of AGC voltage until the received signal reaches a predetermined value, sometimes called the **threshold level** of AGC. The accompanying block diagram illustrates a typical delayed AGC system.



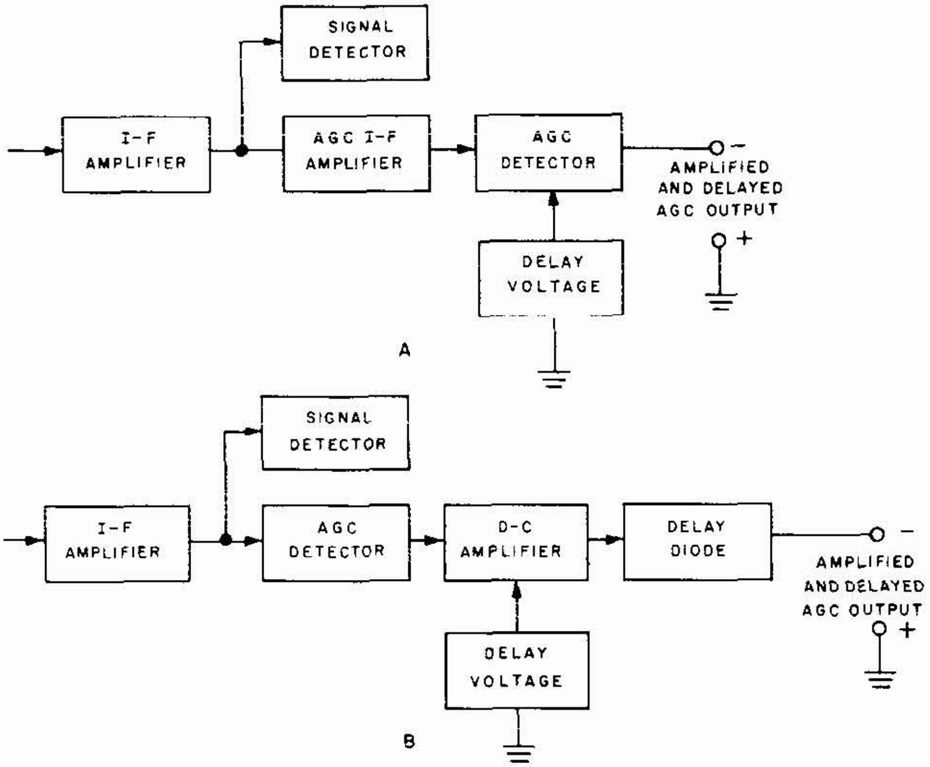
Simple Delayed AGC System

The delayed AGC system makes use of a fixed delay voltage applied to a separate AGC detector. The delayed AGC detector must be a separate diode, independent of the signal detector (demodulator) diode, because the fixed delay voltage prevents the AGC detector diode from rectifying an r-f signal until the signal level exceeds the value of the delay voltage. Thus, if separate diodes were not used, the delay voltage would prevent the detector (demodulator) diode from rectifying weak signals which are below the threshold level established by the value of the delay voltage. Once the signal level rises and exceeds the value of the delay voltage, the AGC detector begins to rectify and produce a d-c output voltage which is applied as bias to the controlled stages. The requirement for filtering of the d-c output voltage to remove amplitude modulation components and the R-C time-constant considerations are essentially the same as for the simple AGC system. The delayed AGC circuit is employed in many AM broadcast, communication, and dual-diversity superheterodyne receivers, as well as in similar microwave and radar receiving systems.

Amplified and Delayed AGC. There are many variations in amplified and delayed AGC systems. However, these various AGC systems can be classified according to two categories: systems which amplify a signal **before** rectification, to obtain the AGC voltage, and systems which amplify the AGC voltage **after** signal rectification. In either case, a form of delay voltage is incorporated so that the maximum sensitivity of the receiver can be realized for weak-signal reception. When amplified and delayed AGC is used to control a receiving system, the over-all output versus signal input characteristics can be made to approach an almost ideal condition.

The accompanying illustration shows block diagrams for two basic types of amplified and delayed AGC systems. Part A of the illustration shows a system in which the signal is amplified by an AGC i-f amplifier **before** rectification by the AGC diode. Part B shows a system in which the signal voltage is amplified by a d-c amplifier **after** rectification by the AGC diode. The d-c amplifier stage is followed by a delay diode which supplies AGC voltage to the controlled stages only when its cathode is negative with respect to its plate, and the diode conducts; when the delay diode is not conducting, the AGC output voltage is zero and the receiver gain is at maximum for all signals below the threshold of AGC operation.

Note that both AGC systems illustrated incorporate a form of delay voltage. In the amplified and delayed AGC system illustrated in part A, the delay voltage is applied to the AGC detector, which follows a separate amplifier; the separate amplifier receives its signal from the last i-f amplifier of the receiving system. Another variation of this AGC system employs an independent AGC amplifier channel consisting of several stages and having a greater over-all amplification (gain) than does the signal i-f ampli-



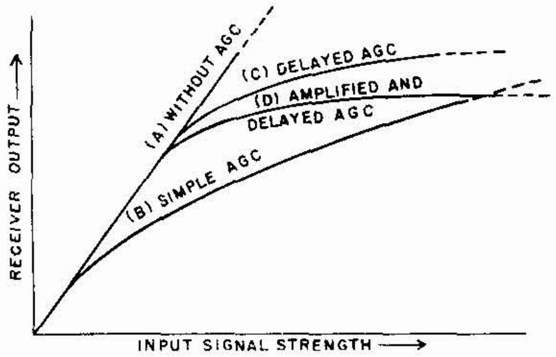
Amplified and Delayed AGC Systems

fier channel. In the AGC system illustrated in part B, the delay voltage is shown applied to the d-c amplifier stage. One possible variation of this circuit applies a delay voltage to the AGC detector as in the circuit for the delayed AGC system shown in part A. In practice, however, almost all AGC circuits using a d-c amplifier to control the AGC voltage employ a delay diode in the output to prevent the d-c output voltage from ever becoming positive with respect to ground.

TYPICAL AGC CHARACTERISTICS.

One of the purposes of the AGC system is to hold the i-f (or r-f) signal input to the detector (demodulator) relatively constant over a considerable range of received signal strength at the input terminals to the receiving system. It was previously stated that a simple AGC system accomplishes control of receiver gain by varying a negative d-c bias voltage applied to the control grids of remote cutoff tubes in the r-f and i-f stages of the receiver. Thus, as the received signal increases, the signal at the detector also increases, resulting in a greater negative d-c voltage available for control purposes. The control (bias) voltage is applied to the early stages of the receiver to reduce the over-all gain. The reduction in receiver gain lowers the input to the detector and, within limits, tends to keep the detector output from rising too rapidly as the input signal increases. However, it is virtually impossible to hold the input to the detector (demodulator) constant, because the AGC voltage is dependent upon the strength of the received signal, which is amplified by the controlled stages of the receiver and rectified by the detector. Thus, an increase in the strength of the received signal means that the rectified output of the detector also increases, and this voltage (or a corresponding voltage) is, in turn, fed back as a control voltage. Therefore, it is reasonable to assume that there must always be some increase in the receiver-output voltage. The rate of increase, however, is determined by the individual circuit design, and desirable characteristics can be attained which approach the ideal characteristic.

The accompanying illustration graphically compares the receiver-output characteristics of typical AGC systems with the characteristic of a receiver using a conventional diode detector without AGC. The plot of receiver output versus input signal strength for a receiver without AGC (curve A) shows that the output rises rapidly for an increase in signal strength; however, the receiver output soon becomes distorted because of overloading which occurs with large input signals. The plot of receiver output for a receiver with simple AGC (curve B) shows that even small input signals are acted upon by the AGC voltage, and, as a result, the output obtained from weak signals is reduced. The plot of receiver output when delayed AGC is used (curve C) shows that the output for small input signals closely follows the output obtained when no AGC is used and that, when the input signal reaches some predetermined strength, the output is prevented from rising too rapidly as the input signal is further increased. The plot of receiver output when amplified and delayed AGC is used (curve D) approaches an ideal condition wherein the receiver is sensitive to weak signals and the output is held relatively constant once the input signal exceeds some predetermined strength.

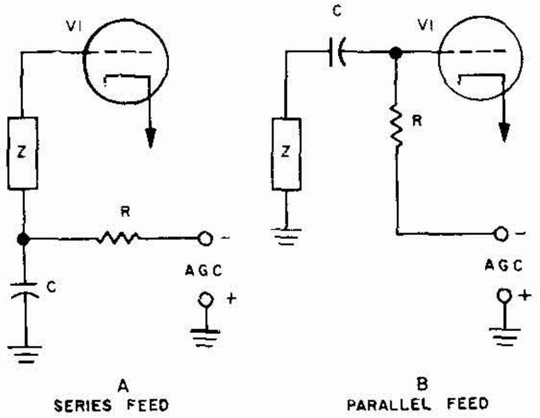


Receiver Output Versus Input Signal Strength

METHODS OF FEEDING AGC-CONTROLLED STAGES.

Two methods are used to feed AGC voltage to the grid of a controlled amplifier tube. These two methods are commonly called **series feed** and **parallel** (or **shunt**) **feed**. In either method, the AGC voltage is actually in "series" between the control grid and the cathode of the controlled tube. The terms **series feed** and **parallel feed** are used for convenience to identify the circuit arrangement which enables the AGC voltage to be applied to the control grid. AGC systems utilize one method or the other in feeding the control voltage to an individual tube. Sometimes, because of resonant circuit design or interstage coupling arrangements, one method is used to feed one stage of the receiver and the other method is used to feed another stage. For example, in a typical VHF superheterodyne receiver, the single r-f amplifier is a parallel-fed stage while the i-f amplifier channel incorporates several series-fed stages.

The series-feed arrangement is illustrated in part A of the accompanying simplified schematic diagram. Impedance Z is normally a tuned circuit, transformer, or other coupling impedance. Resistor R and capacitor C form a decoupling network; in addition, capacitor C must also be considered as a d-c blocking and r-f bypass capacitor for the grid-circuit impedance, Z. The d-c path for the application of control voltage to the grid of the tube is through impedance Z; in other words, the impedance is in "series" with the control voltage.



A
SERIES FEED

B
PARALLEL FEED

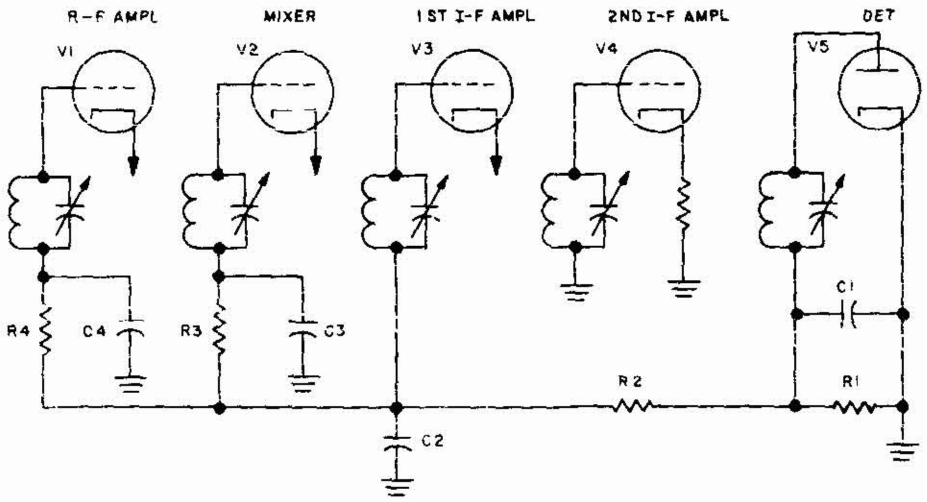
Methods of Feeding AGC-Controlled Stages

The parallel-feed arrangement is illustrated in part B of the accompanying simplified schematic diagram. In this circuit, resistor R is effectively in parallel with impedance Z, and provides a "parallel" (or "shunt") d-c path for the application of control voltage to the grid of the tube. The value of the resistor is usually made high so as not to "swamp" or "load" the impedance; however, the actual value of resistor R together with the other resistors in the series circuit between the control grid and cathode must not exceed the rated maximum grid-circuit resistance recommended for use with the particular type of tube. Capacitor C is a d-c blocking capacitor, and is used to prevent impedance Z from acting as a voltage divider in conjunction with resistor R.

AGC TIME-CONSTANT CONSIDERATIONS.

In a previous paragraph it was mentioned that a d-c control voltage obtained from a detector must be filtered to remove any modulation or alternating component of the rectified pulsating voltage; otherwise, if not removed, the modulation or alternating component would be applied to the controlled stages, along with the d-c voltage. If any modulation component is fed back to the grids of the controlled stages, a degenerative effect occurs and, as a result, the percentage of modulation on the carrier signal being amplified by the controlled stages will be reduced accordingly. Also, this effect may introduce considerable amplitude distortion in the output (demodulated) signal.

An R-C circuit is normally used to filter the d-c control voltage. The design of a suitable R-C filter, of necessity, may be a compromise; the time constant must be sufficiently long to effectively filter out the lowest modulation-frequency component from the control voltage, and the time constant must be short enough to permit a change in d-c control voltage when rapid fluctuations in signal level occur. (Time constants are discussed in Section 2.) Thus, the R-C networks of the AGC circuit influence the ability of the con-



Simple AGC System

trol voltage to follow rapid changes in the strength of the received signal.

A simple AGC system is illustrated in the above simplified schematic diagram. The r-f amplifier, mixer, and first i-f amplifier stages are series-fed and controlled by AGC voltage taken from the detector (demodulator) diode. (The second i-f amplifier stage is self-biased and is not controlled by AGC voltage.) R1 is the detector load resistor and capacitor C1 is the r-f bypass capacitor for R1. Resistor R2 and capacitor C2 form an R-C network to filter the AGC voltage obtained from the detector. Resistor R3 and capacitor C3 form a decoupling network for the mixer stage; similarly, resistor R4 and capacitor C4 form a decoupling network for the r-f amplifier stage.

The time constant of an AGC system will depend largely upon the design of the receiving system and the type of transmissions to be received. Typical values of time constants used in communications work range from 0.1 second to 0.5 second. The time constant of an R-C circuit is given as:

$$TC = RC$$

where:

TC = time in seconds
R = resistance in megohms
C = capacitance in microfarads

However, the typical AGC circuit is usually a complex network, and, because of the action of the detector diode in the circuit, the charge time constant and the discharge time constant of the circuit are not the same. The charge time constant for the AGC system shown in the illustration when the detector diode is conducting and rectified d-c output is developed across load resistor R1 can be expressed as follows:

$$\text{Charge } TC = R2\,(C2 + C3 + C4) + R3C3 + R4C4$$

The discharge time constant for the system when the detector diode is not conducting (or is conducting less) can be expressed as follows:

$$\text{Discharge } TC = (R4 + R2 + R1)C4 + (R3 + R2 + R1)C3 + (R2 + R1)C2 + R1C1$$

Note that the discharge path for the network is not the same as the charge path. Furthermore, because detector-load r-f bypass capacitor C1 is usually a small value, the term R1C1 in the discharge time-constant expression can be neglected because its effect on the over-all time constant is small.

Occasionally, the detector load resistor, R1, is used as a manual volume control for the receiver; the variable contact of the volume control is coupled by means of a capacitor to an audio amplifier stage. When this is the case, the audio coupling capacitor, together with the grid resistor for the succeeding amplifier stage, may have an effect upon the AGC time constant, especially when the volume control is adjusted for maximum volume. Although the effect upon AGC action by the audio coupling capacitor and the grid circuit of the amplifier stage is a design consideration, the effect is usually neglected when making time-constant calculations.

The following example illustrates the difference between the charge and discharge time constants in a typical AGC system. The resistors and capacitors in the simplified schematic given earlier are assigned typical circuit values as follows:

R1 = 1 meg C1 = 0.0001 μf
R2 = 1 meg C2 = 0.05 μf
R3 = 0.1 meg (100K) C3 = 0.05 μf
R4 = 0.1 meg (100K) C4 = 0.01 μf

To calculate the charge time constant in seconds:

$$\text{Charge TC} = R2(C2 + C3 + C4) + R3C3 + R4C4$$
$$= 1(0.05 + 0.05 + 0.01) + (0.1 \times 0.05) + (0.1 \times 0.01)$$
$$= 0.11 + 0.005 + 0.001$$
$$= 0.116 \text{ second}$$

To calculate the discharge time constant in seconds:

$$\text{Discharge TC} = (R4 + R2 + R1)C4 + (R3 + R2 + R1)C3 + (R2 + R1)C2 + R1C1$$
$$= (2.1)0.01 + (2.1)0.05 + (2)0.05 + (1)0.0001$$
$$= 0.021 + 0.105 + 0.1 + 0.0001$$
$$= 0.2261 \text{ second}$$

Thus, from the calculations made above, the charge time constant is found to be 0.116 second and the discharge time constant 0.2261 second. From this example it can be seen that if the discharge time constant is too long and the received signal fades rapidly, the output of the receiver will be reduced until the R-C networks have discharged sufficiently to permit the receiver gain to increase and compensate for the drop in input signal level. This inability of AGC voltage to respond and follow rapid changes in input signal level is called **time delay** (or **time lag**) in the AGC response. The greater the values of R and C, the longer the AGC time constant and the time delay of the AGC system; the smaller the value of R and C, the shorter the time constant and the time delay. However, if the charge time constant is too short, modulation components which are present on the d-c control voltage may cause degenerative effects. (These effects were mentioned earlier in this discussion.) Thus, reducing the values of R and C below some practical minimum for a particular AGC system results in a reduction of filter efficiency; therefore, it is usually necessary to reach some compromise between filter efficiency and time delay in the design of an AGC system.

SIMPLE AGC CIRCUIT.

APPLICATION.

The basic AGC circuit is used in many communications and broadcast receivers and in certain radar and television receivers, to obtain a d-c control voltage which is supplied as an automatic bias for the r-f and i-f stages of the receiver.

CHARACTERISTICS.

D-C control voltage is obtained directly from a detector (demodulator) diode or from an additional diode used as a half-wave rectifier.

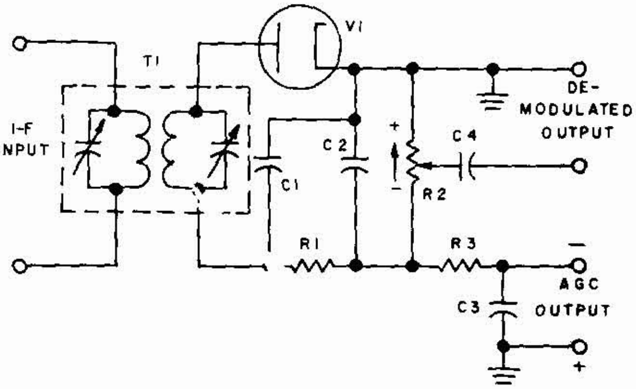
Uses an R-C network as an output filter.

D-C output voltage varies in proportion to r-f input voltage. This circuit has a disadvantage in that weak input signals produce a small output voltage which, in turn, tends to lower over-all receiver sensitivity to weak signals.

CIRCUIT ANALYSIS.

General. The diode detector circuit, described in Section 11, and the diode detector with AGC circuit, described in this section, are very similar. Because of this similarity and because it is a simple matter to add a few components and make use of the detector output as a source of control voltage, the functions of the detector and AGC circuit are frequently combined in a single stage. The rectified voltage produced by the detector (demodulator) diode across its load resistance is proportional to the amplitude of the received carrier; therefore, the resulting rectified d-c output voltage can be used to control the over-all gain of the receiving system. An R-C network is used to filter the pulsating d-c output of the detector and also to remove any modulation component which might be present.

Circuit Operation. A combined detector and AGC circuit is illustrated in the accompanying circuit schematic. (A comparison of this circuit with the typical diode detector given in Section 11 will show that the circuits are basically the same except for the addition of resistor R3 and capacitor C3.) Transformer T1 consists of tuned primary and secondary windings which are resonant at the frequency of the i-f amplifier; T1 is the output transformer of the i-f amplifier channel in a conventional receiving system.



Combined Detector (Demodulator) and AGC Circuit

Electron tube V1 is an indirectly heated cathode-type diode, and may be included within the envelope of a multipurpose tube; the filament (heater) circuit is not shown on the schematic.

Capacitor C1, resistor R1, and capacitor C2 form a low-pass R-C filter network. Potentiometer (variable resistor) R2 is the diode load resistor, and also the manual volume control for the receiver. The setting of potentiometer R2 determines the amplitude of audio output signal which is coupled by capacitor C4 to succeeding amplifier stages. Resistor R3 and capacitor C3 form an R-C network to filter the d-c voltage applied to the controlled stages as automatic bias.

The operation of a typical detector (demodulator) circuit is given in the circuit analysis portion of DIODE DETECTORS, Section 11, and may be reviewed at this time if desired. Thus, for the purpose of this discussion, it is sufficient to say that a d-c voltage which varies in amplitude according to the modulation frequency is developed across diode load resistor R2 whenever a modulated signal is applied to the input of the detector circuit. The polarity of the rectified voltage is given on the simplified schematic diagram.

The R-C network consisting of resistor R3 and capacitor C3 is connected to the junction of resistors R1 and R2. The negative voltage at this point is a d-c voltage with an alternating component which is the result of amplitude modulation present on the r-f signal. The purpose of resistor R3 and capacitor C3 is to remove the modulation components so that a steady d-c voltage is available as a bias voltage for the controlled stages of the receiver.

Assume for the moment that a weak signal is being received. In this case the voltage developed across diode load resistor R2 will be a small voltage, and the resulting AGC output voltage will also be small; therefore, the value of grid bias voltage applied to the controlled stages will be small, and the gain of controlled stages will be reduced only a slight amount.

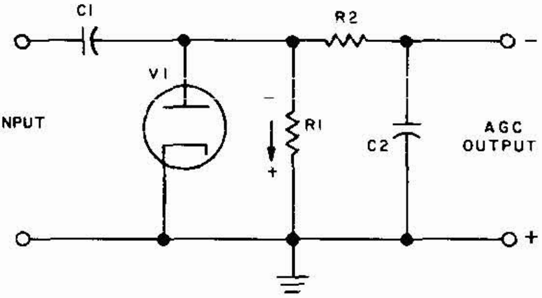
Next, assume that a moderate signal is being received. In this case the voltage developed across diode load resistor R2 will increase in value, and, as a result, the value of grid bias voltage applied to the controlled stages will also increase; thus, the gain of the controlled stages will be further reduced.

Now, assume that a strong signal is being received. In this case the voltage developed across diode load resistor R2 will increase considerably, and, as a result, the bias voltage applied to the controlled stages will also increase; thus, the gain of the controlled stages will be still further reduced.

From the three signal input conditions just described, it can be seen that as the strength of the input signal to the receiver increases, the detector output and the value of the control voltage increase as a result, and, to offset the increase in input signal strength, the over-all gain of the receiver is reduced. Conversely, as the strength of the input signal to the receiver decreases, the detector output and the value of the control voltage decreases as a result, and, to offset the decrease in input signal strength, the over-all gain of the receiver is increased.

The effect of an automatic bias control voltage is to "level out" the response of the receiving system. Thus, the change in receiver output for a given change in input signal is always less with an AGC circuit than it is without an AGC circuit.

A simple AGC circuit which is independent of the detector (demodulator) diode is illustrated in the accompanying schematic; this circuit is a variation of the basic diode detector circuit discussed previously in Section 11. The diode, V1, is not used to demodulate the signal; instead, it is used only as a half-wave rectifier to obtain an AGC voltage which is proportional to the input signal. The diode may be a separate electron tube, or may be included within the envelope of a multipurpose tube. Capacitor C1 is an r-f coupling capacitor, and is normally connected to a relatively high-impedance signal source, such as the plate of the detector (demodulator) diode or the plate of the last i-f amplifier tube. The d-c output voltage is developed across diode load resistor R1 as the result of signal rectification by diode V1. Resistor R2 and capacitor C2 form an R-C network to filter the d-c voltage applied to the controlled stages.



Simple AGC Diode Circuit

The main disadvantage of the two AGC circuits just described is that **all** received signals — including weak signals — will develop AGC voltage. Thus, even a very weak signal will produce a small amount of AGC voltage, causing a reduction in the over-all receiver gain at a time when maximum gain is desired.

FAILURE ANALYSIS.

General. Before suspecting trouble in the AGC circuit, it must first be established that the detector (demodulator) circuit and the r-f and i-f amplifier circuits are functioning normally. Checks must be made to determine whether there are any shorted, leaky, or open components in the R-C networks of the controlled stages (either series- or parallel-fed). Defective components in these networks will affect the AGC voltage distribution, the AGC circuit time constant, and perhaps the resonance and selectivity of the tuned coupling circuits.

No AGC Voltage. The AGC voltage no-output condition is generally caused by a failure in the detector (demodulator) circuit, and is usually accomplished by a lack of detector output. Since the AGC circuit is often a part of the detector circuit, the correct operation of the detector should be determined (as given in Section 11) before investigating the AGC circuit for a possible failure. An exception to this procedure is the case where a diode which is independent of the detector (demodulator) diode is used to obtain AGC voltage. The procedure for failure analysis of the independent AGC diode circuit is essentially the same as the procedure given for the detector (demodulator) diode circuit.

In either the simple AGC circuit or the independent AGC diode circuit, if the output capacitor of the R-C filter network is shorted, the AGC output voltage will be developed across the filter resistor, and, therefore, no AGC voltage will be applied to the controlled stages.

Because AGC circuits are nearly always low-voltage, high-impedance circuits, it will be necessary to use a suitable vacuum-tube voltmeter when making AGC voltage measurements.

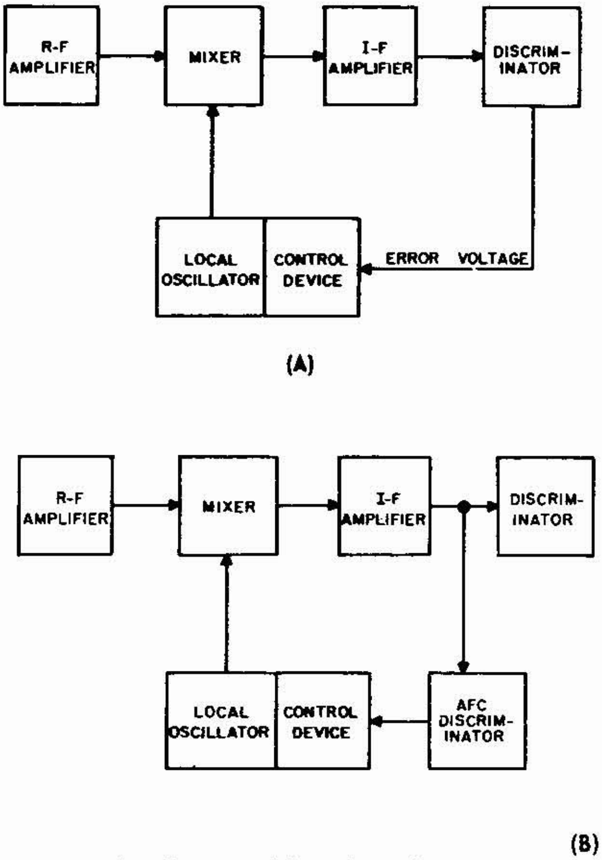
Low AGC Voltage. Low AGC voltage will result in greater than normal over-all receiver gain, and will often cause distortion when a strong signal is received. With a known r-f or i-f signal (either modulated or unmodulated) applied to the input of the receiver or to the input of the detector circuit, a d-c voltage measurement should be made across the diode lead resistor to determine the value of negative AGC voltage present. (AGC voltages should always be measured with a suitable vacuum-tube voltmeter.) A second voltage measurement should then be made at the output terminals of the AGC circuit (across the output capacitor of the R-C filter network) to determine whether the voltage at the output is the same value as the voltage measured at the input to the R-C filter network. If the output voltage measured is less than the input voltage, it is likely that a voltage-divider action is taking place, causing a current to flow in the circuit, with a consequent voltage drop across the filter resistor. In this case, the output capacitor of the R-C filter network may be leaky, or the capacitors, tuned circuits, or other impedances in the controlled stages may have leakage paths to ground (chassis). Measurements may be made throughout the voltage distribution system to determine the points at which voltage-divider action is occurring, in order to further isolate the faulty component. As an alternative, the circuit connection at the output of the R-C filter network, sometimes referred to as the AGC bus, should be disconnected to isolate the controlled stages; the components of the networks associated with these stages should then be checked by means of resistance measurements to locate the faulty component(s) in the voltage distribution system.

AFC CIRCUITS.

Automatic Frequency Control circuits have a wide range of applications in radio, television, and radar. Their purpose is to automatically compensate for any drift in local oscillator frequency, as well as to automatically lock onto the selected frequency once the receiver is tuned to the approximate frequency. Thus, it is the function of afc to compensate for the warmup time of the receiver, during which the receiver is very susceptible to drift, as well as to compensate for any error in the mechanical tuning of the receiver.

Our discussion here will be primarily concerned with afc systems which change the frequency of the local oscillator to compensate for any frequency drift which may occur in the r-f stage of the receiver, and also counteracts any tendency towards a frequency drift in the local oscillator.

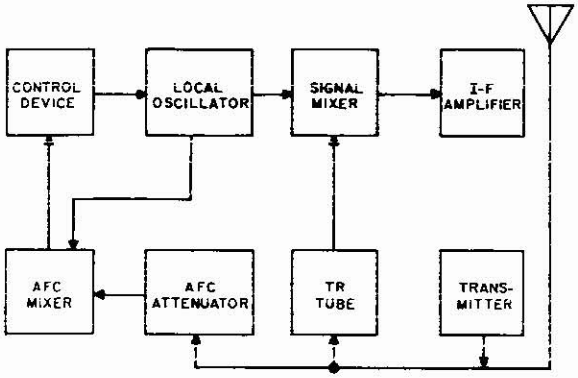
The introduction of afc to a receiver necessitates the employment of one or more additional circuits, consisting essentially of a discriminator and a control device. The function of the discriminator is to change the direction and amount of the frequency error into a corresponding correction or control voltage variation. Many discriminators or detectors employed in f-m receivers are capable in themselves of providing an afc voltage, so it may not be necessary in these cases to add a discriminator to the receiver. This type of afc system is shown in part A of the accompanying illustration. If the receiver detector is not capable of producing an afc error voltage, the addition of an afc discriminator becomes necessary, as shown in part B of the illustration. This error voltage, regardless of how it is obtained, is now applied to the control device, whose function it is to receive the error voltage from the discriminator and change it into a frequency correction for the local oscillator.



Block Diagrams of Typical AFC Systems

If the output of the i-f amplifier is at the proper frequency, it is coupled directly through the discriminator and no error voltage is coupled back to the control device. Thus, the local oscillator frequency remains the same. If the i-f frequency is too high, the error voltage, for example, increases, and provides the necessary adjustment to the local oscillator. Conversely, if the i-f frequency is too low the error voltage, for example, decreases, and provides the necessary adjustment to the local oscillator.

A more refined method of afc contains its own separate mixer. This type of afc is used primarily in radar and thus the receiver employs two converters: one converter is used to mix the echo signal, and the other is used for the afc. A block diagram illustrating such a system is illustrated below.



Block Diagram of Double Mixer AFC

Since the transmitted pulse is used as the frequency sample for the afc mixer in this application, it is not necessary that a TR tube preceed the afc mixer. A fixed attenuator can be used instead, as a protection for the afc circuit. The remainder of the afc operation is the same as that of any other afc system, that is, the mixer discriminator produces an error voltage for application to the control device, and the control device changes the local oscillator frequency as necessary. It should be noted that the local oscillator now supplies two mixer circuits instead of the usual one, but this power requirement is easily attained by the use of a special oscillator tube.

Examples of circuits which may be used as control devices are discussed in this chapter. The particular control circuit chosen is contingent upon the receiver in which the circuit is to be used. The phantastron control circuit, for example, is most commonly used in radar receiver applications because of its sweep voltage characteristics, while for the same reason, it is not used in the standard f-m radio receiver. A control device commonly found in the f-m radio receiver is the reactance tube control device, or the thyratron control device.

PHANTASTRON AFC CIRCUIT.

APPLICATION.

The phantastron afc circuit is used in radar and other electronic equipment to control the local oscillator and maintain the i-f within the receiver passband to minimize the effect of local oscillator or transmitter drift.

CHARACTERISTICS.

Uses a hard tube phantastron oscillator as a search sweep.

Search sweep operates at a rate of about one cycle per second.

Automatically controls the local oscillator repeller voltage to maintain the proper i-f difference frequency.

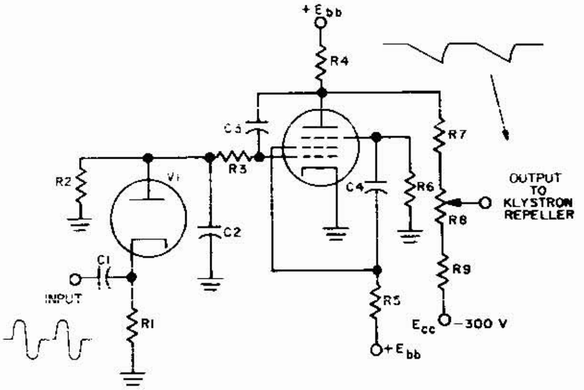
Output may be taken from the cathode, screen, or plate, and be either positive or negative.

Combines a stable multivibrator action with d-c amplifier action in one tube.

CIRCUIT ANALYSIS.

General. The phantastron afc system provides a means of automatically controlling the frequency of a klystron local oscillator. The output of the receiver discriminator is coupled through a pulse amplifier stage to a diode search stopper stage. The phantastron search tube, in the absence of control signals from the search stopper diode, applies a one cycle per second sawtooth wave to the klystron repeller. When the sweeping klystron reaches a frequency which produces the proper output from the discriminator, the search stopper diode applies a blocking bias to the grid of the phanstastron search tube and converts it into a d-c amplifier. Corrections for small frequency changes are then accomplished by the search stopper diode and the d-c amplifier.

Circuit Operation. The accompanying schematic illustrates a typical phantastron-diode afc sweep circuit.



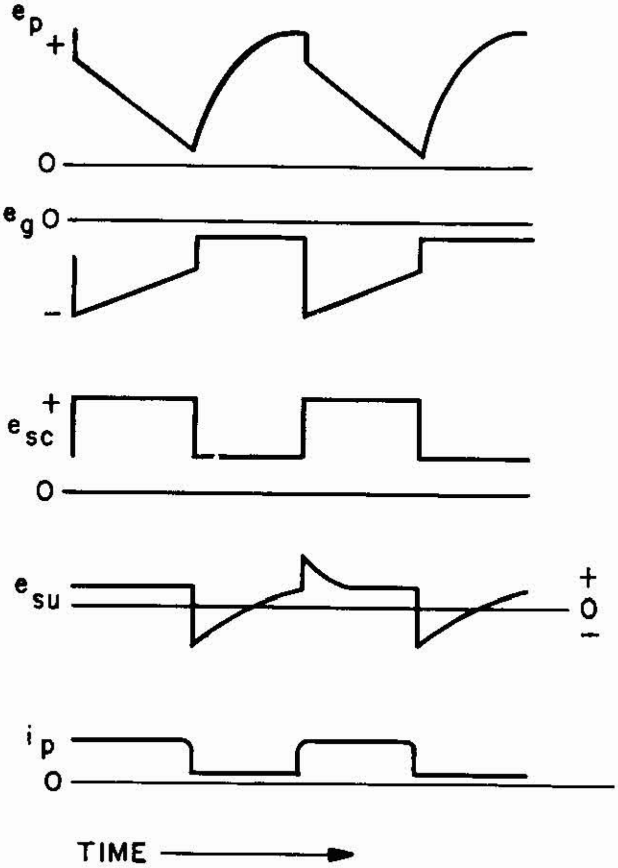
Phantastron AFC Circuit

Only the search sweep tube and the search stopper diode are shown in the schematic, since the discriminator and pulse amplifier used to furnish the afc control pulse are common basic circuits discussed in other sections of the Handbook. Capacitor C1 is the input coupling capacitor with R1 operating as the input coupling resistor and cathode bias resistor for diode V1; it also offers a d-c return path to ground for the diode. Resistor R2 is the diode load resistor across which the rectified afc control pulses develop a d-c bias to charge filter capacitor C2. Resistor R3 couples the search stopper diode direct to the grid of phantastron sweep amplifier tube V2, and incidentally acts as a series filter resistor to eliminate any ripple frequency appearing across C2. Resistor R4 is the phantastron plate load resistor, and R5 is the screen resistor for V2. Capacitor C3 is the plate-to-grid feedback capacitor. Capacitor C4 couples the suppressor of V2 to the screen and also acts as a screen bypass to ground via resistor R6. Resistor R6 serves the dual function of acting as a charging and discharging resistor for C4, and as a ground return resistor for the suppressor of tube V2. The voltage divider network consisting of R7, R8, and R9 is connected between the plate of phantastron sweep tube V2 and the -300 volt repeller supply to the klystron local oscillator. Resistor R8 is a potentiometer to permit manual adjustment of the local oscillator voltage for approximately the proper frequency.

In normal operation, the application of plate voltage to phantastron tube V2 causes the plate to draw current, which decreases the plate voltage abruptly because of the high resistance of R4. This drop is applied through capacitor C3 to the control grid. The control grid voltage will not decrease far enough to cut off the plate current, since the source of voltage is in the plate circuit. The plate voltage e_p now begins to decrease gradually while the control grid voltage e_g of V2 now rises slowly as C3 discharges, causing plate voltage e_p to continue to drop and produce a negative-going output sweep voltage as shown in the accompanying waveform illustration.

Since the plate current of a pentode remains nearly constant over a specific range of plate voltage, the discharge of C3 is fairly linear. When the plate voltage drops sufficiently to reach the bend or knee in the tube E_p - I_p characteristic curve the plate current no longer remains constant and decreases towards zero. Since the cathode current of the phantastron is essentially constant, the screen grid draws the current not being drawn by the plate, and the screen voltage drops. This drop in screen voltage is applied to the suppressor grid through C4 and develops a suppressor voltage across R6 which causes an additional drop in plate current. The process is regenerative and soon cuts off the plate current. The plate current remains cut off until C4 discharges sufficiently to allow the plate to start drawing current again. During plate current cutoff C3 charges. This circuit action is repeated at a rate of about one cycle per second, developing a negative sawtooth sweep at the plate of the phantastron. As the negative sweep voltage is applied to the voltage divider consisting of R7, R8, and R9 the klystron repeller voltage becomes more negative, and the klystron frequency increases.

Normally, the discriminator stage is connected to produce negative output pulses for an intermediate frequency greater than 30 megacycles. Since these pulses are inverted by the pulse amplifier stage and produce a positive pulse input to the cathode of search stopper diode V1 through C1 the diode will not conduct, and the klystron frequency is permitted to rise until the intermediate frequency becomes less than 30 megacycles, at which time the discriminator produces positive output pulses. At this point the locking action begins to take place. The positive discriminator pulses are amplified and inverted by the pulse amplifier stage. The input to the cathode of the search stopper now is a series of negative pulses which cause the diode to conduct. After a few pulses capacitor C2 is charged sufficiently by the voltage drop across R2 to hold the phantastron grid bias constant. The gradual decrease of V2 plate voltage now ceases and stops the negative sweep of repeller voltage, and the repeller voltage is held constant at this point. A small displacement of the intermediate frequency from 30 megacycles will exist in order to maintain a charge on C2, and keep the phantastron plate at the desired potential.



Phantastron Waveforms

If the klystron local oscillator frequency or the magnetron transmitter frequency now change to produce an i-f greater than 30 mc, positive pulses are applied to the search stopper diode to prevent it from conducting and the negative going plate voltage sweep continues until it brings the intermediate frequency back to 30 mc. If the drift is in the opposite direction and causes the intermediate frequency to further decrease in frequency the search stopper diode conducts heavier and develops a larger bias on the grid of V2. Tube V2 now acts like an amplifier and the plate current decreases as the negative grid bias increases, developing a positive voltage swing in the output across the plate voltage divider. Thus the klystron frequency is lowered to bring the intermediate frequency back to the normal 30 mc difference value.

FAILURE ANALYSIS.

No Output. Loss of plate or screen voltage due to failure of the power supply, or if resistor R4, R7, R8, R9 and R5 are defective, or a defective tube V2 can make the circuit inoperative and produce a no-output condition. Measure the positive and negative supply voltages with a voltmeter to make certain that the supply or a blown fuse is not the fault. Check the resistance of R4, R5, R7, R8 and R9 with an ohmmeter for continuity and proper value. If the resistors are satisfactory and the voltages are normal, V2 may be at fault. Usually failure of any other components will produce an improper sweep or a constant output rather than none at all.

Low Output. Low supply voltage, a defective tube V2, or a change in value of resistors R4, R5, R6, R7, R8 and R9 can produce a low output. Check the supply voltage with a voltmeter, and the resistor for value with an ohmmeter.

Improper Sweep. Normally, with no input to search stopper tube V1, a constant negative output sweep voltage should occur about once each second, indicating that V2 is operating normally. A faster or slower sweep indicates that V2 is not operating correctly. A faster sweep will indicate reduced time constants such as a shorted resistor or lower valued capacitor, while a slower sweep indicates an increased time constant such as a larger value of resistance or capacitance. Check the values of R2, R3, and R6 with an ohmmeter, and check C3 and C4 with an in-circuit capacitance checker. If circuit voltages are normal and the capacitance and resistance are satisfactory, V2 is most likely at fault. It is usually necessary that the afc circuit be adjusted so that the local oscillator frequency cannot pass through the wrong sideband, or improper locking will result.

Constant Sweep. A constant sweep with no lock-in occurring indicates either a failure of the search stopper circuit, diode V1, or failure of the preceding pulse amplifier or discriminator stages. Check for a pulse input from cathode to ground of V1 with an oscilloscope. If pulses exist on the input side of C1 but not across R1, capacitor C1 is open. If pulses exist across R1 and no voltage appears across R2, either C2 is shorted, or V1 is defective. If the voltage at the anode of V1 is low, check the values of R1 and R2 with an ohmmeter and the capacity of C2 with a capacitance checker.

THYRATRON AFC CIRCUIT.

APPLICATION.

The thyratron afc circuit is used in radar or other electronic equipment to maintain the i-f frequency within the receiver pass band, and minimize the effect of local oscillator drift.

CHARACTERISTICS.

Utilizes two thyratrons, functioning as relaxation oscillators.

Changes an error voltage input into a sweep voltage output.

Sweeps continuously with no input.

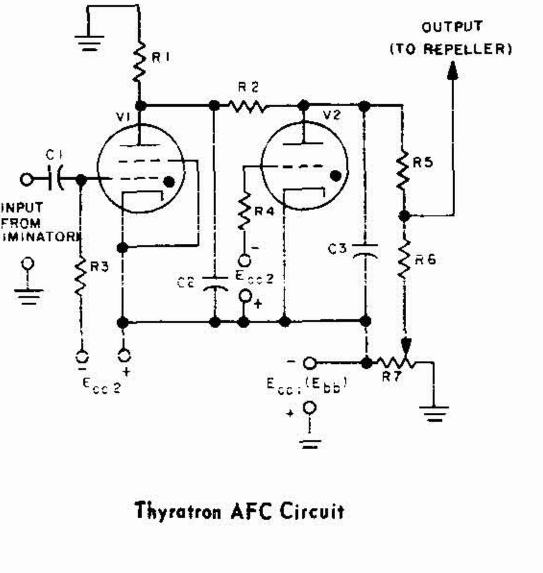
Sweep speed changes for a change in error voltage.

CIRCUIT ANALYSIS.

General. The thyratron afc system provides a means of controlling the frequency of a klystron local oscillator. The output of the receiver discriminator is coupled through a pulse amplifier stage, and is applied to the input of the first relaxation oscillator (hence-forth referred to as the search stopper). A frequency hunting afc system is necessary because of the relatively large oscillator frequency drifts encountered in high frequency radar. Two thyratrons provide a coarse and a fine tuning system, in which the sweep generator brings the i-f frequency within range of the search stopper. The search stopper, in turn, acts as the fine tune control, tuning the klystron local oscillator so as to produce precisely the correct i-f frequency for lock-in.

System design is such that it sweeps a large band of frequencies, and locks onto the desired frequency when it reaches the discriminator cross-over point. An error voltage from the discriminator controls the speed of the search stopper (the first thyratron), and in the absence of an error voltage, such as when the transmitter is not operating, the sweep generator (second thyratron) hunts continuously. When the transmitter is operating, and when the i-f frequency is within the receiver bandwidth, the error voltage is supplied by the discriminator, the value of which determines the output of the search stopper.

Circuit Operation. A schematic diagram of a thyratron afc circuit is illustrated in the accompanying schematic.



Thyratron AFC Circuit

Thyratron V1 is the search stopper, functioning as a relaxation oscillator. Capacitor, C1 is the input coupling capacitor, and R3 is the grid resistor. Capacitor C2, connected between the plate and cathode of V1, determines the repetition rate of the search stopper. R1 and R2 form a resistive series charge path for capacitor C3, which determines the repetition rate of sweep generator V2. R4 is the grid resistor for V2, and R5 and R6 form an output voltage divider, to supply a portion of the output to the repeller of the klystron. Bias supply E_{cc_2}, applied to the grid of each tube, determines the firing point of the thyratron. Variable resistor R7 permits setting the repeller voltage to the proper value so that the sweep generator output causes the klystron local oscillator to hunt by an equal amount above and below the cross over frequency.

If the transmitter is operating, and the local oscillator and the transmitter differ by approximately the intermediate frequency, the search stopper receives a series of pulses from the discriminator (one pulse for each pulse of transmitted energy). The time constant of capacitor C2 in the plate circuit of the search stopper is such that it charges sufficiently to allow V1 to fire once for every three or four discriminator pulses at the input. When the thyratron ionizes, the plate potential drops to a voltage which is very close to the cathode potential. This is due to the low conduction resistance of the tube. The capacitor begins to rapidly discharge, and as soon as it discharges sufficiently, the tube deionizes. Immediately upon deionization, the capacitor begins recharging, and the cycle repeats. The search stopper continues to ionize and deionize at the same rate, as long as the pulses from the discriminator remain at the same amplitude. These sawtooths generated by the search stopper are smoothed out to a pulsating d-c voltage, by the RC network in the plate circuit, and are applied to the repeller of the klystron. Under these conditions, the klystron repeller is kept at its proper operating voltage, and the i-f frequency is correct. If there is a change in the intermediate frequency because of local oscillator drift, the amplitude of the pulses arriving at the input to the search stopper changes. For an increase in the i-f frequency, the pulses for example, decrease their amplitude. Since the amplitude of the pulses on the grid are now less positive, C2 in the plate circuit must charge to a higher voltage to ionize the tube. Thus it takes a longer period of time for the tube to reach the ionization potential, and the repetition rate is slowed down. A slower repetition rate produces a lower average plate current, so that the average plate voltage is increased in a positive direction. This voltage change appears at the repeller of the klystron, and the klystron local oscillator changes its frequency accordingly, automatically correcting the i-f frequency.

For a decrease in the i-f frequency, the opposite condition prevails. The pulses arriving from the discriminator arrive at a greater amplitude, causing VI to ionize more frequently, and produce a higher average plate current. The higher plate current causes the average plate voltage to decrease, and this decrease (a change in the negative direction) is applied to the repeller of the klystron. The more negative repeller voltage changes the klystron local oscillator frequency accordingly, and the change in the i-f frequency produced by oscillator drift is corrected.

During the time that V1 controls the repeller voltage, sweep generator V2 remains cut-off, because its plate voltage is not positive enough to allow it to ionize. The search stopper's ability to vary the repeller voltage, however, is limited. If the i-f should drift too far off frequency, the search stopper no longer receives pulses of sufficient amplitude from the discriminator to ionize V1, and the plate voltage increases towards the value of supply voltage E_{bb}. It is under this condition that the sweep generator tube is activated. As the plate voltage begins rising, C3 in the plate circuit of V2 begins charging, and the output voltage to the repeller begins increasing positively. The ionization point of the tube is established by grid bias E_{cc_2}, and as soon as C3 charges sufficiently to bring the plate voltage to the proper level, the tube ionizes, rapidly discharching C3, and dropping the plate voltage (and thus the repeller voltage) to almost cathode potential. When the capacitor discharges sufficiently, the tube deionizes, and C3 again begins charging, repeating the cycle. The sweep output which is generated by this action is applied to the repeller. As the sweep voltage rises (during the time that V2 is deionized), the repeller voltage also rises and the local oscillator frequency changes accordingly.

When the sweep voltage at the repeller reaches the proper voltage to produce the correct i-f frequency, search stopper tube V1 once again receives operating pulses from the discriminator, and prevents V2 from ionizing, stopping the long sweep and locking-in the local oscillator. Once again search stopper tube V2 "fine tunes" the local oscillator, until the next large oscillator frequency shift occurs, whereupon the long sweep cycle repeats.

FAILURE ANALYSIS.

No Output. A defective V1 and V2, an open resistor R1, R2, R5, R6, or R7, a shorted C2 or C3, or the loss of supply voltage can cause a no-output condition to exist. Check R1, R2, R5, R6, and R7 with an ohmmeter for proper value. Check capacitors C2 and C3 for value, or possible shorts or opens with an in-circuit capacitor checker. Measure the plate supply voltage, and the bias supply voltage with a voltmeter for proper value, and correct if necessary.

Continuous Hunting. The loss of input from the discriminator, an open C1 or C2, or an open R3 can cause the failure of the afc system to lock on to the correct frequency. With an oscilloscope, check for the presence of the pulses from the discriminator at the input. If not present, a defect is present in some preceding circuit, and the afc system is probably not defective. If a signal is present, thyratron V1 may be at fault. Check R3 with an ohmmeter for proper value, and check capacitors C1 and C2 with an in-circuit capacitor checker for proper value.

No Hunting. A defective thyratron V2, an open C3, or an open R4 are the only components which can cause the system not to hunt when the frequency drifts beyond the control of the search stopper. Check resistor R4 with an ohmmeter for proper value, and capacitor C3 for proper value with an in-circuit capacitor checker.

REACTANCE TUBE AFC CIRCUIT

APPLICATION.

The reactance tube afc circuit is used in radio receivers when it is desired to maintain the local oscillator frequency or the output of the mixer stage of the receiver at a specific frequency, which is always in the i-f pass band.

CHARACTERISTICS.

Converts an input voltage change to a reactance variation at the output.

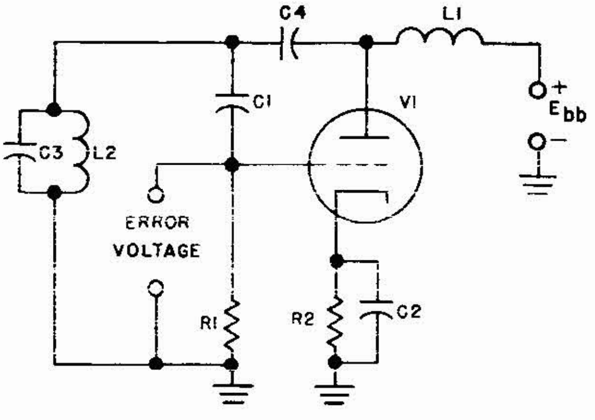
Controls the frequency of the receiver local oscillator.

Utilizes a triode, with cathode (self) bias.

CIRCUIT ANALYSIS.

General. In the basic reactance tube AFC system, a reactance tube is used to change the resonant frequency of the receiver local oscillator by an amount and direction which corresponds to the amount and direction of the frequency shift of the incoming signal. If the i-f frequency of the input changes, it causes the discriminator to produce a d-c voltage at its output having an amplitude and polarity which is proportional to this change. It is this d-c voltage which is applied to the grid of the reactance tube. The reactance tube circuit is connected across the tank circuit of the local oscillator, and its characteristics are such that a change in its conduction produces the same effect as a change in reactance across the oscillator tank circuit. Thus, the resonant frequency of the local oscillator tank circuit changes, compensating for the frequency drift in the i-f stage.

Circuit Operation. A schematic diagram of a basic reactance tube AFC control circuit is illustrated below.

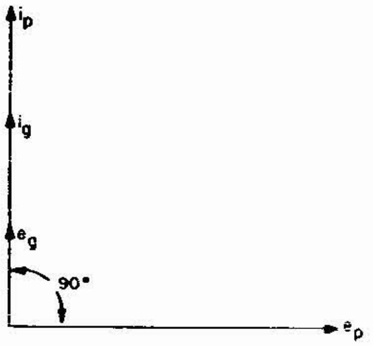


Basic Reactance Tube AFC Control Circuit

Triode V1 is the reactance tube, using cathode bias, supplied by resistor R2 and capacitor C2. L1 is an r-f choke which keeps the r-f out of the plate voltage supply. L2, together with C3, is the oscillator tank circuit, connected across the C1-R1 combination. C1 and R1 make up the variable capacitive reactance circuit, and capacitor C4 prevents the d-c from being applied to the oscillator tank circuit. The error voltage from the discriminator is applied between the grid of V1 and ground, as shown on the illustration.

With no error voltage applied to the grid of V1, the only voltage present across the C1-R1 network is the voltage across the oscillator tank circuit, L2 and C3. The values of C1 and R1 are chosen so that the reactance of C1 is large in comparison to the resistance of R1, permitting the capacitive reactance to be the current controlling component, and causing the voltage across it to lag the current through it by approximately 90 degrees. Since the same current which flows through C1 also flows through R1, and since this current leads the applied voltage by 90°, it produces a voltage drop across the resistor which leads the applied voltage by 90 degrees. The reactance tube is effectively in shunt with the oscillator tank (C3 and L2) and the phase shift network (C1 and R1). Capacitor C4 allows the a-c component of current to pass through it, and at the same time, prevents the d-c plate voltage from being applied to the phase-shift circuit and the tank.

The relationship of the currents and the voltages in the circuit can be best explained through the use of a vector diagram, as illustrated below.



Relationship of Currents and Voltages with no Modulation Input

Voltage e_p is the alternating component of the plate to ground voltage which appears simultaneously across the reactance tube, the phase-shift network and the oscillator tank circuit. The ac grid-input voltage is applied across R1. This voltage drop across R1 is in phase with the plate current i_p and the grid current, i_g, a relationship characteristic of amplifier tubes.

Since both i_p and i_g are in phase with e_g, and since e_g leads e_p by approximately 90 degrees, i_p and i_g also lead e_p by 90 degrees. Both of these currents are supplied by the oscillator tank circuit, and since they lead the tank voltage, they act like the current in a capacitor. Thus the injection of these currents into the tank circuit accomplishes the same effect as placing a capacitor across the oscillator tank circuit. The frequency of the tank in this case is, therefore, decreased. With no error voltage applied at the input, this frequency is the operating frequency of the local oscillator.

If the i-f frequency drifts, the output of the mixer changes, and the discriminator produces an error voltage at its output which is proportional to the drift in i-f. This error voltage is produced as result of the input frequency to the discriminator being different than the frequency to which it is tuned. The amplitude and polarity of the error voltage is determined by the amount and direction of the frequency drift, respectively.

Consider now the application of this error voltage to the grid of the reactance tube. It is important to keep in mind that we are not speaking of actual capacitive reactance or capacitance changes. Our concern here is an **effective** capacitance produced by the leading current in the R1-C1 combination. If the voltage applied to the grid of V1 increases in a positive direction, the plate current of V1 also increases, and since this current is an effective capacitance shunt across the oscillator tank circuit, the frequency of the oscillator is decreased. Conversely, when the grid signal shifts in a negative direction, V1 plate current decreases, and since this current is an effective reduction in capacitance across (shunting) the oscillator tank circuit, the frequency of the oscillator is increased.

To summarize, a positive error voltage causes an increase of frequency, while a negative signal causes a decrease in frequency. Likewise, a large amplitude error voltage causes a greater frequency change than a smaller amplitude error signal.

If resistor R1 and capacitor C1 were reversed, and their values were changed so that the resistance of R1 becomes large in comparison to the reactance of C1, circuit operation will be reversed. The result of the change is that an inductive (lagging) current is injected into the local oscillator tank circuit instead of a capacitive (leading) current, as in the previous example. A positive error voltage will now produce a decrease in local oscillator frequency, and a negative error voltage will produce an increase in local oscillator frequency.

FAILURE ANALYSIS.

No Output. An open or shorted L1, an open R2 or C4, the absence of the plate supply voltage, the absence of the input error voltage, or a defective V1 may cause a no-output condition to exist. Check L1 for an open, and R2 for proper value with an ohmmeter. Check capacitor C4 for value with an in-circuit capacitance checker. Check for the presence of the plate supply voltage and the presence of the input error voltage with a voltmeter. If plate voltage is not present, either choke L1 is open or the power supply is defective. If an error voltage is not present the trouble is in the discriminator or i-f stages. If the output is still not restored with normal plate and input voltages, the tube is probably at fault.

Improperly Controlled Output. A defect in nearly any component in the circuit can produce a condition in which the afc circuit does not control the local oscillator. Check L1 for continuity, and capacitors C1, C2, and C4 with an ohmmeter for opens or shorts, and resistors R1 and R2 for value. Check for the proper value of plate supply voltage, and the correct error voltage. If the condition still exists, check all capacitors with an in-circuit capacitor checker for their proper value. Also, do not neglect the possibility that the discriminator may be detuned from the proper frequency, causing the frequency to shift in the wrong direction.

DC AMPLIFIER AFC SYSTEM.

APPLICATION.

The dc amplifier afc system is used in cw, radar, or radio applications where a slowly varying dc error voltage is used directly to produce automatic frequency control action.

CHARACTERISTICS.

DC coupling is used between the discriminator and control stage.

No afc sweep is used (it is a non-hunting system).

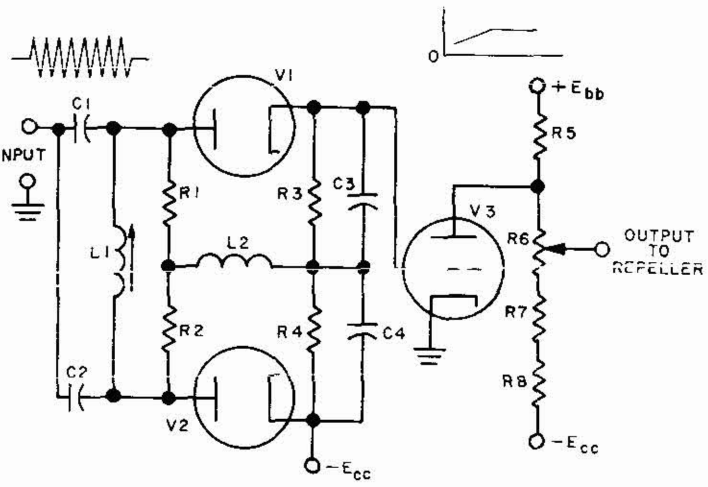
The error voltage is generated by a discriminator.

Can be used on either CW or pulsed systems.

CIRCUIT ANALYSIS.

General. The dc afc amplifier system forms a simple tracking system for a reflex klystron. It uses a discriminator to convert any deviation from the i-f amplifier center frequency into bias variations which are applied to the grid of a dc amplifier. Since the plate of the dc amplifier is connected to the repeller of the klystron local oscillator, any variation of the grid bias varies the plate voltage of the dc amplifier and thus the repeller voltage of the klystron. This, in turn, varies the frequency of the local oscillator in such a direction as to return the local oscillator to the proper frequency with respect to the transmitter frequency. The system requires manual adjustment of the klystron resonator and of the repeller voltage, to bring the difference-frequency signal within the bandpass of the afc discriminator, before the system can produce any tracking action. Although this system will compensate automatically for slight frequency variations of the transmitter, or of the local oscillator, it will not correct the klystron frequency if ever the difference signal falls outside the bandpass of the afc discriminator. Such a situation commonly occurs whenever the receiver is turned on after having been inoperative for a number of hours, and necessitates a manual readjustment of the repeller voltage. More complicated afc systems use a simple search sweep to obviate the necessity for initial adjustment.

Circuit Operation. A schematic diagram of a typical dc amplifier afc circuit is shown in the accompanying illustration.



DC Amplifier AFC Circuit

A Weiss discriminator is used to supply the dc afc error voltage. Capacitors C1 and C2 couple the discriminator to the last i-f stage. Inductor L1 is slug tuned to the i-f or crossover frequency. Resistors R1 and R2 are diode return resistors which effectively center-tap the tuned input circuit, thus half the input voltage is impressed across each diode. L2 is an r-f choke which forms part of the d-c return to the load resistors. V1 and V2 are the discriminator diodes, with R3 and R4 acting as load resistors. Capacitors C3 and C4 filter the i-f ripple from the output and furnish a practically pure d-c output from the discriminator. The grid of dc amplifier V3 is connected to the cathode of V1 and through diode load resistors R3 and R4 to a negative bias supply. This forms the quiescent or resting bias above and below which the discriminator output varies V3 grid. Resistor R5 is the plate resistor for dc amplifier and also forms a portion of a voltage divider connected between the positive and negative power supplies, consisting of R5, R6, R7, and R8. Resistors R5, and R7 and R8 limit the range over which R6 operates, and R6 is variable and used to manually adjust the klystron repeller voltage for the desired center frequency. Normally, with the local oscillator tuned so that the i-f is at the center frequency, say 30 megacycles, L1 offers a maximum impedance and equal voltages are supplied to the plates of diodes V1 and V2. Thus equal load currents flow through R3 and R4 in opposite directions and develop equal and opposing voltages. Hence there is no change in bias on V3 and the klystron reflector voltage is not affected, so there is no change in frequency. Coupling capacitors C1 and C2 are unequal in value and are designed to control the peak separation of the tuned input circuit. When the transmitter frequency increases, the i-f increases and a more positive output voltage is applied to V1, and a lower output to V2. Consequently, V1 conducts more heavily than V2 and a large positive output voltage is developed at the cathode. This positive increase in bias causes the plate current of dc amplifier V3 to increase, lowers the plate voltage, and consequently increases the negative repeller voltage. As a result, the local oscillator frequency increases and returns the i-f difference frequency back to its original value.

Conversely, when the transmitter frequency decreases, and a negative output voltage is applied to V1 while a more positive output is applied to V2. Diode V2 now conducts more heavily than V1 and a large negative voltage is developed across R4. The negative output developed across R4 is larger than the positive output across R3, so that the grid of V3 is driven in a negative direction. The increased positive output across R5 produces an effectively less negative repeller voltage and the klystron is shifted in the correct frequency direction to compensate. These changes are slowly varying d-c voltages for cw operation. For pulse operation, design is such that the filter capacitors are quickly charged by the low resistance path through the diodes, while the discharge is slow through the high resistance shunting load resistors. Thus an effective pulse stretching action is produced which provides well filtered dc for pulse control.

FAILURE ANALYSIS.

No Output. Lack of klystron voltage or improper repeller voltage can cause a no-output condition. Check both the positive and negative supply voltages with a high resistance voltmeter to determine that a fuse or the supply is not at fault. Do not neglect the fact that potentiometer R7 may be misadjusted and cause the klystron to operate on a frequenc out of range of the discriminator. Lack of reflector voltage on the klystron may be caused by a defective R7 or R8. Check the resistors for proper value with an ohmmeter. Resistors R5 and R6 will affect the klystron voltage also, and may be checked with an ohmmeter. If resistors R5, R6, R7, and R8 appear satisfactory and the power supplies are normal, tube V3 may be drawing abnormal current and preventing circuit action. Normally, failure of the discriminator or input circuit will show as an inability to provide proper local oscillator action rather than no output at all. If resistor R3 or R4 opened, or if the grid of V3 were shorted, lack of grid bias on the dc amplifier might cause the local oscillator to operate outside the range of the discriminator. Check the voltage from V3 grid to ground and the values of R3 and R4 with an ohmmeter.

Improper AFC Action. Usually improper afc action can be isolated to a malfunction in the discriminator. Diode V1 and its associated circuit controls i-f shifts in a higher frequency direction, that is when the output of V1 is positive. When lower i-f shifts occur they are controlled by V2 and its associated circuit. If either C1 or C2 were shorted a continuous positive plate voltage would be applied V1 or V2 and cause the repeller frequency to increase greatly. If the capacitors were open, afc control would only occur in one direction, depending upon which capacitor is open.

Use an in-circuit capacitance checker to check for the proper capacitance value. Use an ohmmeter to check L1 and L2 for continuity, and also R1, R2, R3 and R4 for proper value. Check C3 and C4 for proper value with a capacitor checker.

SERVOMECHANISM CIRCUITS.

In radar systems, as well as in industrial and other widespread applications, it is often necessary to control the angular position of one shaft by the positioning of another shaft. When the two shafts are close together this control may be accomplished directly, by gears, or by some other mechanical means. However, when the controlled shaft is located some distance from the controlling shaft it is usually impractical to interconnect the two shafts mechanically and, as a consequence, some other method must be employed to move the controlled shaft in correspondence with the controlling shaft. Two systems used to transmit mechanical shaft angles to a remote location by means of electrical voltages are the synchro system, and the servomechanism. The synchro system accomplishes mechanical shaft transmission without power amplification. That is, mechanical power output is equal to mechanical power input, neglecting losses. In applications where the torque of the controlling shaft must be amplified before it is applied to the controlled shaft, the system used is known as a servomechanism. The synchro system employs two or more self synchronizing units, similar in appearance to small electric motors. Synchros are used extensively in remote indicator systems, where information is to be transmitted between two points. Such information includes antenna position data in azimuth, or in elevation, meter readings, and many types of computer data. Since the controlled shaft is usually fastened to a dial or pointer, the synchro system adequately supplies the small amount of torque required to move the shaft. In addition to remote indicator applications synchro devices are widely used as basic elements of servomechanisms. Synchro systems are discussed in detail in the following paragraph of this Handbook.

The servomechanism is essentially a high gain power amplifier operating on the closed loop, or error-sensitive principle. That is, the action of the power amplifier is governed by an error, which exists when there is an angular displacement between the controlling (or input) shaft, and the controlled (or output) shaft. Servomechanisms may be classified according to motive characteristics. Three types of motor drives are used extensively in positioning systems: the d-c motor, the a-c motor, and the hydraulic motor.

The d-c servo motor is a high torque device widely used in servomechanisms where smooth control of heavy loads is desired. The d-c servo motor is a specialized form of d-c motor in that it is designed to provide nearly linear changes in speed with proportional changes in armature current. This feature permits the d-c servo motor to change direction and speed of rotation smoothly, and with minimum mechanical stress on the controlled mechanism. A servomechanism utilizing a d-c- servo motor drive frequently uses a synchro system to produce an error voltage, which is indicative of the angular error between the input and output shaft. This error voltage is applied to a phase sensitive d-c servo-amplifier, also called a d-c servo motor-controller, which compares this error voltage to an a-c reference voltage, and produces an output which drives the d-c servo motor. The polarity of the servo-amplifier output is dependent upon the direction, either clockwise or counter-clockwise, of the angular displacement between the input and output shaft, and hence, the servo drive motor rotates the controlled device in the desired direction. As the output shaft is rotated by the servo motor toward a position of alignment with the input shaft, the error voltage produced by the synchro control transformer (the synchro output device, which is mechanically coupled to the output shaft) decreases, since the amplitude of the error voltage is proportional to the amount of error between the input and output shafts.

The output of the d-c- servo motor-controller decreases and, therefore, the servo motor rotates slower. When the output shaft reaches a position of alignment with the input shaft, an error voltage is no longer produced, and the servo motor comes to rest. In systems where heavier loads must be positioned, thyratron servo motor-controllers are sometimes used because of their higher efficiency and power handling capabilities, which are necessary to drive the larger servo motors used with the heavier loads. In applications where very large loads are positioned, the servo motor-controller does not directly drive the servo motor. Instead, it excites an electromechanical power amplifier, such as a d-c generator, several cascaded d-c generators, a Ward-Leonard system, or an Amplidyne, which is used to drive the d-c servo motor. The Ward-Leonard system may be used, either with or without the electronic servo motor-controller. Electromechanical power amplifiers provide substantial gain, and in the Amplidyne system, which provides the highest gain of them all, a power gain of 10,000 may be realized. An important refinement that is frequently found in servomechanisms is an anti-hunt circuit. Anti-hunt provisions are necessary because of the tendency of the load to coast past its ordered position due to inertia. When the load comes to rest, there is an angular displacement between the input and output shaft in the direction opposite to the original error, and an error voltage is produced which causes the output shaft to be rotated back toward the ordered position. Again, due to inertia, the load coasts past its ordered position and again an error voltage is produced, which again causes the servo motor to rotate the load toward its ordered position. The load is now oscillating about the ordered position. Friction losses in the servomechanism would dampen out this oscillation, or hunting, as this condition is commonly referred to, if it were not for another factor. This factor is the existence of a time delay in the positioning system which tends to cause the applied torque to be proportional to a past error, rather than a present error. The torque applied to the load by the servo motor lags the error voltage by some angle, and is thereby applied in the wrong direction for a short period of time after the load coasts past the zero-error, or ordered position.

Thus, the time delay in the controller creates a regenerative action, reinforcing the oscillations each time the ordered position is passed in much the same way that regenerative feedback in an oscillator sustains oscillations. Overshoot and hunting may be eliminated by increasing the friction of the mechanical drive, by decreasing the gain of the power amplifier, or by compensating electronically for the time delay of the servo motor-controller. The first two methods mentioned are usually unsatisfactory, since increasing the friction of the drive train decreases system efficiency, and decreasing power amplifier gain leads to sluggish response. Anti-hunt circuits, therefore, suppress oscillations by compensating for the effects of the time delay of the servo motor-controller. Anti hunt devices for servomechanisms are many and varied. In small servos a simple inertia damper may suffice, whereas in larger applications various electronic anti-hunt circuits are used. In general, an anti-hunt circuit provides regenerative feedback when the error voltage is increasing, and degenerative feedback when the error voltage is decreasing.

Servomechanisms using a-c servo motors are used where a rapid, accurate, and low cost servomechanism is required. The a-c motor is, however, essentially a constant speed device and this characteristic makes it less desirable than the variable speed d-c motor in some applications. A few advantages of the a-c servo motor servomechanism are, no commutator or brush maintenance, and the a-c servo motor-controllers, used with a-c servomechanisms are not subject to drift (development of an output signal with no signal input) which is sometimes encountered in d-c-servo motor-controllers. An a-c servo motor servomechanism may be quite similar to the d-c system. The only variations would be the type of servo motor-controller, and the servo motor itself. This system, like the d-c servo motor system and all other servomechanisms operates on the error-sensitive principle.

The servomechanism is one type of servo system. A servo system may or may not involve mechanical motion. Automatic frequency control and automatic gain control circuits are examples of non mechanical servo systems. In all cases, however, the output of the system is fed back for comparison with the input, and the error, or difference voltage is used for control of the system. By strict definition, a servomechanism is a servo system which includes mechanical motion. However, the terms servomechanism, servo system, and servo, are often used interchangeably.

The hydraulic servomechanism is a rugged power amplifying device operating on the hydromechanical principle. This system may be used to position very large loads, and has the advantage of relatively small physical size. Hydraulic servomechanism systems are beyond the scope of this Handbook, however, they deserve mention since they are frequently controlled by relatively small electrical servomechanisms.

SYNCHRO CONTROL SYSTEMS.

APPLICATION.

Synchro control systems are used in radar sets, computers, and in any other system where it is necessary to indicate the angular position of a shaft, or to transmit mechanical shaft angles to some remote location.

CHARACTERISTICS.

Electrically transmits mechanical shaft data, (angular position) from one point to another.

Does not provide power amplification, i.e., mechanical power output is equal to mechanical power input.

CIRCUIT ANALYSIS.

General. Synchros are known by a wide variety of trade names such as Selsyn, Autosyn, Telesyn, Teletorque and others which are not too frequently encountered. The preferred name however, is synchro, which applies to all the various types. Synchros are devices which convert mechanical shaft angular rotation to electrical signals and vice versa. When information is in the form of a shaft position so that it is expressed in terms of the angle between the actual shaft position and some zero or reference position, it can be converted by a synchro to a set of three voltages called synchro data. In this form such information can easily be transmitted to another point where a second synchro is used to set a second (repeater) shaft to a corresponding angular position. In some instances this second synchro, directly or indirectly through gears, mechanically positions the repeater shaft. In other instances where power amplification is required, the second synchro provides only a voltage output, which drives a servo system. It is important to note that there is no power gain in a pure synchro system. Neglecting friction losses the mechanical power output of the repeater (or receiver) synchro is equal to the mechanical power input to the transmitter. There are five general types of synchro units, each classified according to function. These include transmitters, receivers, differential transmitters, differential receivers, and control transformers

The synchro transmitter, which is sometimes called a synchro generator consists of a rotor which carries a single winding, and a stator made up of three separate windings displaced 120°. The rotor is excited by an a-c source and it is usually coupled directly or through gears to a controlling shaft. The rotor is usually so restrained that it cannot turn except under the influence of the controlling shaft. The voltages induced in the stator windings as a result of the alternating field created by the rotor winding, are representative of the angular position of the rotor at any instant.

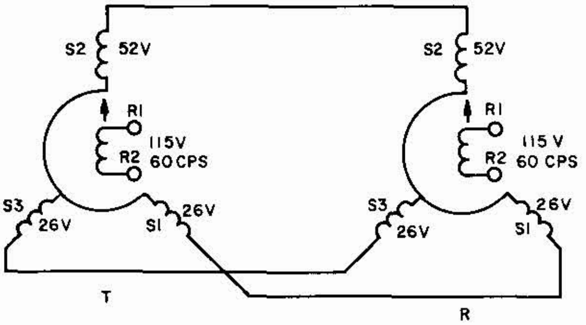
The synchro receiver, sometimes referred to as synchro motors are similar electrically to the synchro transmitter. The rotor of the synchro receiver is, in contrast to the synchro transmitter, free to turn and usually drives a light load, such as a pointer, dial, or some other indicating device. The drive is accomplished directly, or through a light gear train. The angular position that the rotor assumes is dependent upon the stator voltages received from the synchro transmitter.

The differential synchro transmitter (abbreviated DT), resembles the regular synchro transmitter in that the rotor is mechanically driven, and the stator is similar. However, there are three separate windings on the rotor, and these windings are electrically displaced 120 degrees. Differential transmitters are used to compensate for errors existing in various parts of a synchro system. With the insertion of a differential synchro transmitter in a synchro system, the angular position of the receiver rotor with respect to the transmitter rotor may be varied by turning the rotor of the differential transmitter.

The differential synchro receiver is similar in design to the differential transmitter, but the rotor is free to turn. It is used when it is desired to interpret the sum or difference of two angular positions. If the differential synchro receiver is connected to two synchro transmitters, the differential synchro receiver assumes a position corresponding to the angular sum or difference (depending on the connections) of the transmitter rotor positions.

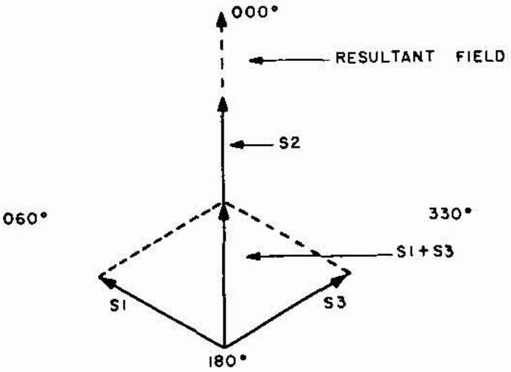
The synchro control transmitter is somewhat similar to the synchro receiver. The windings of the control transformer have a higher impedance than the windings of the other synchro units, and the rotor of the control transformer is not free to turn. Voltages from a synchro transmitter produce a voltage in the rotor of the control transformer, which is representative of the angular displacement of the transmitter rotor. The control transformer is used where it is desired to obtain a voltage output only, which is indicative of angular position.

Circuit Operation. The synchro transmitter operates as a variable transformer with its rotor as the primary and the stator windings as secondaries. The voltages induced in each stator winding are proportional to the cosine of the angle between the rotor and the individual stator winding. The following diagram illustrates a typical synchro circuit consisting of a synchro transmitter and receiver.



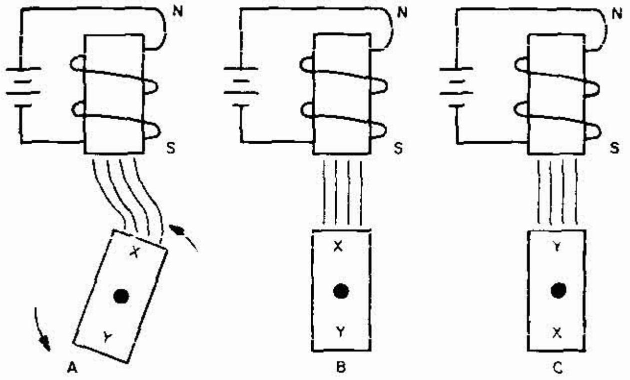
Synchro Transmitter-Receiver Circuit

When a-c voltage is applied to the rotor of the synchro transmitter, voltages are induced in the stator windings (S1, S2, and S3), and the magnitude and phase of these voltages are dependent upon the position of the synchro rotor. The turns ratio between the synchro rotor and stator is generally 2.2:1, so that the maximum voltage that can be induced across an individual stator winding is 52 volts when standard 115V, 60 cycle, AC is applied to the rotor. The rotor of the synchro illustrated is, by convention, in the zero degree position. This reference is used throughout synchro systems. Designations S1, S2, S3, R1, and R2 are also standard designations for all synchros. When the rotor of the synchro transmitter is in the 0° position flux linkage between the rotor and winding S2 is maximum, and 52 volts is inducted across S2. Stator windings S1 and S3, however, are at 60° angles to the rotor and only half as much voltage (26 volts) is induced across S1 and across S3, since the cosine of 60° is 0.5. At this point, circuit operation can be more easily understood by assuming that the receiver rotor is removed. Since the stator windings of the transmitter are connected directly to the stator windings of the receiver, the voltage applied to each individual receiver stator winding corresponds to the voltages induced in each stator winding of the transmitter. Current flows from S2 of the transmitter through S2 of the receiver, and divides equally through S1 and S3, since equal voltages are applied to S3 and S1. Current flow will, of course, be reversed when the polarity of the input voltage reverses. Each stator winding in the receiver generates a magnetic field, but the important point to consider is the resultant field. The following vector diagram illustrates the direction and magnitude of each receiver stator field and the resultant field.



Resultant Receiver Field Vector Analysis (Transmitter Rotor At 0°)

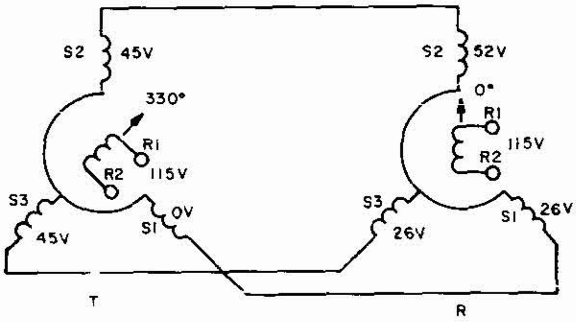
As can be seen from the vector diagram, the resultant field points in the same direction as the transmitter rotor. Should an iron bar rotor be placed in the receiver field it tends to line itself up with the resultant field. However, the iron bar rotor can align itself in either of two positions 180° apart as shown in the following illustration.



Behavior of Electromagnet and Iron Bar

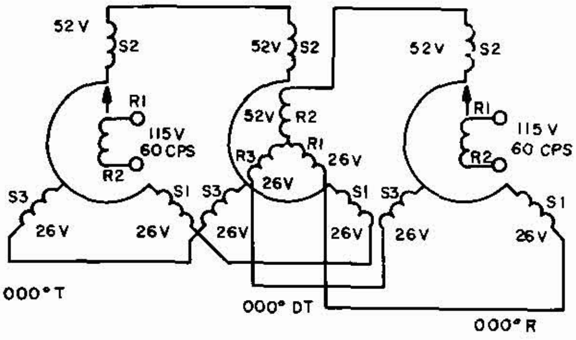
In figure A the iron bar rotor is held in the position illustrated. The paths of the magnetic lines of force are lengthened and when the bar is released it quickly rotates to position B in accordance with the stretched rubber band concept for the behavior of magnetic lines of force. Figure C illustrates the position that the rotor would assume if it is rotated to a position, where the "Y" end of the bar is nearer to the electromagnet than the X end, and is released. Thus a synchro receiver with an iron bar rotor displays ambiguity, that is, it has two stable positions 180° apart. To avoid the possibility of this 180° error the rotors on synchro receivers are energized by the same a-c source as the transmitter rotor. This makes the receiver rotor an electromagnet, and there is now only one stable condition. In addition to the advantage of having only one stable condition, the energized rotor provides much greater torque, and synchro receivers with energized rotors do not have constant stator current as an iron bar receiver would have. Illustrated below is a standard synchro transmitter receiver system with the transmitter rotor positioned at 330° and the receiver rotor held at 0°.

Voltages are induced in the synchro transmitter stator windings which are proportional to the cosine of the angle between the rotor and the stator windings. S2 and S3 are each displaced 30° from the rotor and the voltage induced in S2 and S3 is, therefore, 45 volts. S1 is now at right angles to the rotor and no voltage is induced in S1. The receiver rotor, which is being held at 0°, induces voltages in the synchro receiver stator windings, which are again proportional to the cosine of the angle between the receiver rotor and the receiver stator windings. Receiver stator winding S2 is parallel to the rotor and 52 volts is induced in S2. S1 and S3 are displaced 60° from the rotor and 26 volts is induced across S1 and S3. The synchro transmitter receiver circuit is now unbalanced, that is, voltage differences exist between the stator windings of the transmitter and receiver, and stator current flows, setting up a stator field in the receiver in such a direction as to exert a clockwise torque on the receiver rotor. Remember that the transmitter is so constructed that the transmitter rotor cannot rotate except under the influence of the controlling shaft. When the synchro receiver rotor, which is being held at 0°, is released it rotates in a clockwise direction due to the clockwise torque applied to it as a result of the receiver stator field, generated by stator current. As the receiver rotor approaches 330° the degree of unbalance between the transmitter and receiver diminishes, and hence, stator current decreases, since the voltages induced in the receiver stator windings by the receiver rotor approach the voltages induced in the transmitter stator windings by the transmitter rotor. When the receiver rotor reaches the same bearing as the transmitter rotor (in this case 330°) the voltages induced in the receiver stator windings are equal to the voltage induced in the transmitter stator windings. A balanced condition now exists, and stator current no longer flows, hence, torque is no longer produced, and the receiver rotor ceases to turn. It can be seen, then, that the transmitter supplies stator current to establish a field in the receiver, and produces torque only when the receiver is out of alignment with the transmitter. Torque produced in the receiver is proportional to the amount of error between the transmitter rotor and the receiver rotor. At very small error angles, the torque produced in the synchro receiver is insufficient to overcome the friction of the bearings and load. For this reason, friction is made as low as possible in the synchro receiver, and the maximum error in synchro receivers is generally less than 1°. Another important synchro unit frequently encountered is the differential transmitter. The differential synchro transmitter is used in circumstances where a correction must be inserted in the angular information being transmitted, or where the sum or difference of two angles must be transmitted. An example of this is the conversion of the relative bearing of a target to true bearing. It has been previously stated that synchros operate as variable transformers. This statement applies to the syn-



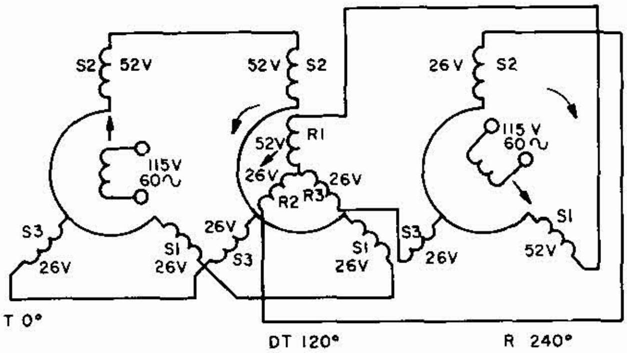
Transmitter 330°, Receiver Held At 0°

chro differential transmitter as well as all synchro units. In the case of the synchro differential transmitter, the stator is the primary of the variable transformer, while the rotor windings serve as the secondary. The following schematic diagram illustrates a differential transmitter inserted between a synchro transmitting and receiver.



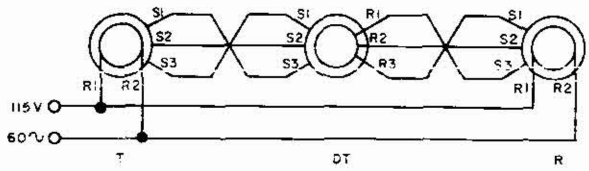
Differential Transmitter Connections

In a differential synchro transmitter the voltage ratio is one to one. With the differential transmitter at its electrical zero (0°) synchro data is passed from the transmitter to the synchro receiver without alteration. In the above illustration both the synchro transmitter and differential transmitter are mechanically positioned to 0°. Since the rotor of the synchro transmitter is at 0°, 26 volts is induced in transmitter stator windings S1 and S3, and 52 volts is induced in stator winding S2. The stator windings of the synchro transmitter are directly connected to the stator windings of the synchro differential transmitter, and the voltages induced across the transmitter stator windings are developed across the differential transmitter stator windings. The differential transmitter rotor windings are directly connected to the stator windings of the synchro receiver and whatever voltages are induced in the differential rotor windings are applied to the stator windings of the receiver. When the differential transmitter rotor is positioned at 0° all three rotor windings, which are positioned electrically 120° apart, form an angle of 0° with their respective stator winding (R1 with S1, R2 with S2, etc) and maximum voltage is induced in each rotor winding. Since the effective turns ratio is 1:1, 52 volts is induced in R2, and 26 volts is induced in R1 and R3. Therefore, 52 volts are applied to receiver stator winding S2, and 26 volts are applied to stator windings S1 and S3. The resultant receiver stator field is in the same direction as the transmitter rotor, and the receiver rotor aligns itself with this field. As long as the DT is positioned at 0° the receiver rotor positions itself at the same bearing as the transmitter rotor. If the differential transmitter is positioned to some bearing other than 0° the receiver indicates the position equal to the transmitter bearing minus the DT bearing, or in other words, the receiver indicates the difference between the transmitter and differential positions.

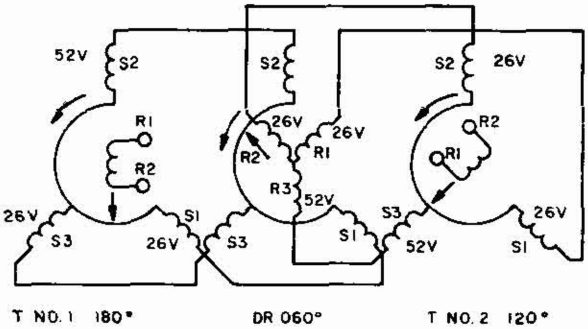


Effect of Changing Differential Transmitter Position

In the above illustration the synchro transmitter is positioned at 0° and the differential transmitter rotor has been rotated to a position of 120°. Maximum voltage is now induced in rotor winding R1 which is connected to stator winding S1 of the receiver. Twenty six volts is induced in rotor windings R2 and R3, and is applied to the receiver stator windings. The resultant receiver stator field points toward 240° and the receiver rotor aligns itself toward 240°. In all cases, where the differential transmitter is directly connected between the transmitter and receiver, the receiver shaft position is equal to the position of the transmitter shaft minus the position of the differential. If it is desired to have the differential position added to the transmitter reading, it is necessary to reverse S1 - S3 and R1 - R3 of the differential. It has been stated that the DT is effectively a 1:1 transformer. Actually there is a slight step-up ratio since extra turns are added to the rotor to bring the voltage ratio up to 1:1 to make up for transformations, copper, and core losses present in the differential transmitter. The fact that this ratio difference between the stator and rotor exists, gives rise to an electrical condition of unbalance, which occurs when a differential transformer is inserted in a synchro system. In a conventional synchro system there is no stator current when the transmitter and receiver are in a balanced state (in alignment). However, when a differential transmitter is inserted in the system, the no stator current condition no longer prevails when the system is in balance. The reason for this is that the differential stator windings can be designed to match the impedance of the transmitter stator windings, or the impedance of the differential rotor windings can be made to match that of the receiver stator windings. Since the differential transmitter cannot be made a one to one transformer in both directions, it is not possible to match both input and output impedances at the same time. As a consequence, there is current flow in both transmitter and receiver stator circuits even when the system is balanced, and the effect of this current is to reduce the accuracy of the system. Synchro capacitors may be used to reduce this stator current and hence, increase system accuracy. Synchro capacitors will be discussed in a subsequent parapraph. The differential synchro receiver is connected between two synchro transmitters, and it is used to indicate the angle between the two transmitter shaft positions.



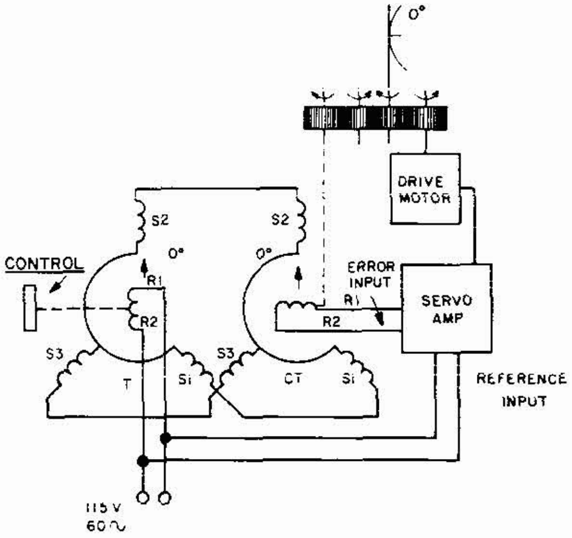
Wiring Diagram of Synchro System Designed to ADD Transmitter Position To Differential Position



Synchro Differential Receiver Inserted Between Two Synchro Transmitters

In the above illustration synchro transmitter number 1 is mechanically positioned to a bearing of 180° and transmitter number 2 is positioned at 120°. The differential receiver is electrically similar to the differential transmitter, but the DR rotor unlike the differential transmitter, is free to turn. In a simple transmitter-receiver synchro system a balanced state is achieved when the voltages applied to the receiver stator windings by the transmitter are canceled by equal and opposing voltages induced across the receiver stator windings by the receiver rotor. The synchro system illustrated above attains a balanced state when the differential receiver assumes an angular position equal to the difference between the angular positions of the two transmitters. If either, or both, of the synchro transmitters are moved the synchro system becomes unbalanced, and stator current flows, creating torque which causes the differential receiver to rotate until once again a balanced condition is reached. The synchro control transformer (CT) is used to produce an output voltage which is indicative of the error between two shafts. This output voltage is called an error voltage because it exists only when the two shafts are not in alignment.

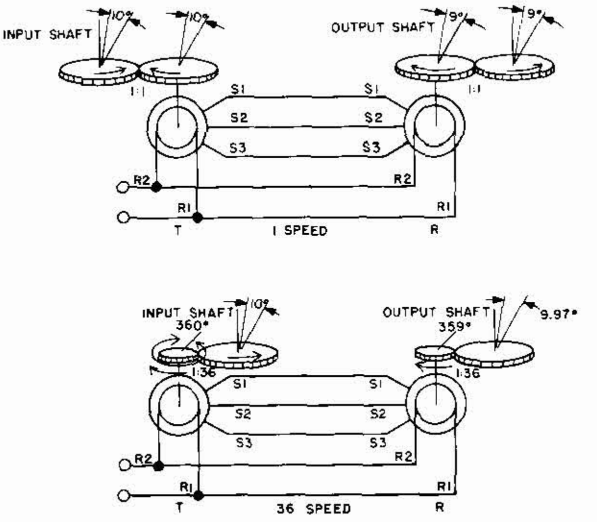
The following illustration depicts a simple synchro transmitter CT circuit and associated drive equipment.



Simple Antenna Control System

The synchro transmitter is mechanically positioned by a hand crank. The synchro transmitter is connected to the synchro control transformer in the standard manner, that is, S1 of the transmitter to S1 of the receiver, etc. The control transformer rotor is connected to a servo amplifier and the servo amplifier drives a drive motor, which is geared to the device being controlled; in this case, it is an antenna. The antenna is mechanically connected back to the control transformer to provide feedback. When the CT rotor is in alignment with the transmitter rotor there is no error voltage produced, and hence there is no output from the servo amplifier and the drive motor does not operate. It is important to note that the CT rotor is considered to be in alignment with the transmitter rotor when the CT rotor is displaced 90° from the transmitter rotor. In this position no voltage is induced in the CT rotor since the CT rotor is now perpendicular to the resultant CT stator field. When the synchro transmitter rotor is turned to some new position, the resultant control transformer stator field also rotates to some new position, and this field is no longer perpendicular to the CT rotor so that a voltage is now induced across the CT rotor. This a-c voltage is fed to the servo amplifier where it is compared with a reference voltage, which is of the same phase as the transmitter rotor excitation voltage, and an output is produced from the servo amplifier, which causes the antenna drive motor to rotate the antenna. As the antenna rotates toward the desired position the error voltage produced by the CT diminishes, since the CT is mechanically coupled to the antenna. When the antenna reaches the desired position the rotor of the CT is now perpendicular to the resultant receiver stator field set up by the synchro transmitter and the CT output error voltage is zero. There is no longer an output from the servo amplifier and the drive motor ceases to rotate the antenna. The stator windings of a control transformer consists of many turns of fine wire, and presents a high impedance to current flow, thus reducing the load presented to the transmitter, and allowing several control transformers to be utilized in conjunction with a single transmitter. High impedance windings are also necessary since the rotor of the control transformer usually operates into a high impedance load such as a servo amplifier.

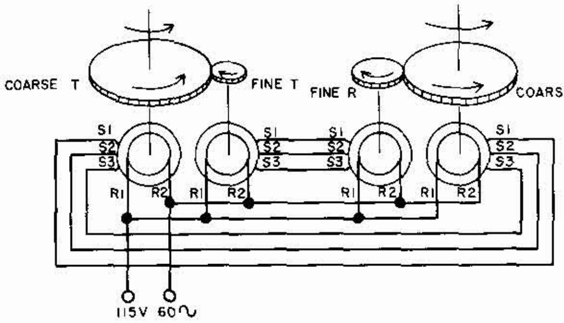
When the rotors of synchro devices turn in unison with their input and output shafts such devices are known as one-speed synchro systems. When a synchro receiver is in alignment with the transmitter no torque is developed, and with any movement of the transmitter rotor, the receiver must first overcome the restraining forces of the load before it can follow the transmitter. Even with no load the receiver must first overcome the restraining forces due to the friction of the receiver bearings before rotation occurs. This results in an angular displacement between the input and output shafts, called the no load error. Geared synchro systems are used when a high degree of accuracy is required. The following diagram illustrates the difference in error between 1-speed and 36-speed systems.



Comparison of ERROR Between 1-Speed and 36-Speed Synchro System

It can be seen in the above illustration that the 36-speed synchro system is far more accurate than the one-speed system. In both systems the error caused by bearing friction and resistance of the load amounts to one degree. In both systems the controlling shaft is rotated 10°. In the 1-speed system the transmitter is rotated 10° and the 1° error limits the receiver rotation to 9° and hence the output shaft rotates only 9°. In the 36-speed system, however, the transmitter is rotated 350° when the controlling shaft is rotated 10°, and the 1° error limits the receiver to 359° of rotation. This 359° of rotation causes the output shaft to rotate 9.97°. In other words, system error of the 36-speed system is only approximately .03° compared to 1° for the one-speed system. One disadvantage of geared synchro systems is that the self synchronous feature of the one-speed system is lost. When power to a one-speed system is interrupted, and the transmitter is turned the receiver of course does not follow, but when power is restored it aligns itself correctly with the transmitter. However, in a geared system, such as the 36-speed system used extensively in the Navy, 36-positions of the output shaft exist for which the receiver is in alignment with the transmitter.

The self-synchronous feature of the one-speed system and the high accuracy of the 36 speed system can be combined by making use of coarse and fine synchros connected to the same input and output shaft. Such a system is illustrated below.



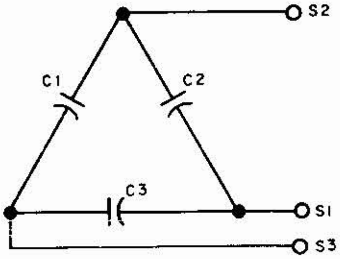
36-Speed Synchro System Using Coarse-Fine Synchros (Dual Speed System)

In the coarse-fine synchro system, incorrect alignment of the 36-speed system is prevented, because when the shaft error is large the one-speed system has control, and reduces the error to a small value. At this point the 36-speed synchro takes over, and further reduces the error to a very small value. When a dual-speed synchro system utilizes a control transformer to drive a servomechanism a cross-over system or synchronizer must be used. The function of this system is to determine whether the coarse or fine CT error voltage is fed to the servo amplifier. When the input shaft of a 36-speed system is turned 2.5° the fine CT rotor is displaced

90° from its zero voltage position. This position provides maximum induced voltage in the fine CT rotor, but, more important, this is the first maximum voltage point since the zero error position. For this reason, cross-over systems are designed so that the fine CT has control for error angles less than 2.5°. For larger error angles the synchronizer or cross-over system cuts out the fine CT and the coarse CT takes control. There are a variety of cross-over circuits in use. One system utilizes a plate-circuit relay which normally allows the 36-speed CT to control the servo system. However, when the error angle increases beyond 2.5°, increasing the output of the coarse CT, the relay is energized and the coarse (1-speed) CT assumes control of the servomechanism. Some cross-over arrangements use purely electronic switching; these usually depend upon biasing and limiting circuits.

It has been pointed out that the differential synchro and the synchro control transformer both draw current from the transmitter, even when the system reaches a position of electrical and mechanical balance. The differential draws current because of the step-up turns ratio between stator and rotor. In the case of the control transformer current is drawn from the transmitter, because the CT rotor is not energized, and opposing voltages are not induced in the CT stator.

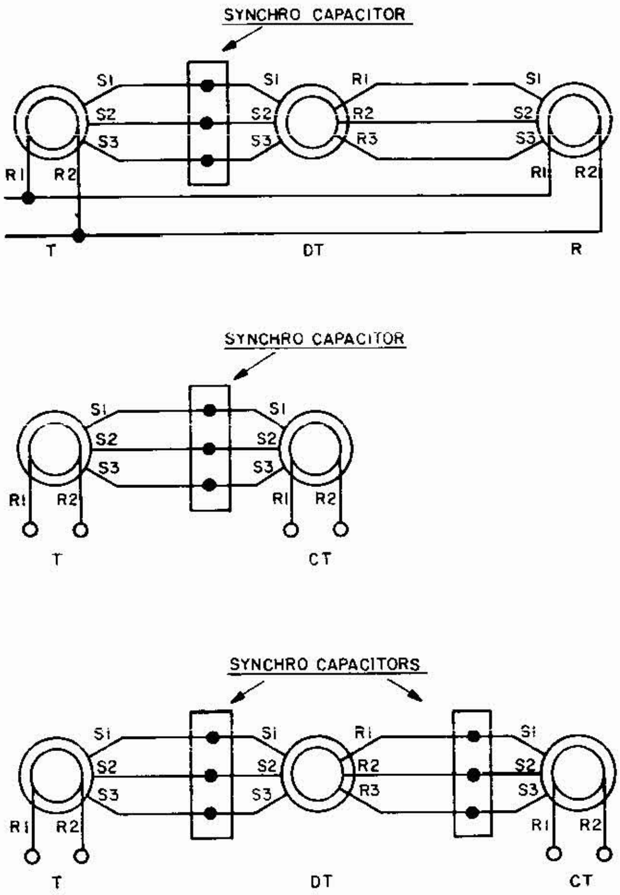
In order to reduce the current flow when either or both of these units are used, synchro capacitors are connected into the circuit. Current flow in a synchro system is comprised of resistive and inductive current. If the inductive reactance of a differential stator winding is shunted by an equal capacitive reactance the inductive current is then effectively cancelled by the capacitive current. In this case all that the transmitter actually does is to supply power demanded by the resistive losses of the circuit. Synchro capacitors are manufactured with three capacitors contained in a single unit and are internally connected as illustrated below.



Synchro Capacitor

The individual capacitors are matched to a tolerance of less than one percent to maintain proper current balance. Synchro capacitors are connected into various synchro systems as illustrated below.

Part A of the illustration shows the connections for a differential transformer as used with a transmitter and receiver, while Part B shows the connections for a control transformer and transmitter. In Part C both a differential transformer and a control transformer are used and each requires a separate capacitor unit.



Synchro Capacitor Connections

Synchro capacitors are used only when it is desired to cancel or partially cancel existing current. The synchro capacitor is never used in simple transmitter-receiver circuits because in such a system the reactive component of stator current is assumed to be zero and insertion of a synchro capacitor only increases current and throws the system out of balance. However, exciting current in this type system may be reduced by connecting a capacitor across the rotor.

FAILURE ANALYSIS.

No Output. Failure of a receiver rotor to rotate when the transmitter is rotated, or no-voltage output from a control transformer are considered no-output conditions. Frozen bearings or a jammed load could restrain a receiver rotor, and lack of excitation to the transmitter rotor would disable the synchro system. Existence of the first condition can be readily ascertained by attempting to manually rotate the receiver rotor. Existence of the second condition (no transmitter excitation) can be readily checked by measuring the voltage across the transmitter rotor. If no voltage is present check for a blown input line fuse, or an open input line. If voltage is present across the transmitter rotor, but the system is inoperative, deenergize the system and check the continuity of the transmitter rotor. If any two stator lines are open the synchro system will be inoperative. Resistance checks can be used to determine continuity of stator windings and stator leads.

Improper Operation. Improper operation is the result of incorrect wiring or an open or shorted winding in any of the synchro units, or excessive friction in bearings. If any of the stator windings are reversed, the units will not overheat and they will develop normal torque, but the receiver will turn in the direction opposite to that of the transmitter and a 120° bearing error will exist. If the rotor windings are reversed, operation will be normal except that a 180° bearing error will exist. An open receiver rotor results in weak torque, receiver hum, and possible ambiguous behavior, since the receiver rotor now operates as an iron bar rotor. The transmitter supplies excessive current when the receiver rotor is not energized, and may burn out or blow line fuses. An open or shorted stator winding results in erratic operation and could possibly overheat synchro units.

In general, if the synchro units operate smoothly, do not overheat, and produce normal torque, but do not rotate in the proper direction and/or an error which is some multiple of 60° exists, the probable cause is incorrect wiring. Since different units of a synchro system are usually located some distance from each other, and are connected by busses or cables which often pass through junction boxes, wiring errors are frequently made during repair, or during new installations, or modifications to existing installations. Symptoms such as overheating, blown fuses, hum, or erratic operation are indicative of a short or open winding within the synchro units, or open or shorted interconnecting cables. Resistance measurements are valuable in locating shorts and opens in synchro units. While resistance values vary from one type of synchro to another it should be assumed that an ohmmeter will show the same reading across rotor or across stator windings of similar units, within close tolerances. Be certain that all power is disconnected before resistance or continuity measurements are attempted. Typical resistance values are low, ranging from a fraction of an ohm in the rotor of large synchros, to several hundred ohms in the stator windings of smaller units.

SERVO MOTOR-CONTROLLER CIRCUIT.

APPLICATION.

The d-c servo motor-controller, also called a servo amplifier, is used in conjunction with a synchro system to control a servo motor which operates an indicator dial or rotates a load to a similar position.

CHARACTERISTICS.

Drives d-c servo motor.

Output is proportional to magnitude of error input.

Is phase sensitive, direction of servo motor rotation is determined by phase of error input.

Use is limited to low power applications.

CIRCUIT ANALYSIS.

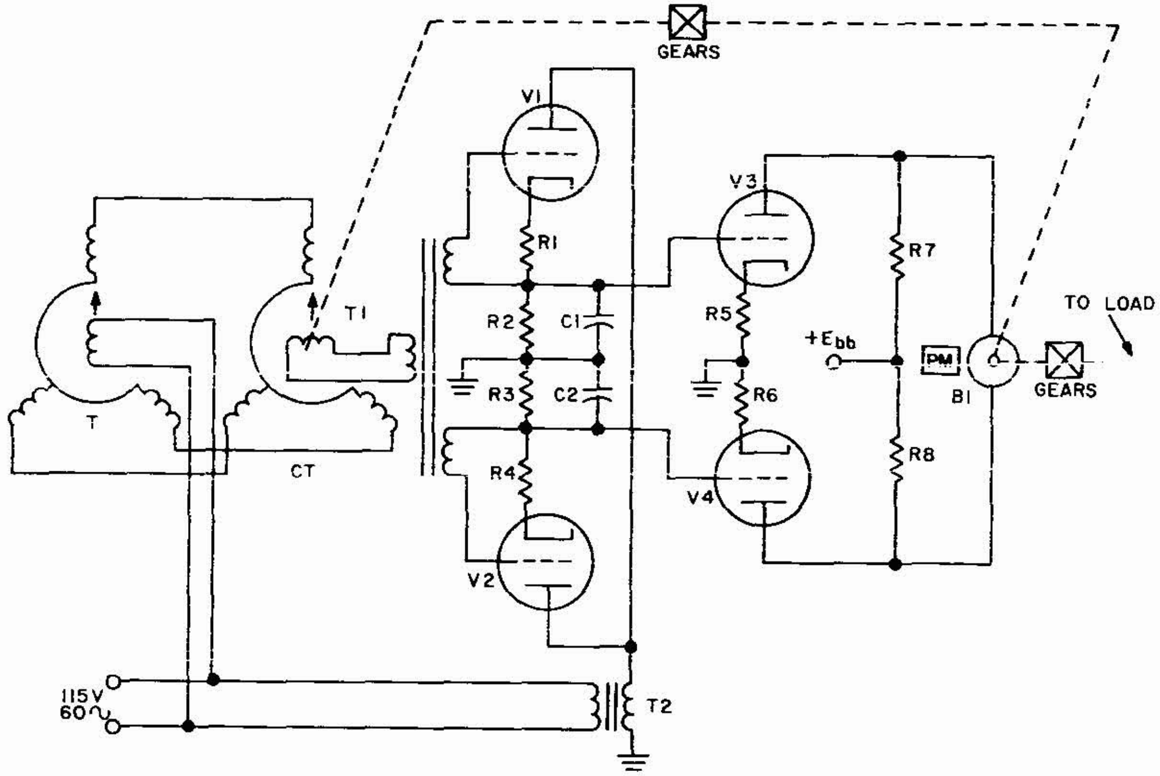
General. The d-c servo motor-controller receives an error voltage input from a synchro control transformer (CT) and effectively compares this error voltage with an a-c reference voltage to provide an amplified d-c output which drives a d-c servo motor. The d-c servo motor-controller circuit consists of a phase sensitive detector-amplifier, with the a-c reference voltage used as plate voltage, coupled to a d-c amplifier, whose output drives a d-c servo motor. The magnitude of the d-c output, which determines the speed of the drive motor, is dependent upon the amplitude of the error voltage. The polarity of the d-c output, which determines the direction of servomotor rotation, is dependent upon the phase relationship between the error voltage input and the a-c reference voltage.

Circuit Operation. The accompanying schematic diagram illustrates a typical d-c servo motor-controller circuit and associated synchro and drive equipment.

Transformer T1 couples the error voltage in push pull (180° out-of-phase), from the rotor of the synchro control transformer to the grids of detector amplifier tubes V1, and V2. Resistors R2 and R3 serve as load resistors for V1 and V2, respectively. Resistors R1 and R4 provide degenerative feedback to the cathode of V1 and V2.

Transformer T2 applies the a-c reference voltage in parallel (in-phase) to the plates of detector-amplifier tubes V1 and V2. Capacitor C1 and C2 filter the pulsating dc developed across R2 and R3. V3 and V4 serve as d-c amplifiers with R5 and R6 as their cathode resistor, and R7 and R8 as their plate load. D-C servo motor B1 is mechanically geared to the load to be positioned and is also mechanically coupled back to the synchro control transformer.

Tubes V1 and V2 conduct only on positive alternations of the a-c reference voltage. When the synchro control transformer is in alignment with the synchro command transmitter there is no error signal input, and V1 and V2 conduct equally during the positive portion of the reference signal. Thus equal voltages are developed across R2 and R3. At this point V1 and V2 are functioning as rectifiers, and the voltage across R2 and R3 is pulsating d-c, which is filtered by capacitors C1 and C2, and applied to the grids of V3 and V4. D-C amplifier tubes V3 and V4 conduct equally under this condition, and the voltage developed across R7 is equal to the voltage across R8. Therefore, no difference in potential exists between the plates of V3 and V4 and, hence, no current flows through the armature of servo motor B1, and the motor will not rotate. When the synchro command transmitter is moved to some new position, the synchro control transformer is no longer in alignment with the command transmitter rotor and an error voltage output is produced by the synchro control transformer and is applied to the servo motor-con-



Servo Motor-Controller Circuit

troller circuit. It is important to keep in mind that, the a-c reference voltage applied to the plates of V1 and V2 is from the same source as the synchro excitation voltage, and any error voltage induced into the control transformer rotor is either in-phase or 180° out-of-phase with the reference voltage. Assume that the angular displacement between the synchro command transmitter and the synchro control transformer is in such a direction that the error voltage induced across the CT rotor is in-phase with the reference voltage. When the reference voltage goes positive, a positive half cycle is applied to the grid of V1 and a negative half cycle of error voltage is applied to the grid of V2 (remember that T1 is effectively a push-pull transformer). The conduction of V1 increases and, therefore, an increased voltage drop occurs across R2 and this voltage is filtered by C1 and applied to the grid of d-c amplifier V3, causing the conduction of V3 to increase. At the same time, the negative half cycle of error voltage applied to the grid of V2 decreases conduction of V2, causing a decreased voltage drop across R3, and consequently the d-c voltage coupled to the grid of V4 decreases, reducing the conduction of V4. Since the conduction of V3 increased, while the conduction of V4 decreased, a difference in potential now exists between the plates of V3 and V4 due to the increased voltage drop across R7, and the decreased voltage drop across R8. Current now flows from the plate of V3 through the armature of drive motor B1 to the plate of V4 and the motor rotates driving the load in the desired direction. V1 and V2 conduct only during the positive half cycle of the a-c reference input. Drive motor operation, however, is not erratic since filter capacitors C1 and C2 maintain fairly constant voltages across the grids of V3 and V4, causing the servo-motor-controller output to be fairly constant. The drive motor is also mechanically connected through gears to the synchro control transformer and rotates the synchro CT rotor toward the position of alignment with the synchro command transmitter. As the angular displacement between the CT rotor and the transmitter rotor diminishes the error voltage produced by the CT diminishes and the d-c output of the servomotor-controller decreases, causing the drive motor to rotate slower. When the CT reaches the same bearing as the command transmitter, drive motor rotation ceases because no error voltage is produced by the CT, and consequently there is no longer an output from the servo motor-controller. If the synchro command transmitter is rotated in the other direction, the resulting error voltage produced by the synchro control transformer will be 180° out of phase with the reference voltage. Circuit operation will be the same, but the polarities are reversed. V1 is driven negative causing a negative voltage to be applied to the grid of V3, and the voltage on the plate of V3 increases. V2 is driven positive causing a positive voltage to be applied to the grid of V4, and the voltage at the plate of V4 decreases. Current flows from the plate of V4 through the armature of servo motor B1 to the plate of V3, causing the servo motor to rotate in the direction opposite to the direction that it rotated previously.

FAILURE ANALYSIS.

No Output. Failure of the drive motor to rotate is considered to be a no-output condition. In a positioning system such as the dc servomotor system, no output could result from a defective synchro system, a defective servomotor-controller or a defective servomotor, or associated mechanical drive equipment. The synchro system can be checked by measuring the voltage across the CT rotor with an a-c voltmeter as the command transmitter is rotated 360°, and the servo motor-controller circuit disabled by removing V3 and V4. If the rotor voltage (called the error voltage) should vary smoothly from zero volts to about 55 volts the synchro system is operating normally. To check for a jammed gear train, load, or servo motor, attempt, with the power disconnected, to manually rotate the servo motor shaft. If the windings of the servomotor show the proper resistance when checked with an ohmmeter and there is not excessive leakage between windings the motor is most likely good. However, if a spare motor is available, substitution is a sure way of determining the merit of the servo motor. If the servo motor, gear train and synchro system is good, inability to position the load is most likely due to a defective servo motor-controller. Failure of error input transformer T1 and reference voltage transformer T2 would render the servo motor-controller inoperative. Using an ac voltmeter, check for 115 VAC on the plates of V1 and V2 to determine whether or not T2 is defective. T1 can be checked by observing the presence of an a-c error voltage on the grid of V1 and V2, while the synchro command transmitter is rotated. Check the voltage present at the junction of R7 and R8 to determine whether or not lack of plate supply voltage is the cause of no output. Failure of detector-amplifier tubes V1, V2, or failure of d-c amplifiers V3, or V4, could cause no-output. Failure of an individual circuit component is not likely to cause a no-output condition, but instead, an unbalanced condition would result between the output of d-c amplifiers V3 and V4, and improper operation would most likely result.

Improper Operation. Improper operation is considered any type of operation other than proper operation, such as, sluggish or slow rotation of the drive motor, erratic or jerky rotation, or a tendency to rotate better in one direction than the other. Improper operation could result from a defective synchro system, excessive binding of the gear train or load, a defective servomotor, or defective servo motor-controller circuit. The synchro system, gear train, and servo motor can be checked as explained previously, and if these associated components are satisfactory, improper operation is likely due to a faulty servo motor-controller circuit. The servo motor-controller circuit can be thought of as consisting of two branches. V1, V3, and associated circuit components comprise the upper branch, and V2 and V4 together with their associated components, comprise the lower branch. Any component defect that alters the performance of one branch as compared to the other could result in improper operation, possibly manifesting itself as a tendency of the drive motor to rotate better in one direction than the other, or possibly continuous or erratic rotation in one direction. A possible cause of improper operation is defective tubes. It would also be advisable to check the d-c power supply voltage, since low supply voltage could possibly cause sluggish operation. A change in value, short, or open of R1 or R2 would, of course, affect the operation of detector amplifier V1 and, likewise, a defect in R3 or R4 would adversely affect V2. If C1 or C2 shorted, V3 or V4, respectively, would be inoperative as amplifiers and improper operation would result. A change in value or defect in either R5, R6, R7, R8, would destroy the balance between d-c amplifiers V3 and V4, and improper operation could result. With the equipment deenergized all resistors can be checked for proper value with an ohmmeter, capacitors C1 and C2 can be checked with an in-circuit capacitor checker.

RESOLVER-DRIVER CIRCUIT.

APPLICATION.

The resolver-driver circuit is used to drive an a-c resolver, which is used as a computing element in problems involving coordinate conversion, coordinate rotation, and resolution of vectors. Resolver-drivers are also used to drive sweep resolvers in radar indicators.

CHARACTERISTICS.

Utilizes a pentode and a triode to drive a resolver.

Operates on the principle of a feedback amplifier.

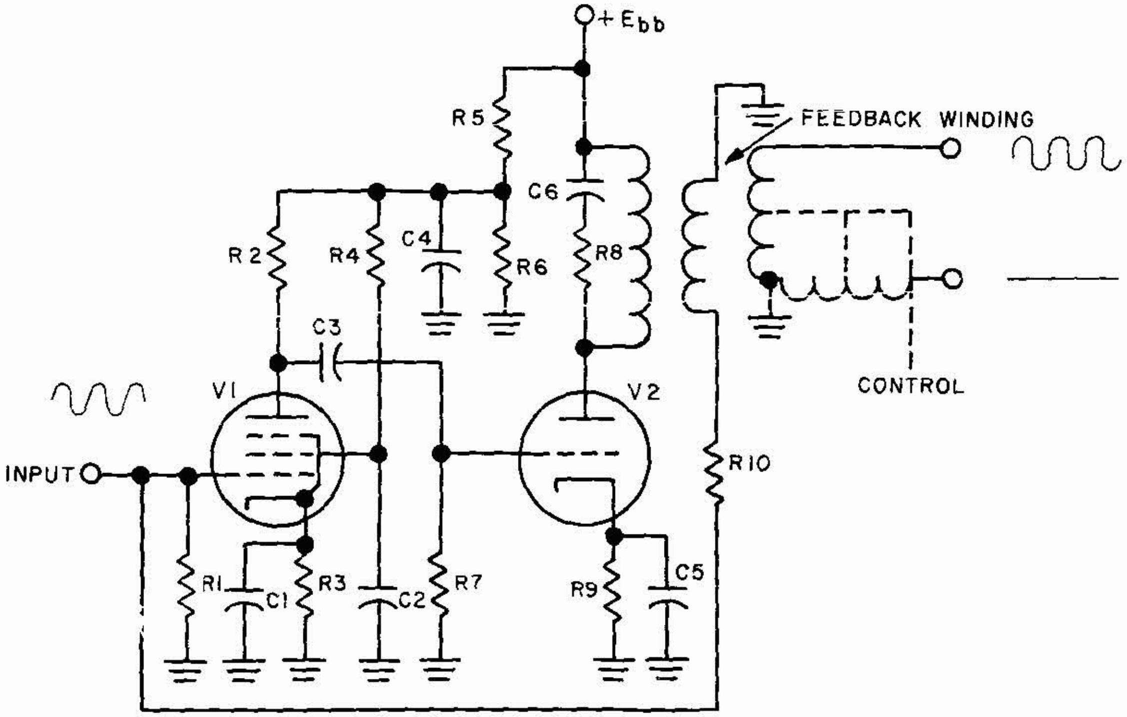
Provides power amplification with minimum distortion, voltage gain is unity.

CIRCUIT ANALYSIS.

General. The resolver-driver circuit amplifies an a-c synchro voltages to a power level sufficient to drive an a-c resolver with a minimum of distortion. The resolver-driver is basically a feedback amplifier consisting of a pentode voltage amplifier, coupled to a triode amplifier which drives the resolver primary winding. R-C coupling is used between the first and second amplifier stage, and distortion is minimized by the use of degenerative feedback which is obtained from a feedback winding within the resolver and is coupled back to the grid of the first amplifier.

Circuit Operation. The following schematic diagram illustrates a resolver-driver circuit.

Resistor R1 is the input grid resistor for pentode amplifier V1. Resistor R2 is the plate load and R3, which is bypassed by C1, provides cathode bias for V1. Resistor R4 is the screen dropping resistor for V1, and C2 is the screen bypass capacitor. R-C coupling consisting of capacitor C3 and resistor R7 is employed between V1 and V2. A



Resolver Driver Circuit

voltage divider consisting of R5 and R6 is used to drop the plate supply voltage to the proper value of plate voltage for V1. Capacitor C4 bypasses a-c voltage variations to ground and prevents unwanted degeneration. Resistor R9 which is bypassed by C5 serves as the cathode bias resistor for triode amplifier V2. The plate load for V2 is the primary winding of the resolver. The primary winding of the resolver is shunted by a series r-c network, consisting of R8 and C6, which is intended to compensate for the inductive impedance of the resolver winding and thereby maintain the power factor near unity. Degenerative feedback is developed across the feedback winding within the resolver and applied to the grid of V1 through resistor R10.

When an a-c input is applied to the input of the resolver-driver it is amplified by conventional a-c amplifier stage V1, and is capacitively coupled to the grid of driver stage V2. The a-c synchro voltage applied to the grid of V2 is amplified and developed across the primary of the resolver, and is inductively coupled to the resolver feedback winding and the resolver secondary windings. R-C network, R8-C6, cancels the effects of the inductive reactance of the resolver windings and makes the output load appear resistive, thus bringing the power factor of the output load to unity. Degenerative feedback developed by the resolver feedback winding is attenuated by resistor R10 and is applied to the grid of V1. The value of R10 is such that the amplitude of the degenerative feedback is great enough to reduce the closed loop voltage gain of the resolver-driver to unity. The degenerative feedback improves the fidelity and stability of the resolver-driver. Stability is improved since a decrease in emission of the tubes, which would normally reduce the output (if feedback were not present), instead tends to decrease the magnitude of the present feedback and results in increased closed loop gain, since there is less degenerative feedback (which is 180° out-of-phase with the input) present at the grid of V1.

FAILURE ANALYSIS.

No Output. A no-output condition in the resolver-driver circuit could result from failure of the power supply or failure of one of the tubes. Check the power supply voltage with a voltmeter, and also check the tubes. If operation is not re- tubes which are known to be good. If operation is not restored a defective circuit component is most likely the cause of no output. Voltage checks of tube elements may be helpful in localizing the fault to a stage. Keep in mind that a fault in one tube element circuit such as the grid or cathode circuit, may effect the voltage present on other tube elements. Voltage checks are, therefore, only a means of localizing the trouble, and further resistance measurements are usually necessary to locate the component at fault. Improper plate and screen voltage on V1 could be caused by a defect in voltage divider R5, R6 or capacitor C4. Check R5 and R6 for proper value and check C4 for a possible short with an ohmmeter. If either plate voltage or screen voltage is incorrect check for proper value plate load resistor R2 and also check C3 for a possible short. Also check screen resistor R4 and its bypass capacitor C2 for a possible short or excessive leakage with an ohmmeter. Improper cathode bias could be caused by a defect in cathode resistor R3 or bypass capacitor C1. Check R3 for proper value with an ohmmeter, and check C1 for a possible short or excessive leakage, also with an ohmmeter. Improper grid bias could be caused by a defect in R1 or possibly a defect in the feedback circuit, consisting of the feedback winding within the resolver and R10, or by a defect in the output circuit of the preceding stage. Check the resistors in question with an ohmmeter and also check the continuity of the resolver winding. Improper grid bias on amplifier V2 would result if coupling capacitor C3 becomes shorted or if there is a significant change in the value of grid resistor R7. No output would also result if capacitor C3 opens, since the a-c signal would not reach the grid of V2. Check R7 for proper value with an ohmmeter and check C3 with an in-circuit capacitor checker, since both a short or an open could cause a no-output condition. Improper cathode voltage on V2 could be caused by a defect in R9 or a short in bypass capacitor C5. Check R9 for proper value and check C5 for possible leakage or a short. If the primary of the resolver opened there would be a no-output condition. This can easily be detected since there would be no plate voltage on V2. Various defects within the resolver could cause a no-output condition to exist. The resolver may be checked by measuring the resistance of its windings and by checking for excessive leakage between windings.

Low Output. The resolver-driver is basically a feedback amplifier. A prime characteristic of a feedback amplifier is the ability to maintain their gain at a predetermined level regardless of variations in tube characteristics with age. This characteristic exists because a tendency for the output amplitude to decrease also results in a decrease in the amplitude of the degenerative feedback, which is developed in the output circuit. This decrease in degenerative feedback has the same effect as increasing the input amplitude, and the overall effect is for the gain to remain constant. However, if the components deteriorate beyond the limits of feedback control low output could result. Check the power supply voltage and adjust if necessary.

If proper operation is not restored a defective circuit component is most likely the cause of decreased output. A decrease in value of R10 would result in a greater amount of negative feedback reaching the grid of V1 and result in decreased closed loop gain, hence, decreased output would result. Check R10 for proper value with an ohmmeter. Voltage checks of tube elements should reveal whether or not a change in operating levels caused by a defective component is the cause of low output. Any discrepancies found during voltage checks can be followed up with resistance measurements of suspected components, as explained in the previous paragraph, to locate the component at fault. A decrease in value of R8 or a shorted C6 could shunt a portion of the output signal around the primary of the resolver, resulting in decreased output. Check R8, with an ohmmeter, for proper value and C6 with an incircuit capacitor checker. A defective resolver can also cause a low output condition to exist. Measure the resistance of all resolver windings being alert for a lower than normal reading which would indicate that some of the turns on the winding in question are shorted. Also check for excessive leakage between windings and to ground.

Distorted Output. A defect in the feedback circuit is a prime cause of distorted output in resolver-driver circuits. Measure the resistance of the resolver feedback winding and check the ungrounded end of the feedback winding for a possible short to ground. Also check feedback resistor R10 and V1 grid resistor R1 for proper value. If the feedback circuit checks out good, check the power supply voltage and check the tubes by exchanging them with tubes which are known to be good. If the resolver-driver output is still distorted a defective component could be altering the operating level of one of the stages and causing distortion to occur. Voltage and resistance checks may be made, as explained previously, to locate the component at fault.

PHASE SENSITIVE NULL DETECTOR CIRCUIT.

APPLICATION.

The phase sensitive null detector is used in servo control circuits to operate a dc relay when the input error voltage is in phase with the reference voltage.

CHARACTERISTICS.

Output (position of d-c relay) is dependent upon phase relationship between an input error voltage and a reference voltage.

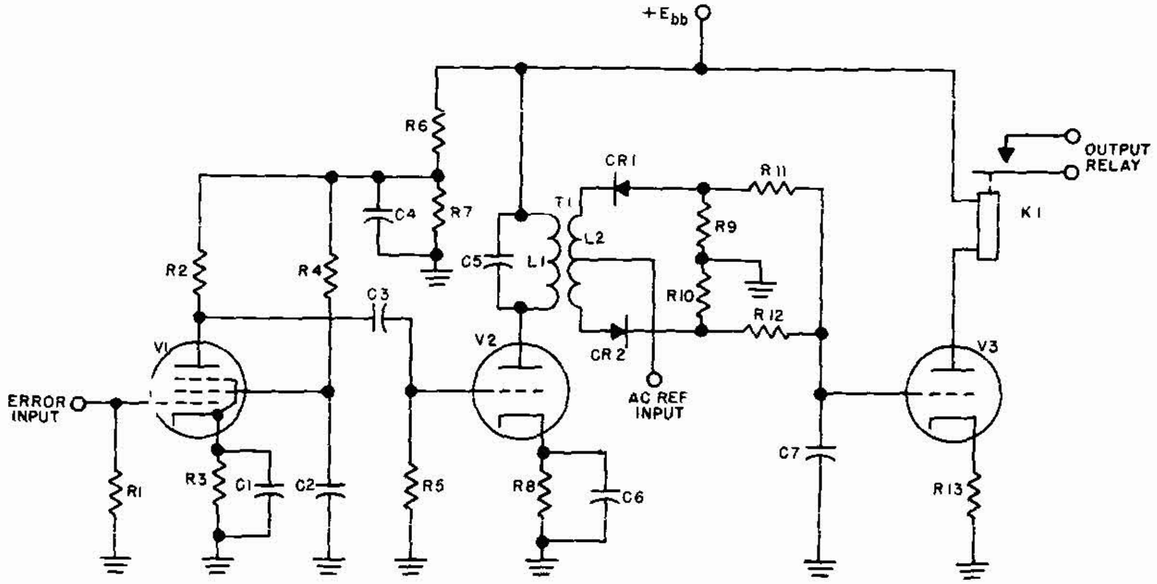
Circuit may be connected so that the output relay is energized when both signals are in-phase, or when they are out-of-phase.

Use a pentode and two triodes.

CIRCUIT ANALYSIS.

General. The phase sensitive null detector consists of a two stage a-c amplifier, a phase sensitive detector, and a relay control tube with a d-c relay in its plate circuit. Basically the phase sensitive null detector compares a-c error voltage to a reference a-c voltage and determines whether or not they are in phase. The a-c amplifiers provide sufficient gain so that very small error voltages may be effectively compared with the reference voltage, allowing an output to be produced almost immediately after the error voltage becomes in phase with the reference voltage. The amplified a-c error voltage is applied to the phase sensitive detector stage through a transformer. The amplitude and polarity of the phase detector output is dependant upon the amplitude of the error voltage input and the phase of the error input with respect to the reference voltage. With the circuit connected in the standard manner the phase sensitive detector stage produces a positive voltage output when the error signal and reference signal voltages are in phase. The detector stage output voltage is filtered and applied to the grid of the final stage, a d.c relay control tube. When the detector output voltage is positive, as it is when the error and reference voltages are in phase, conduction of the relay control tube is increased and the relay becomes energized. If the error voltage is out-of-phase with the reference voltage, the detector output voltage is negative, and the relay control tube does not energize the output relay.

Circuit Operation. The following schematic diagram illustrates a phase sensitive null detector.



Phase Sensitive Null Detector

Resistor R1 serves as the input grid resistor for pentode amplifier V1. Resistor R2 serves as the plate load for V1 while R3 which is bypassed by C1 functions as the cathode bias resistor for V1. Resistor R4 is a series screen dropping resistor, and capacitor C2 is the screen bypass for V1. R-C coupling between V1 and triode amplifier V2 is provided by capacitor C3 and grid resistor R5. Resistor R8 which is bypassed by C6 serves as the cathode bias resistor for V2, while the primary L1, of transformer T1 which is shunted by C5 serves as the plate load for V2. Resistors R6 and R7 form a voltage divider between the plate supply and ground to provide the proper plate voltage to V1 with capacitor C4 functioning as a bypass capacitor. Transformer T1 couples the error voltage to a phase sensitive detector consisting of diodes CR1 and CR2 and resistors R9 and R10. The reference voltage is coupled to the phase detector stage via a centertap on the secondary of T1. The output of the phase detector is applied to a filter network consisting of resistors R11, R12 and capacitor C7. The filtered phase detector output is applied to the grid of relay control tube V3. Resistor R13 serves as an unbypassed (degenerative) cathode bias resistor for V3, while d-c relay K1 forms the output load for V3.

The a-c error voltage is applied to the grid of amplifier V1, and the large amplitude error voltage developed across plate resistor R2 of amplifier V1 is coupled through capacitor C3 to the grid of amplifier V2. Amplified error voltage is developed across the primary of transformer T1 and is inductively coupled to the secondary of T1. The a-c reference voltage is applied to the phase sensitive null detector through a center top on the secondary of T1. For ease of explanation assume for a moment that only the a-c reference voltage is applied to the phase detector stage. During the positive half cycle of the a-c reference voltage, current flows from ground, through R10, through CR2, and back to its source, the secondary of T1. Diode CR1 is reverse-biased for the positive half cycle of a-c reference voltage and does not conduct. Voltage is developed across R10 and the junction of R10, and R12 is above ground potential. During the negative half cycle of the reference voltage, reference diode CR2 is reverse-biased and does not conduct. However, diode CR1 is forward biased and current flows from the transformer centertop through the top half of the winding, through CR1 and through R9 to ground. A voltage is developed across R9 and the junction of R9 and R11 is below ground potential. The positive voltage produced by the rectifying action of CR2, and the negative voltage, produced by the rectifying action of CR1, deviate equally, in their respective directions, from ground potential since CR1 and CR2 have the same operational characteristics and resistors R9 and R10 are of equal value. The negative voltage is filtered by R11 and C7 and the positive voltage is filtered by R12 and C7. The d-c level applied to the grid of relay tube V3 is, therefore, zero volts, when only the reference voltage is applied to circuit. The relay control tube V3 is self biased by its cathode resistor to a conduction level insufficient to energize output relay K1. Since in effect there is no output from the phase detector portion of the phase sensitive null detector when only the a-c reference voltage is applied, conduction of V3 does not increase and the output relay remains deenergized. When an a-c error voltage is applied in addition to the a-c referenced voltage, there is an output from the detector circuit. The polarity of this output is dependent upon the phase relationship between the error and reference signals. Only a positive output from the detector causes the output relay to become energized. When the a-c reference voltage and the error voltage are in phase the output relay becomes energized in the following manner. During the period of the positive half cycle of input signal, a positive half cycle of reference voltage is applied to the centertap of T1, and is applied equally to both diodes. The error voltage, after being amplified by V1 and V2, is applied to primary winding L1 of T1. A negative half cycle of error voltage is induced across the top half of L2 while a positive half cycle of error voltage is induced across the bottom half of L2. The a-c reference voltage and the a-c error voltage add across the bottom half of L2 while across the top half of L2 they oppose. The result is a positive detector output during the positive half cycle of inputs, since diode CR2 conducts more heavily than CR1 and the resultant voltage drop across R10 exceeds that of R9. When the input signal swings negative, the voltages across the top half of L2 again oppose while across the bottom half they add, but they are of such a polarity that CR2 is back biased and does not conduct. There is therefore a positive output from the detector portion of the phase sensitive null detector when the input signals (error and reference) are in phase. After being filtered by R12 and C7 this positive voltage is applied to the grid to relay control tube V3, causing conduction of V3 to increase, and thereby energizing output relay K1. If the error voltage developed across T1 is of greater amplitude than the reference voltage, a negative voltage is developed across R9 during the positive alternation of the error input. However, the positive voltage developed across R10 due to the conductions of CR2, is of greater magnitude than the voltage developed across R9 since the reference voltage opposes the error voltage applied to CR1 while it aids the error voltage applied to CR2. The d-c level after filtering remains positive and the output relay remains energized. When the error voltage is out-of-phase with the reference voltage, circuit operation is basically the same, except that a negative output is produced by the detector stage and is applied to the grid of V3. The negative output is produced because the two signals applied to the detector stage now add across the top half of L2, and oppose across the bottom half. The magnitude of the current through R9 exceeds that of R10, and the resultant negative voltage developed across R9 exceeds the positive voltage developed across R10. The negative voltage applied to the grid of V3 reduces rather than increases conduction of V3 and output relay K1 is not energized. The phase sensitive null detector may also be connected so that the relay becomes energized when the error voltage and the reference voltage are out-of-phase. This may be done simply by reversing either the primary or secondary windings of T1 or by reversing the diodes.

FAILURE ANALYSIS.

No Output. Failure of the output relay to become energized when the proper conditions are met, i.e., error and references voltages either in or out-of-phase depending upon how the circuit is connected, is considered to be a no-output condition. Failure of any of the three stages (the a-c amplifier, the phase detector, or the relay control tube) of the phase sensitive null detector could cause a no-output condition to exist. Failure of the power supply would of course disable the circuit and no output also would result. Check the plate supply with a high resistance voltmeter and likewise check the tubes. If the power supply voltage is satisfactory and the tubes are good, a defective circuit component is most likely the cause of no-output. With an error voltage applied to the input and the reference voltage removed check with an oscilloscope for presence of amplified error voltage on the secondary winding L2 of T1. Also observe the waveform present at the grid of V1 to make sure that the no-output condition is not caused by no input. If there is no error voltage present at the secondary of T1 check the primary of T1 to determine whether or not T1 is defective. If the a-c error voltage is present in sufficient amplitude at the plate of V2 the a-c amplifier stages may be assumed to be good. If the error voltage is not present at the plate of V2 a defect likely exists in the a-c amplifier stages. Voltage checks of tube elements, which should give an indication of the locality of the faulty components may be made, and then with the circuit deenergized, resistance measurements of suspected components may be made to determine the component at fault. Improper grid bias on V1 could be caused by a defect in R1, or in the output circuit of the preceding stage, while improper cathode bias could be caused by a defect in R3 or a shorted C1. A defect in voltage divider R6, R7 or a shorted or leaky bypass capacitor C4 would alter both plate and screen voltage on V1. A change or defect in R2 would alter the plate voltage on V1, and a defect in R4, or a short in C2, would affect screen voltage on V1. Keep in mind that improper grid or cathode bias would also alter plate voltage on an amplifier stage. Improper grid bias on a-c amplifier stage V2 could be caused by a shorted coupling capacitor C3 or a defective grid resistor R5, while improper cathode bias could be caused by a defect in cathode resistor R8, or a shorted cathode by pass capacitor C6. Lack of plate voltage on V2 could be caused by an open primary winding, L1 of T1. Capacitor C5 should be checked since the a-c error signal would be shunted around T1 if C5 shorted. If the a-c reference voltage is not present check the source of the a-c reference. If the a-c amplifier is operating normally, and the reference voltage is applied to the detector stage, a no-output condition could be caused by a defective phase detector stage or relay control stage. The relay control stage may be easily checked by measuring the resistance of R13, the cathode resistor for V3, and by checking the continuity of relay coil K1. Also check the mechanical action of relay K1 since it could become jammed. Diodes CR1 and CR2 of the phase detector stage should be checked by disconnecting one lead of each diode and measuring the front to back ratio of each diode. In general the back ratio of most diodes should be greater than 10:1. The other components of the phase detector stage, resistors R9, R10, R11, and R12, may be checked by measuring their resistance. Filter capacitor C7 may be checked for proper value with an in-circuit capacitor checker.

Improper Operation. Erratic operation, failure of the output relay to energize, or any type of operation rather than proper operation could be caused by improper plate voltage, a decrease of gain of the a-c amplifiers, an unbalance of the phase detector stage, or it could be caused by decreased emission of the relay control tube, or a mechanical defect in output relay K1. Check the power supply voltage and adjust or repair it if necessary. If proper operation is not restored, the tubes may be at fault. If the phase sensitive null detector still does not function properly, the various stages may be checked individually to localize the trouble. The gain of the ac amplifier may be checked by comparing the amplitude of the error voltage input with the amplitude of the error voltage developed across the primary, L1 of T1 using an oscilloscope. For small error voltages the gain should be around 3000. Be sure to remove the reference voltage when making the previous check since the reference voltage applied to the secondary of T1 could be inductively coupled to the primary of T1 and cause a possible erroneous reading. If the a-c amplifier is determined to be defective, the faulty component may be located as explained in the preceding paragraph. The phase detector stage may be checked by removing either V1 or V2 (this disables the a-c amplifier) and measuring the voltage on the grid of V3. Any voltage reading other than zero volts indicates an unbalance of the phase detector stage. Check the components as explained in the previous paragraph paying particular attention to the front to back ratio of CR1 compared to CR2 and the resistance of R9 compared to R10 and R11 compared to R12. Filter capacitor C7 should be checked for proper value with an in-circuit capacitor checker, since a change in value of C7 can adversely affect circuit performance. Relay control stage V3 may be checked by measuring the d-c resistance of the output relay winding and by checking the mechanical operation of the relay and also checking the resistance of cathode resistor R13.

PART B. SEMICONDUCTOR CIRCUITS

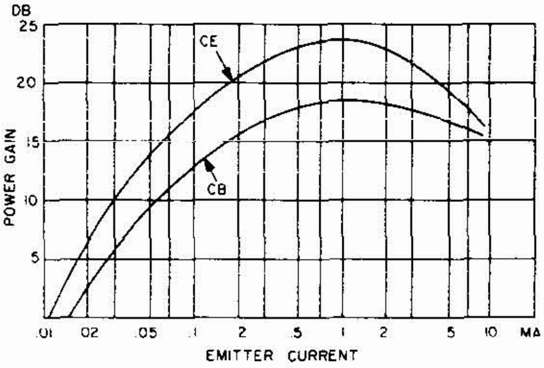
AGC (OR AVC) CIRCUITS.

It is often desirable to control automatically the output of a number of amplifier stages so that a relatively constant output level is maintained regardless of input signal variations. For example, in communications circuits, signal fading will cause the signal at the input of a receiver to vary from a few microvolts to thousands of microvolts almost instantly. Consequently, without automatic volume control, the receiver output would be unbearably loud and greatly distorted on strong signals if the receiver were set for reception of weak signals. In electron tube receivers, the common method of controlling the volume is to incorporate a circuit which automatically varies the bias voltage of the r-f and i-f stages to control the over-all gain. This is known as **automatic gain control** (AGC) and is sometimes referred to also as **automatic volume control** (AVC). Similar circuit arrangements are used for transistorized equipment. In other instances it is desired to keep an audio or video output level constant regardless of input level variations; circuits used for this purpose are called **volume compression circuits** and are discussed in Section 6, AMPLIFIER CIRCUITS, in this handbook. The circuit discussions on AGC in this section will be limited to circuits used to control the gain of r-f or i-f stages.

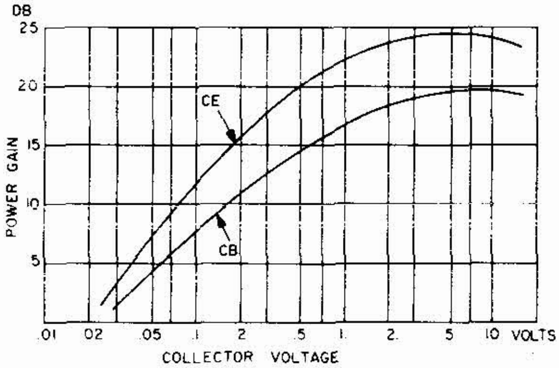
AGC circuitry in the semiconductor field falls into two general classes. One class uses the variation of d-c bias on one or more elements of a transistor amplifier stage to control its gain. The other class employs a diode or another transistor to shunt the input signal to ground (or around the controlled stage) and thereby reduce the over-all gain. The output of the second detector in a superheterodyne receiver provides, in addition to the desired signal, a d-c component which is proportional to the carrier strength of the received signal. This d-c component offers a convenient method of controlling the bias on a preceding r-f or i-f amplifier and thus controlling the stage gain.

Variation of transistor bias to control the gain may be accomplished either by changing the emitter current (I_E) while the collector voltage is held substantially constant, or by changing the collector voltage (V_C) by means of the collector current. These two methods are sometimes called **reverse AGC** and **forward AGC**, respectively. The accompanying figure shows a comparison of the two methods. In the figure, curves are shown for both the common-emitter and common-base circuit configurations. Upon examination of the figure, it is evident that the two configurations perform similarly, with the common-emitter circuit providing a somewhat greater control range. The emitter current control circuit is more generally used than the collector voltage control circuit, mainly because of the very low collector voltage provided. At low collector voltages the collector capacitance is increased (an inherent disadvantage in the transistor); consequently, the alpha cutoff frequency is reduced, making the transistor a poor r-f or i-f amplifier. The illustration also indicates an important difference between the semiconductor AGC circuit and the electron tube AGC circuit; namely, the transistor AGC unit operates at very much lower power and voltage levels. For example, over the first decade (between .01 and 0.1 ma), the CE emitter-control circuit provides a range of from approximately 0 to 18 db gain variation with a current variation of only 100 microamperes. In the collector-voltage control circuit a similar range is covered with a variation of only 0.28 volt. Over the second decade, this performance is halved with the curve reaching its zenith and then declining.

When the bias of the transistor is changed by AGC control, the input and output impedances also change and produce a shift in the bandwidth and center frequency to which the circuit is tuned. For example, when the emitter current of a CE stage is reduced to decrease the gain, it causes an increase in input impedance



Emitter Current Control



Collector Voltage Control

Comparison of Bias Control Methods

and capacitance. As a result, the bandwidth of a parallel resonant circuit used with it is decreased (because of the increased Q), and its center frequency is shifted higher. This is a basic disadvantage of this type of circuit and presents a design problem. In addition, at the very low currents and voltages given in the examples the stage cannot handle much power, particularly since the reduction is usually in a downward direction. The usual practice is to apply AGC control to a single stage (either the 1st rf or if), rather than to a number of stages as is common in electron tube practice. In those cases where substantial power is required to drive and control the emitter current of the transistor gain-controlled stage, a d-c amplifier may be provided. Usually, however, amplification is obtained by applying the control voltage to the base of the transistor amplifier and allowing it to act as its own d-c amplifier. Delayed AGC action can also be provided by adjusting the bias to be effective only above or below the desired operating level. Typical circuits are discussed in the following paragraphs.

EMITTER-CURRENT CONTROL.

APPLICATION.

Emitter-current control of AGC is universally used in transistorized receivers to keep the output voltage relatively constant regardless of input signal variations.

CHARACTERISTICS.

To control a PNP transistor, AGC circuit requires a positive voltage which increases as receiver input signal increases; to control an NPN transistor, it requires a negative voltage which increases as input signal increases.

For CE configuration, provides 18 db control for first decade of emitter current variation, decreasing to half this value for successive decades (for CB configuration, the range is approximately 5 db less).

Uses base bias voltage variation to provide d-c amplification of control signal.

When transistor amplifier is directly controlled by control source (detector), the source must be capable of supplying full emitter current of transistor amplifier.

Resistive component of input impedance increases as CE emitter current decreases.

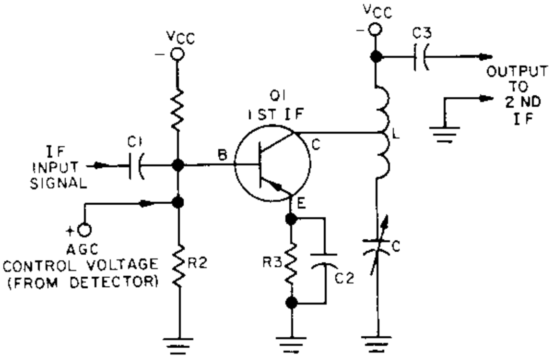
Input and output capacitance decrease as signal strength increases, and this decrease shifts center tuning frequency upward.

CIRCUIT ANALYSIS.

General. The emitter- current controlled AGC circuit operates normally with maximum gain at zero input signal. As the input (detected) signal increases in strength, the emitter current of the controlled amplifier is reduced. Hence, the gain of the transistor is also reduced. Therefore, with a large input signal the emitter- current controlled amplifier operates at a very low level. As a general rule, currents above 500 microamperes have little control over the gain; that is, the gain variation for currents over 500 microamperes is so slight that the circuit provides too small a range of control to be useful. However, as the emitter current is reduced below 500 microamperes, the over-all gain is greatly affected. The most effective control action is obtained over a current range of 10 to 100 microamperes (as illustrated by the emitter current control curve shown above).

Since the emitter current operates over a very small current range for large input signals, distortion is produced by detector nonlinearity. Over the middle range of operation the detector is linear and little distortion is produced. At very low levels of input signal, distortion again occurs because of detector nonlinearity in the small-signal region.

Circuit Operation. The accompanying figure shows a typical emitter-current controlled amplifier.



Emitter-current Controlled Amplifier

Capacitor C1 is a d-c blocking and a-c coupling capacitor which prevents the low d-c resistance of the input transformer from shorting the base and bias network to ground. Resistors R1 and R2 provide fixed voltage-divider bias for the base circuit. Since the base is negative with respect to the emitter, forward bias is applied. The AGC control signal is also applied to the base, and consists of a positive voltage which increases as the signal at the detector increases. When the control voltage increases, the total forward (negative) bias on the base is reduced, and the emitter current is reduced accordingly. Emitter swamping is provided by R3 (by-passed by C2) to provide temperature stabilization of the amplifier (refer to Section 3, paragraph 3. 4. 2, BIAS STABILIZATION, for a discussion of emitter swamping and voltage-divider biasing). The collector is tapped down on inductor L of the series-tuned resonant output circuit, consisting of L and C, to provide proper matching. The output circuit is tuned to provide maximum gain and selectivity at the intermediate frequency. Capacitor C3 is a d-c blocking and a-c coupling capacitor for the next stage (a transformer may be used in place of L, C, and C3 if desired).

Consider now the dynamic operation of the circuit. Normally C1 is resting, with the base biased for class A operation by voltage divider R1 and R2. Emitter and collector current values are normal class A values for quiescent conditions. When an i-f signal is applied between base and ground through C1, normal CE amplifier action occurs (assuming, of course, that no AGC voltage is applied from the control circuit). This, then, is the condition for no AGC where the amplifier operates at full gain with a very weak input signal. It is further assumed that the AGC control circuit is inoperative because of delayed AGC since the circuit is normally almost instantaneous in action. For this condition the emitter d-c current is at its maximum value. As amplification occurs, the instantaneous emitter current varies (decreases for the positive portion of the signal and increases for the negative portion). Since both positive and negative variations of signal are equal (assuming a sine wave), there is no average change in emitter current. The instantaneous i-f variations, however, are amplified and appear in the collector circuit (refer to Section 6, R-F AMPLIFIERS, TUNED INTERSTAGE (I-F) AMPLIFIERS for a complete discussion of normal amplifier action). As far as the amplifier is concerned, R3 is effective only for temperature variations, because it is bypassed by C3 for i-f signals. When the amplified signal appears in the detector, a d-c voltage is developed, in addition to the demodulated signal. This d-c voltage is proportional to the carrier strength and is taken at a point in the detector which provides an increasingly positive d-c voltage for an input signal which is increasing (for PNP transistors). Assume that the input signal level rises to a point where the detector positive AGC control voltage exceeds the delay voltage and provides a positive d-c voltage to the base of the transistor. Since the base of the transistor is negatively biased, the positive control voltage adds algebraically to reduce the total forward bias. Consequently, hole flow through the transistor is reduced, and the emitter current is reduced accordingly. (Both base and collector currents are reduced.) Therefore, the transistor forward current gain and the effective amplification of the transistor are reduced. Under these conditions, the transistor still amplifies the i-f signal, but not as much as before the forward bias was reduced. Thus as the input signal increases, the output of the transistor is decreased. When the input signal becomes weaker, the detector control voltage is decreased, the forward bias, in turn, is increased, and the amplifier produces a greater output signal. In this manner, the output of the amplifier is controlled by the input voltage, which automatically controls the gain of the transistor amplifier.

The over-all power gain is contingent upon matched input (and output) conditions. When the base current is reduced by AGC action, the effect is the same as though the input resistance of the transistor were increased ($R_{in} = V_{in}/I_{in}$). The output impedance also changes, but not as much as the input impedance. Thus a mismatched input and output condition results. Such a condition enhances the control action and provides more effective AGC control. Where insufficient range of control is provided by a single stage, more than one stage of control is used. However, this is the exception rather than the rule, since cutoff bias may be reached on extremely strong signals, or AM modulated signals may be compressed to the point where actual suppression of modulation occurs (FM signals are not affected by this amplitude suppression action).

Another design problem is introduced by the change of input and output capacitance with signal strength. In the CE circuit, both capacitances **decrease** with strong signals. As a result, the center frequency of the tuned output circuit is shifted upward. (In the CB circuit this effect is exactly opposite, and a downward shift is produced.) As the design of transistors improves, it is probable that types similar in action to the remote cutoff electron tube will be developed and used in AGC circuits. At present, however, the action is the same as that of a sharp cutoff tube, so that control amplifiers must be restricted to handling fractional powers to avoid blocking and distortion, and some circuit detuning must be expected.

FAILURE ANALYSIS.

No Output. Usually a no-output indication is produced only by an open- or short-circuited condition in the controlled stage. Observation of the signal using an r-f probe and oscilloscope will indicate where the signal disappears. Once this is determined, a resistance or voltage analysis of that portion of the circuit should reveal the defective component.

Low Output. If excessive bias is produced, cutoff current may be reached, or the signal may be reduced so much that little range of control is offered. In such cases the increase in amplitude caused by AM modulation can cause suppression of modulation. Such a condition can be observed on an oscilloscope. If oscillations occur in the controlled stage, a preceding stage or a following stage, an excessively strong input signal to the detector will result, and the control stage may be biased off. Removal of the input signal would cause the gain to increase, as evidenced by an increased noise output with no signal present. If an output signal is still observed, the signal is being produced internally through feedback, and it will probably be necessary to temporarily disconnect each stage preceding the detector and control amplifier from its collector supply to locate the defective stage. An alternative method for an experienced technician is to quickly short-circuit the input or output of a stage to determine whether the oscillation ceases. Do **NOT** short-circuit the input or output to ground, or the transistor rating may be exceeded or the heavy current produced may cause the delicate i-f transformer winding to open.

Distortion. The changing of the input and output impedances and capacitances by changes in signal strength will cause a shift in the tuned frequency and the overall circuit Q. Therefore, it is to be expected that some distortion will occur, particularly on quickly varying strong signals. If the distortion is continuous, an improperly operating circuit or a defective transistor may be the cause. Use an oscilloscope, and simulate a varying input signal by means of a signal generator connected to the input circuit. Observation of the waveform at various points in the circuit should indicate the defective portion, whereupon a resistance analysis will isolate the defective component in this portion of the circuit. If the waveforms preceding and following the controlled amplifier are identical except for amplitude, the distortion is probably occurring in later stages and is not caused by the control circuit.

AUXILIARY DIODE CONTROL CIRCUIT.

APPLICATION.

Auxiliary diode control AGC circuits are used in conjunction with the regular limited range AGC circuit, normally employed in solid-state receivers, to provide additional AGC action when extremely strong signals are encountered.

CHARACTERISTICS.

Provides considerable AGC action for strong signals.

Has little or no effect on weak or medium strength signals.

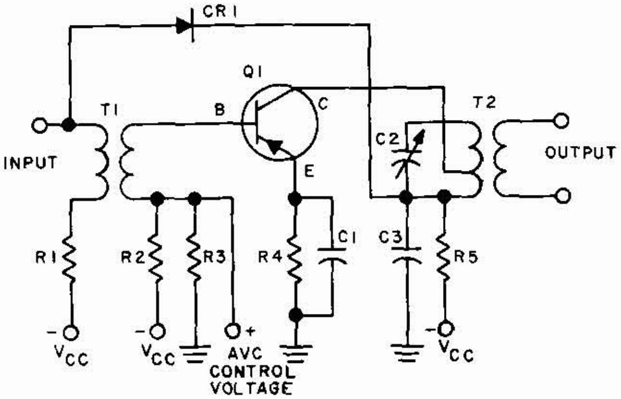
Utilizes a diode to shunt strong signals around one of the i-f amplifier stages, thereby decreasing system gain.

Auxiliary diode operation is indirectly controlled by the regular AGC circuit.

CIRCUIT OPERATION.

General. Automatic gain control circuits in the semiconductor field can be placed into two general classes. One class, referred to in this Handbook as standard AGC, uses a variation of bias on one or more of the transistor elements to control the gain of the receiver, while the other class employs a diode to shunt the input signal around the controlled stage to lower the gain of the receiver. The auxiliary diode AGC circuit operates on the latter principle, however, it is usually used in addition to a standard AGC system to obtain improved control, and to prevent the receiver from being overloaded when very strong signals are received, since the range of control of most standard AGC circuits is somewhat limited, especially at high input signal levels. In a receiver using both auxiliary and standard AGC, the auxiliary AGC circuit is controlled by the standard AGC circuit. When weak and medium strength signals are received the auxiliary AGC circuit is not operated, and the receiver output is held fairly constant through the action of the standard AGC circuit (which frequently uses emitter current control, although collector voltage control can be used, if desired). As the input signal increases beyond a predetermined point, the AGC control voltage increases to a level sufficient to forward bias the auxiliary diode AGC circuit, and the auxiliary diode conducts. The conducting diode provides a low impedance shunt around the standard AGC controlled stage, creating a great deal of additional AGC action. It is important to keep in mind that the auxiliary diode AGC circuit does not operate independently, rather it operates in conjunction with a standard AGC circuit, and its operation is controlled by the standard AGC circuit. A knowledge of standard AGC circuits, (emitter current control or collector voltage control) is helpful in the understanding of the auxiliary diode control circuit. For the interested reader, detailed information concerning these circuits is located in this section of this Handbook.

Circuit Operation. The accompanying schematic diagram illustrates a typical emitter current controlled amplifier with auxiliary diode AGC.



Auxiliary Diode Control Circuit

Transformer T1 provides inductive coupling between the controlled amplifier and the preceding stage. Resistor R1, which is in the collector circuit of the preceding stage develops bias for the anode of auxiliary diode CR1. Resistor R2 together with resistor R3 form a base bias voltage divider between ground and the negative supply to forward bias the emitter base junction of transistor Q1. Resistor R4, which is bypassed by capacitor C1 is a conventional emitter stabilization resistor which compensates for ambient temperature variation. Capacitor C2, together with the primary of transformer T2 forms a tuned output load for amplifier Q1, and the signal developed across the primary of T2 is inductively coupled to the secondary of T2 to the following stage. Resistor R5 also develops cathode bias for auxiliary diode CR1, and capacitor C3 shunts to ground any signal voltage that may be developed across R5. Resistor R5 should not be confused with the resistor used in the collector voltage control AGC circuit since the value of R5 is insufficient to achieve collector voltage control.

When there is no signal input to the receiver, there is no voltage developed. Auxiliary diode CR1 is normally back biased by the voltage drop across R5 caused by the quiescent collector current of Q1, and by the higher negative voltage, applied to R1 and the collector of the preceding converter stage. Component values are such that the voltage across R1 exceeds the voltage drop across R5 thereby back biasing (or reverse biasing) auxiliary diode CR1, since the cathode of CR1 is less negative than the anode. When an input signal is applied to the receiver, AGC voltage is produced by the receiver detector and is coupled to the controlled stage, or stages. This AGC voltage, which is in the form of a dc voltage, is directly proportional to the average carrier power received by the receiver. However, delayed AGC is usually used and the AGC voltage must exceed a fixed "delay voltage" also called the "threshold voltage" before AGC voltage is applied to the controlled stage. In this manner the receiver gain is maintained at a

maximum, since there is no AGC action when weak signals which are below a predetermined level are received. Assume that a signal is received which is of sufficient amplitude to overcome the AGC delay voltage. The positive AGC voltage (positive AGC voltage is used with PNP transistors, negative voltage is used with NPN transistors) developed in the receiver detector is applied to the junction of bias voltage divider R2, R3 and decreases the forward bias applied to the emitter base junction of Q1. The conduction of Q1 decreases, resulting in a decrease in gain of the stage. Decreased conduction of Q1 also results in a decreased voltage drop across R5 which in effect decreases the original back bias applied to diode CR1. As the strength of the input signal increases the level of the AGC voltage increases, resulting in a further decrease in conduction of Q1 and a further decrease in the voltage drop across R5. When the voltage drop across R5 no longer exceeds the voltage drop across R1 (that is the anode of CR1 becomes more positive than the cathode) auxiliary AGC diode CR1 is no longer back biased. CR1 then conducts, and provides a low impedance (shunt) path around IF amplifier stage Q1. Much of the IF signal generated in the converter stage is then shunted around Q1 through CR1 and C3 to ground, providing additional AGC action (signal reduction). Component values are usually chosen so that the auxiliary diode is back biased for all but very strong signals.

FAILURE ANALYSIS.

General. When making voltage checks use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low voltage ranges of the standard 20,000 ohm-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low resistance reading.

No Output. No output from the auxiliary diode AGC controlled amplifier could be caused by defective power supply voltage, defective transistor or diode, or by a defective circuit component. Check the power supply voltage with a VTVM. If the transistor is not defective, a defective circuit component is more likely the cause of no output. An open emitter, base, or collector circuit, or a shorted base or collector circuit, would render Q1 inoperative and no output would result. With the power removed, check the base and collector circuits for a possible short to ground with an ohmmeter, and check R2, R3, R4, and R5 for an open. Also check the secondary of T1 and the primary of T2 for an open, and check C2 and C3 for a possible short. A defective auxiliary diode or a change in value of circuit components is more likely to cause a low output condition, rather than a no output condition to exist.

Low Output. If oscillations occur in the controlled stage, or in a stage following the controlled stage, there could be excessive input to the detector and the resultant excessive AGC voltage produced by the detector could greatly reduce the gain of the controlled stage causing a low output condition to exist. Oscillations of this type usually result in excessive receiver noise, in addition to low output. If an output signal is present with no input applied to the receiver, oscillations are probably being produced internally through feedback and it will probably be necessary to temporarily disconnect each stage, preceding the detector, from its collector supply to locate the oscillating stage. Improper power supply voltage, a defective transistor or auxiliary diode, or a defective circuit component which alters the bias on either the transistor or auxiliary diode could also cause a low output condition to exist. Check the power supply voltage and adjust if necessary. Check the front to back ratio of the diode. If proper operation is not restored a defective circuit component is probably the cause of low output. A change in the value of either R1 or R5 could alter the bias applied to auxiliary diode CR1, possibly causing CR1 to conduct continuously, and greatly reduce the gain of the controlled stage for all input signal levels. A change in value of either R2, R3, or R4, would alter the emitter base bias of Q1 and could also reduce the gain of the stage for all input signal levels. If C1 opens, the resulting degeneration across R4 could also lower the gain of the stage. If C2 or C3 become leaky low output could also result. All resistors should be checked for proper value with an ohmmeter and all capacitors with an in-circuit capacitor checker if the trouble cannot otherwise be located.

Distorted Output. Some distortion may occur in AGC controlled stages, since the input and output impedances vary as the gain of the stage is varied by the AGC circuit. The condition may be especially noticeable on quickly varying strong signals. However, if distortion is continuous an improperly operating circuit or a defective transistor usually is the cause. A resistive analysis, with the power removed, should reveal the component at fault.

COLLECTOR VOLTAGE CONTROL CIRCUIT.

APPLICATION.

Collector voltage control AGC is one method of AGC control used in transistorized receivers to keep the output level relatively constant regardless of input signal strength variations.

CHARACTERISTICS.

Automatic gain control is achieved by varying the collector voltage applied to an i-f amplifier stage.

When PNP transistors are used, the AGC voltage must be negative. For NPN transistors a positive AGC voltage is required.

CIRCUIT ANALYSIS.

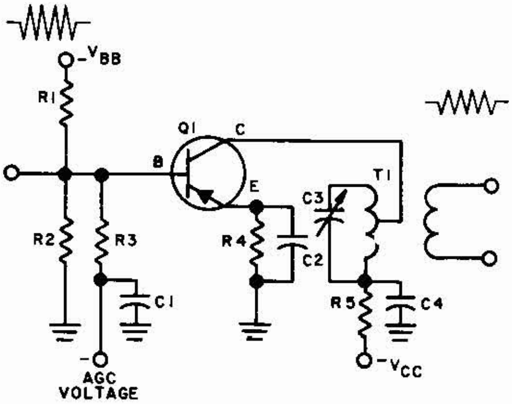
General. The power gain of a common emitter amplifier may be varied by varying the dc collector voltage of the amplifier. This principle is the basis of collector voltage automatic gain control. By applying AGC voltage to the base of the controlled amplifier the dc emitter current is varied which in turn varies the dc collector current. Variation of dc collector voltage (which varies the amplifier power gain) is accomplished by passing the dc collector current through a series resistor in the collector circuit. An increase in dc collector current results in an increased voltage drop across this collector resistor, which lowers the collector voltage and the gain of the amplifier decreases. In the collector voltage control AGC system as in other AGC systems, over all receiver gain is maximum for weak signals and is decreased by AGC action when stronger signals are received, so that the receiver output remains fairly constant.

It is interesting to note the similarities and differences between emitter-current control and collector-voltage control. Circuitwise they are quite similar, the major difference between them is the addition of a large resistor in the collector circuit of the collector voltage control AGC circuit. In both circuits the AGC voltage is applied to the base of the transistor, however, each circuit uses a different polarity AGC voltage. The AGC voltage in the collector voltage controlled circuit is polarized so that it increases the forward bias at the emitter base junction, when a stronger signal is received (as the carrier increases), thereby increasing conduction of the transistor. Thus, an increased voltage drop occurs across the collector resistor as the forward bias increases the collector current, resulting in a decrease of voltage at the collector. This decrease of collector voltage, in turn, lowers the power gain of the amplifier.

In contrast, the AGC voltage applied to the emitter current control AGC circuit, is of such a polarity as to decrease the forward bias at the emitter base junction, when a stronger signal (carrier) is received. As the forward bias is reduced, the conduction of the transistor decreases. Since there is no large series resistor in the collector circuit of the current controlled AGC circuit, the only resistance offered to the flow of collector current is the normally low dc resistance of the output transformer; therefore, the collector voltage remains practically constant despite the change of collector current. The gain of the amplifier, however, decreases since the emitter current decreases. Hence it is seen that the current controlled AGC circuit operates near the region of emitter current cutoff, while the voltage controlled AGC circuit operates near the limits of collector current saturation. As a result, transistorized AGC circuits also usually used a strong signal, shunting device such as an auxillary diode to secure effective AGC action over large ranges.

Circuit Operation. The following schematic diagram illustrates a typical collector voltage automatic gain controlled amplifier.

Resistor R1 together with resistor R2 forms a base bias voltage divider between ground and the negative supply, to furnish fixed forward bias to the emitter base junction of Q1. The negative AGC control voltage from the dectector is applied to the base of Q1 through decoupling resistor R3 and both R2 and R3 are bypassed by C1. Resistor R4, which is bypassed by capacitor C2 is a conventional emitter stabilization resistor, sometimes called a "emitter swamping" resistor, intended to prevent transistor operational characteristics from varying with changes in temperature. Collector voltage control is achieved by the addition of resistor R5 to the collector circuit of Q1. Capacitor C3 together with the primary of output transformer T1 form a tuned output load for amplifier Q1. Capacitor C4 in conjunction with collector voltage control resistor R5 also forms an i-f decoupling network to prevent if energy from feeding back into the power supply.



Collector Voltage Controlled Amplifier

With no signal input the conduction of Q1 is determined by the fixed forward bias applied to the base of Q1 by base bias voltage divider R1, R2. There is no detector output and hence no AGC voltage is developed. The gain of the controlled stage is at a maximum since the voltage drop across collector voltage resistor R5 is at a minimum and the voltage applied to the collector of Q1 is, therefore, maximum. When a signal of sufficient strength to produce a detector AGC output large enough to overcome the AGC delay voltage is received an AGC control voltage is applied to the base of controlled amplifier Q1. The polarity of this voltage is such as to increase the forward bias applied to the base of the transistor. In this case controlled amplifier Q1 is a PNP transistor and the AGC control voltage is, of course, negative. Conduction of Q1 is increased and the resultant collector voltage drop across R5 increases, reducing the actual voltage applied to the collector of Q1, and thereby reducing the gain of the amplifier. The receiver output remains relatively constant since a further increase in input signal strength tends to increase the AGC control voltage. This results in a further increase in conduction of Q1 and an increased voltage drop across R5. As a consequence, the collector voltage of Q1 decreases and the gain of the controlled amplifier is, again, lowered.

Collector voltage control is not frequently used because of the low value of collector voltage applied to the transistor. At low collector voltages the collector capacitance is increased and consequently the alpha cutoff frequency is reduced, making the transistor a poor r-f or i-f amplifier.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of a standard 20,000 ohms per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low resistance reading.

No Output. No output from the collector voltage controlled amplifier could be caused by defective power supply voltage, a defective transistor, or by a defective circuit component. Check the power supply voltage. An open emitter, base, or collector circuit, or a shorted base or collector circuit would render Q1 inoperative, and no output would result. With the power removed, check the base and collector circuits with an ohmmeter for a possible short to ground. If the collector circuit appears to be shorted to ground capacitor C4 may be shorted or the primary of T1 may be shorted to its case. Check the emitter and collector circuits for a possible open, paying particular attention to R4 in the emitter circuit, and R5 and the primary of T1 in the collector circuit. Check resistors R1 and R2 for proper value, since an open or short of either part would alter the bias applied to Q1 and drive Q1 either heavily into saturation or into cutoff. This condition would probably produce little or no output from the controlled stage. If capacitor C3 becomes shorted, the output signal would be shunted around transformer T1 and there would not be any output coupled to the following stage. Improper AGC control voltage caused by a defect in the AGC detector circuit, could also cause a no-output condition to exist. The existence of this condition may be determined by measuring the voltage present at the base of Q1 with no signal applied to the receiver.

Low Output. A low output condition could be caused by defective power supply voltage, a defective transistor, defective circuit components, or by self oscillation. Since self oscillation would result in an excessive detector input, it would also result in the generation of excessive AGC control voltage, and therefore could cause a low output. Oscillations of this type usually also result in excessive receiver noise in addition to the low output. If an output signal is present with no signal input to the receiver, self oscillations are probably being produced internally through feedback. If self oscillations are not the cause of low output, check the power supply voltage with a high resistance voltmeter. If proper operation is still not restored, a defective circuit component is most likely the cause of low output. A change in the value of R1, R2 or R4 would alter the bias applied to the base emitter junction of Q1 and low output could result. If emitter bypass capacitor C2 opened the resulting degeneration would lower the gain of Q1 and a low output would also result. Low output would also result if R5 increased in value since the collector voltage applied to Q1 would be correspondingly reduced. A defect in output transformer T1 would also reduce the output by either detuning the output tank which consists of C3 and the primary of T1, or by reducing the amount of signal coupled to the following stage.

Distorted Output. Since the input and output impedances of the amplifier vary as the gain of the amplifier is varied by AGC, some distortion is to be expected especially when strong signals are received. However, if distortion is severe and continuous a defective transistor, power supply, or circuit component probably exists. The power supply and the transistor should be checked, and if distortion persists, voltage checks of the transistor elements should be made with a VTVM to localize the trouble. Resistance measurements with the power removed, may then be made to locate the faulty component.