CHAPTER 4
STABILIZED MASTER OSCILLATORS

1. TECHNICAL REQUIREMENTS

The frequency accuracy requirements for single-sideband communications are very precise when compared with most other communications systems. A frequency error in carrier reinsertion of 20 cps or less will give good voice reproduction. Errors of only 50 cps result in noticeable distortion, and intelligibility is impaired when the frequency error is 150 cps or greater.

There are significant frequency errors introduced by the propagation medium and by Doppler shifts due to relative motion between transmitter and receiver in aircraft communications. In h-f skywave transmission, the Doppler shifts caused by the motion of the ionosphere introduce frequency shifts of several cycles per second. Doppler shift due to relative motion amounts to one part in 10^6 for every 670 miles per hour difference in velocity between the transmitting and receiving station. At a carrier frequency of 20 megacycles, communicating from a jet aircraft to ground, the frequency shift will be approximately 20 cps. Inasmuch as this represents approximately half of the desired maximum frequency error, the errors introduced by the transmitting and receiving equipment must be comparatively small. This dictates a design goal in the vicinity of ±1/2 part in 10^6 in both ground and aircraft installations.

Present day trends demand that communications be established on prearranged frequencies without searching a portion of the spectrum in order to obtain netting, and therefore, the figure of ±0.1 part in 10^6 presents the required absolute accuracy rather than short term stability. Most military and some commercial applications demand that operation be obtained on any one of the seven thousand SSB voice channels in the h-f band. A channel frequency generator having an absolute accuracy of ±0.1 part in 10^6 (±0.00001%) and providing either continuous coverage or channelized coverage in steps no greater than 4 kc is required in many SSB systems.

2. AFC VS ABSOLUTE FREQUENCY CONTROL

To meet the stringent frequency control requirements, early h-f single-sideband systems utilized various methods of automatic control of the reinserted carrier at the receiver. Either a pilot tone or carrier was transmitted along with the sideband components, and the receiver frequency was synchronized with the transmitter frequency. No stabilization of the transmitter frequency was used other than that obtained by using crystal-controlled oscillators.

The first single-sideband radiotelephony system did not use automatic frequency control and was able to accomplish its purpose because the operating frequency of about 60 kc was low enough that oscillators were then available with sufficient stability. Although oscillators have long been available with sufficient frequency stability and accuracy for use in high-frequency single-sideband equipment, these oscillators were bulky, fragile, and limited in frequency channels. They were used principally as laboratory frequency standards. Improvements in the crystal art, development of circuit technique, and new components have made available the means to obtain h-f receivers and transmitters capable of multichannel operation with sufficient frequency accuracy and stability for independent operation of the receiver.

The advantages obtained through the use of independent absolute frequency control are considerable. The bandwidth required for a communication channel is minimized since there need be no allotment for the synchronizing signal and the frequency tolerance. The relationship between transmitter and receiver carriers is absolute and indestructible and is immune to any type or degree of interference, resulting in maximum fidelity of the received signal. Even in the extreme cases where Doppler effects introduce sufficient frequency shift to upset the system making some form of automatic frequency correction necessary, the use of absolute frequency control assures that the bandwidth and, therefore, the interference susceptibility of the afc circuit will be minimized.

3. DEVELOPMENT OF FREQUENCY CONTROL

It is of some interest to trace the development of frequency control circuits and the technical and economic forces that caused their evolution. In the early days of radio the tunable LC oscillator provided a simple and serviceable answer to the problem of generating channel frequencies. The lower frequency end of the spectrum and amplitude modulation were in use and the spectrum was not unduly crowded.

Later crowding of the spectrum was alleviated by closer channel spacing and expansion into the higher frequency regions. The increased frequency accuracy required was provided by crystal oscillators, and a multiplicity of channels was provided by a like number of crystals. In World War II the logistics of delivering the right crystal to the right place at the right time became untenable.

It became apparent to those involved in multichannel equipment that the simple MOPA circuit would no longer provide desired flexibility. A choice of one of hundreds of channels was required at the flick of a switch, guard bands were narrowed, vhf bands were pressed into more extensive service, and under these forces, the multiple crystal synthesizer soon evolved. The principle was simple: the output frequencies of several crystal oscillators were mixed together to produce the desired output frequencies. Each oscillator was provided with a means of selecting one of ten or more cyrstals so that a large number of channel frequencies may be synthesized. This principle is illustrated in figure 4-1.

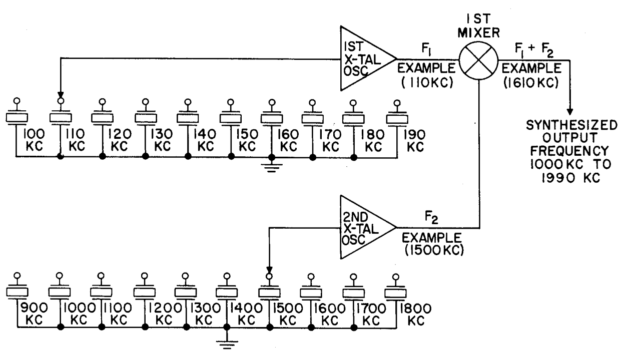


Figure 4-1. Multiple Crystal Frequency Synthesizer

It would be technically and economically unfeasible to maintain all the crystals in a multiple crystal synthesizer to the required accuracy. It would be more practical to place all the stability requirements in one or, at the most, several highly stable oscillators. From this challenge has emerged several operationally satisfactory types of single crystal synthesizers.

4. FREQUENCY SYNTHESIZERS

The frequency synthesizer is basically a circuit in which harmonics and subharmonics of a single standard oscillator are combined to provide a multiplicity of output signals which are all harmonically related to a subharmonic of the standard oscillator. A simple block diagram of such a synthesizer is shown in figure 4-2. A great advantage of this circuit is that the accuracy and stability of the output signal is essentially equal to that of the standard oscillator. The problems involved in building a single frequency oscillator of extreme precision are much simpler than those

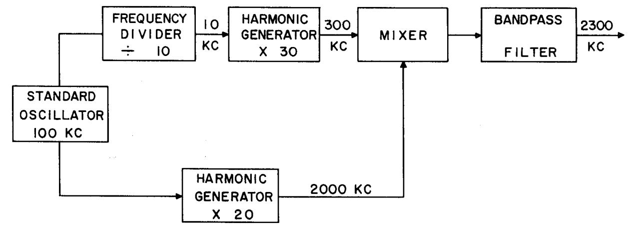


Figure 4-2. Single Crystal Frequency Synthesizer

associated with multifrequency oscillators. Furthermore, as techniques improve, the stability of the synthesizer is readily improved because it is necessary only to replace the standard oscillator to obtain improved precision. The primary difficulty encountered in the design of the frequency synthesizer is the presence of spurious signals generated in the combining mixers. Extensive filtering and extremely careful selection of operating frequencies are required for even the simplest circuits. Spurious frequency problems increase rapidly as the output frequency range increases and the channel spacing decreases.

a. HARMONIC GENERATORS

The generation of higher harmonics of signals from low-frequency sources is a rather difficult problem when carried to higher order harmonics. To obtain stable signals which are exact multiples of a low frequency, several schemes can be used. An ordinary class C amplifier can be used for harmonics up to the ninth. Diode clippers yielding square or rectangular waveforms provide much higher harmonics, but have limited amplitude capability. A blocking oscillator synchronized to the reference frequency generates short, sharp pulses which contain considerable harmonic energy. A particularly effective harmonic generator can be devised using a keyed oscillator (see figure 4-3). In this circuit, the low-frequency reference signal is shaped by a clipper to provide an off-on keying signal which is used to turn on and off a free-running oscillator tuned to the approximate frequency of the desired harmonic of the keying signal repetition frequency. The resulting oscillator output is a train of r-f pulses. If the keying signal is sharply defined and the oscillator starts oscillation uniformly, each pulse will begin on the same r-f phase. The output waveform will then be as shown in figure 4-3. The spectrum of this wave consists of a number of components having various amplitudes grouped around the oscillator free-running frequency. The frequency of each component is an exact integral multiple of the keying signal repetition frequency.

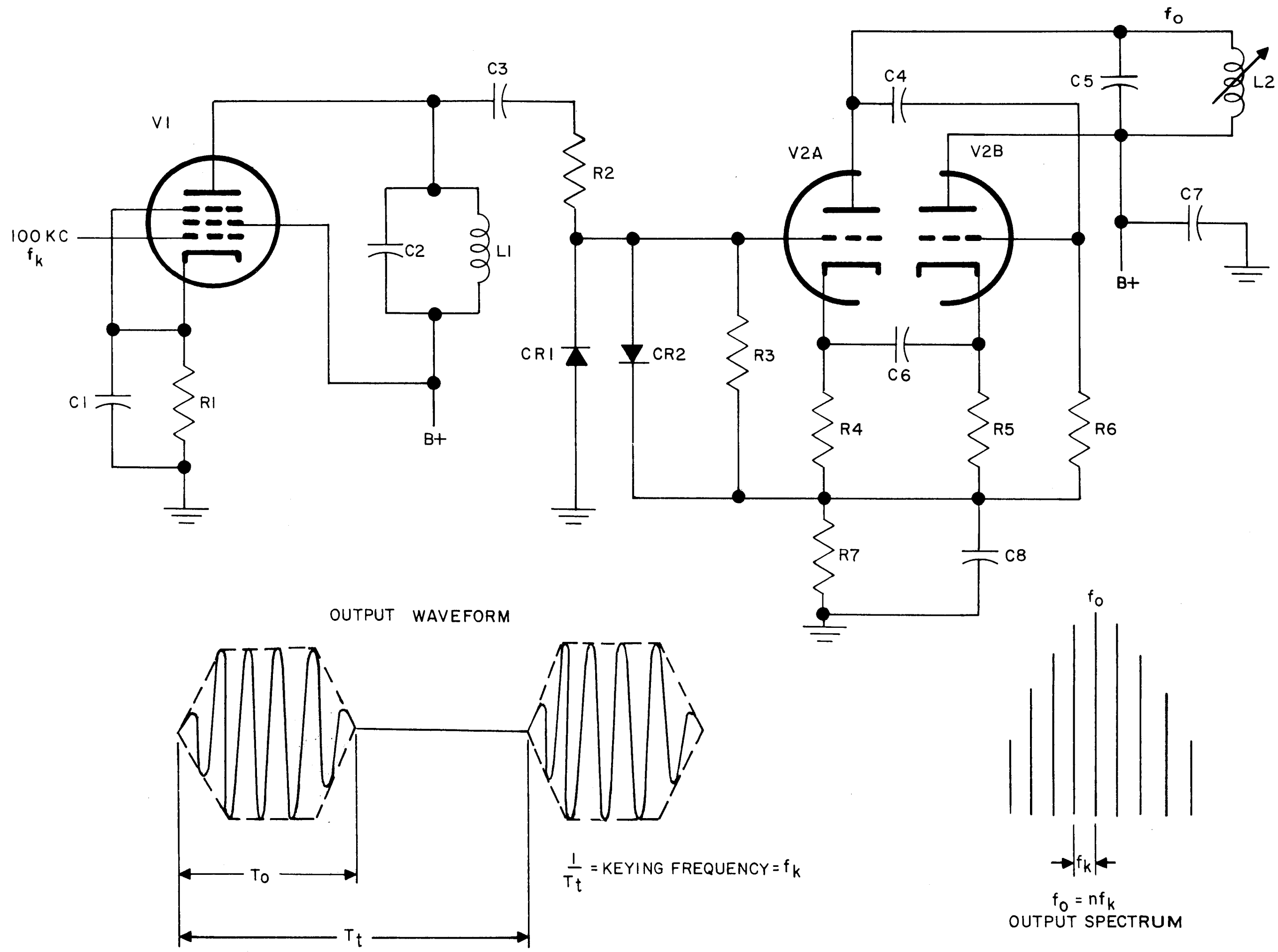


Figure 4-3. Harmonic Generator

b. HARMONIC FREQUENCY SELECTORS

The problem now is to select the desired harmonic while rejecting the adjacent undesired harmonic. Such a selection requires very sharp filters, as the frequency range increases and the spacing between harmonics decreases. By means of an additional mixer it is possible to relieve this situation. Such an arrangement is shown in figure 4-4. In this case it is desired to select higher order harmonics from a one kilocycle source. The one kilocycle reference signal is applied to a harmonic generator, the output of which is tuned to approximately 2.4 megacycles. A considerable number of one kilocycle harmonics will be contained within the harmonic generator output. This harmonic generator output is fed to mixer number one along with a local oscillator of 1945 kilocycles. The desired output of 455 kilocycles is selected by means of a mechanical filter having a bandwidth of less than one kilocycle. This signal is fed to mixer number two along with the output of the same oscillator used to drive mixer number one, and the desired product of 2.400 megacycles is selected in the output filter. To select the adjacent one kilocycle harmonic of the reference signal, the local oscillator is moved to a frequency one kilocycle higher. The desired output is then 2.401 megacycles. The stability of the output signal is dependent entirely upon the stability of the one kilocycle reference signal. The local oscillator frequency accuracy need only be such as to keep the desired 455 kilocycle signal within the passband of the mechanical filter.

5. THE STABILIZED MASTER OSCILLATOR

It is possible to retain the advantage of the frequency synthesizer and avoid many of the spurious frequency

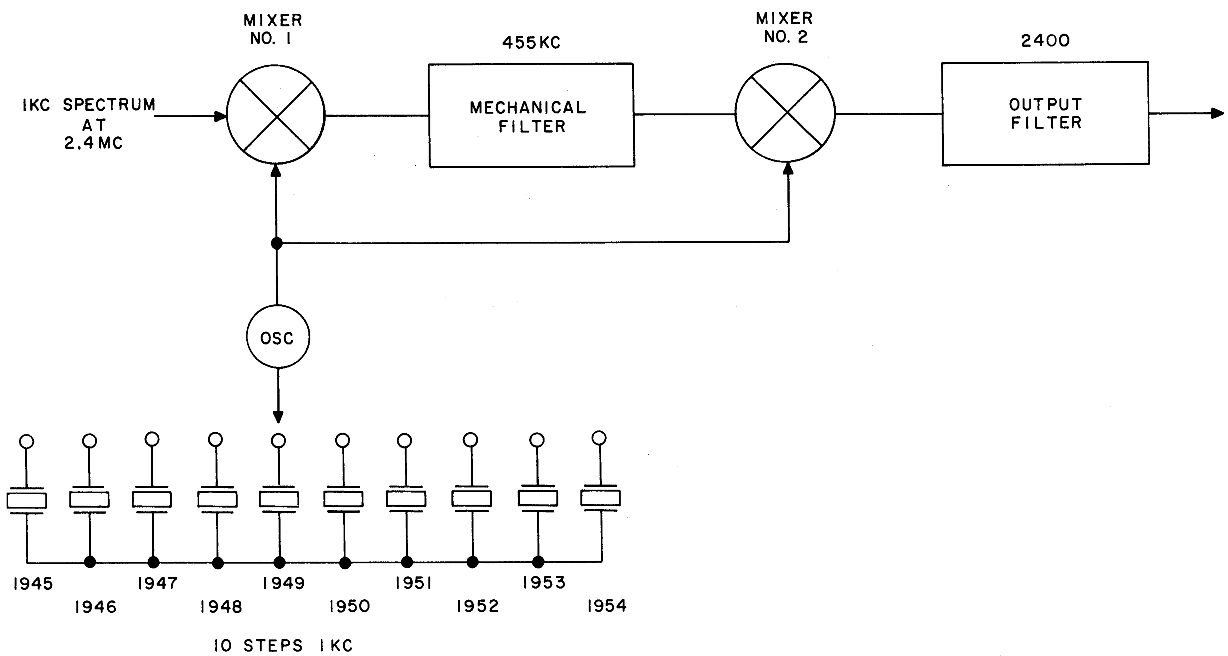


Figure 4-4. Harmonic Frequency Selector

problems by using the synthesizer to provide a reference signal to control the frequency of a variable frequency master oscillator. Such a circuit has come to be known as a stabilized master oscillator (frequently referred to by its initials smo). The basic elements of a stabilized master oscillator circuit are the master oscillator, reactance control, and discriminator (see figure 4-5). The frequency of the master oscillator is determined by the inductance and capacitance of elements L1 and C1. The frequency of oscillation may be manually changed by varying the capacitance of C1, or electronically changed by varying the permeability of the core on which L1 is wound.

a. FREQUENCY DISCRIMINATOR

The operation of the frequency discriminator is such to provide a d-c output signal whose amplitude and polarity is determined by the relationship between the input signal frequency and the frequency to which the discriminator is tuned. The frequency discriminator consists of a double-tuned transformer and two diode rectifiers (see figure 4-6). The transformer is used to supply signals to the two rectifiers, the outputs of which are series connected. The coupling capacitor C1 places the centertap of the secondary at the same r-f potential as the plate end of the primary winding. As a result of this connection the voltage applied to each diode is the sum of one-half the secondary voltages plus the voltage appearing across the primary. The voltage applied to each diode is shown in the vector diagrams below the circuit diagram. The action of the discriminator depends on the fact that the phase of the voltage developed across the secondary of the discriminator transformer will vary as the frequency of the applied signal is varied above and below the transformer resonant frequency. Referring to the vector diagrams (figure 4-6) it can be seen that if the applied signal frequency is equal to the discriminator frequency, the equal voltages are applied to each discriminator diode and the d-c output of the discriminator is zero (figure 4-6B). If the applied frequency is higher than the discriminator frequency, the voltage applied to diode one exceeds that applied to diode two, and the resulting d-c output is positive (figure 4-6A). If the applied signal is lower than the discriminator frequency, the voltage applied to diode one exceeds that applied to diode two, and the resulting d-c output is negative (figure 4-6C). This direct current output is applied to a reactance control device.

b. REACTANCE CONTROL

The reactance control provides the means by which the direct current output of the discriminator is made to alter the inductance or capacitance of the

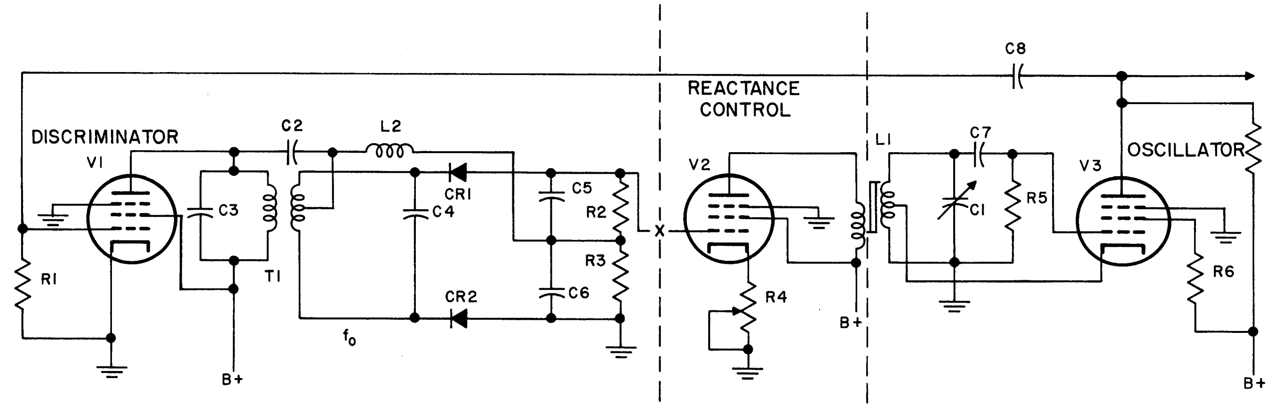
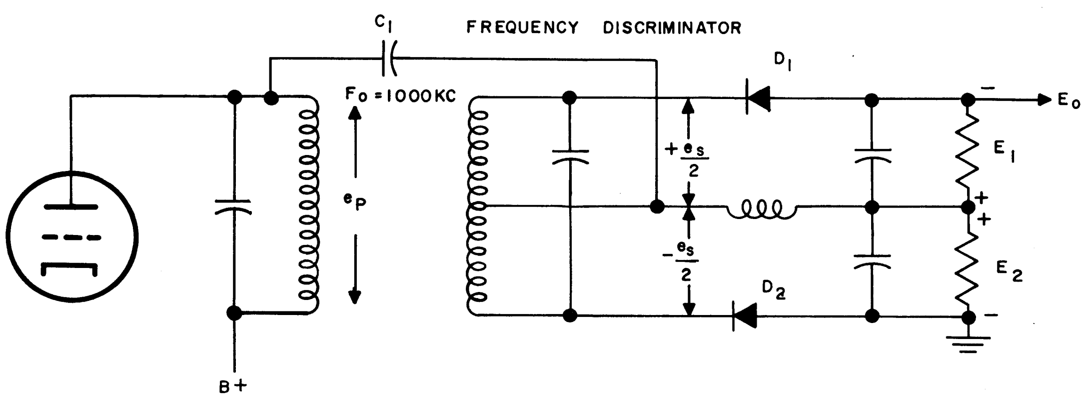


Figure 4-5. Simple Stabilized Master Oscillator with Frequency Discriminator



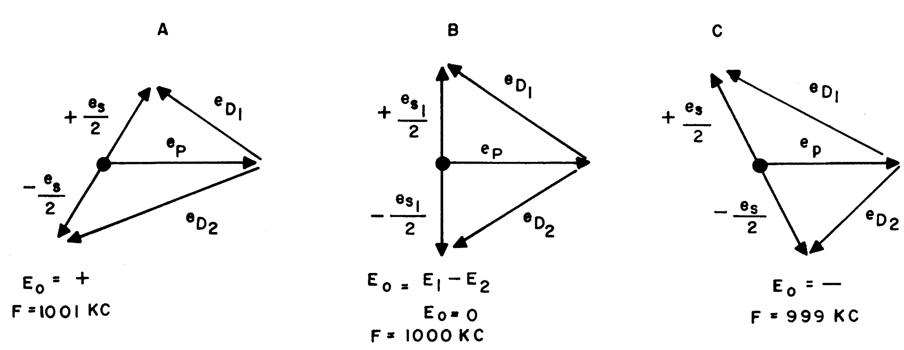


Figure 4-6. Frequency Discriminator

tuning elements of the master oscillator. Devices that have been used for this are reactance tube circuits, saturable reactors (i.e. current-sensitive inductors), voltage-sensitive capacitors, and motor-driven variable capacitors. The saturable reactor is used in the example given as its operation is easily understood. The saturable reactor consists of an inductor wound on a core material having magnetic permeability which is a nonlinear function of the magnetizing force. Such a reactor will have inductance which can be changed by varying the current in its winding or through an auxiliary control winding (see figure 4-7). The change in permeability will be the same for either polarity of magnetizing force. For this reason it is necessary to resort to fixed magnetic bias to obtain inductance change that will reverse polarity when the external magnetizing force polarity reverses. The magnetic bias may be obtained from a permanent magnet or from a bias current in the control winding as is the case in the example shown.

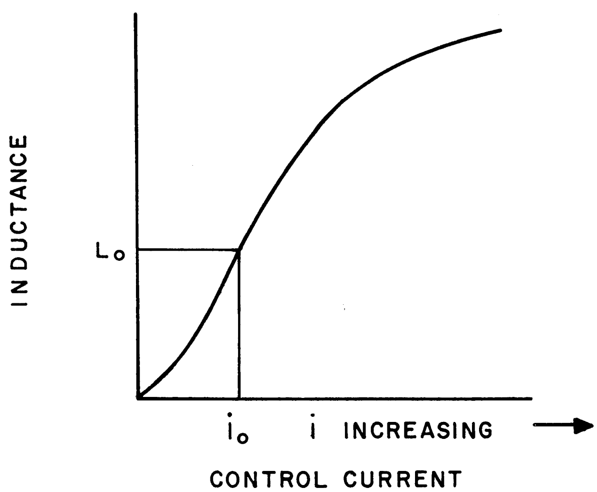


Figure 4-7. Variable Inductor Response Curve

c. BASIC SMO OPERATION

The manner in which the stabilized master oscillator circuit operates may be described in two conditions, open-loop and closed-loop. If the control is opened at the grid of the reactance control tube and the tuning of the oscillator varied with the discriminator tuning fixed at f_o, the output voltage of the discriminator will follow the open-loop curve shown in figure 4-8. In this curve the discriminator voltage is plotted on the vertical scale versus oscillator frequency on the horizontal scale. If the master oscillator frequency differs from the discriminator frequency when the loop is closed, the master oscillator frequency will be pulled toward the discriminator frequency provided the proper polarity of discriminator and control device has been observed. It is important to realize that perfect correction cannot be achieved unless there is an infinite amount of amplification of the error signal from the discriminator. This can be seen by examining the discriminator output when the loop is closed. If perfect correction had somehow been achieved, the discriminator output would be zero. Obviously such cannot be the case as there must be some signal applied to the reactance control to correct the oscillator frequency error. The closed-loop frequency error will depend on the master oscillator error and on the gain of the control loop. The performance of the closed-loop is shown by the dashed curve in figure 4-8.

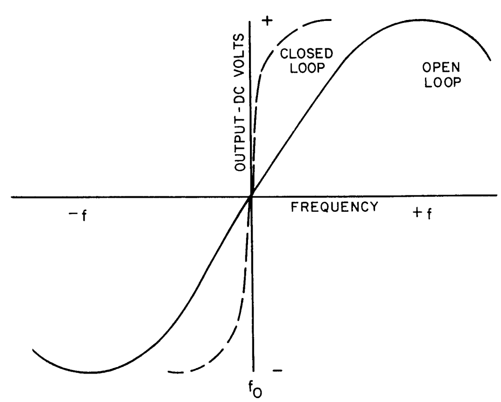


Figure 4-8. Discriminator Frequency Response Curve

In the example shown, the oscillator frequency is effectively compared with the discriminator frequency. There are two fundamental defects in this stabilizing system: (1) there is a residual frequency error and, (2) the stability obtainable from the discriminator is limited. The over-all accuracy of a system using this principle in the h-f band is approximately 50 PPM, insufficient for SSB service.

Both of these shortcomings can be eliminated by utilizing phase deviation rather than frequency deviation error signals in the control-loop. To do this, the frequency discriminator is replaced by a phase discriminator with a reference signal derived from a standard oscillator (see figure 4-9). The stabilized master oscillator is then locked in frequency synchronization with the reference oscillator, and the error signal is the phase angle between the two oscillator voltages. As the frequency of the controlled oscillator drifts away from the reference frequency,

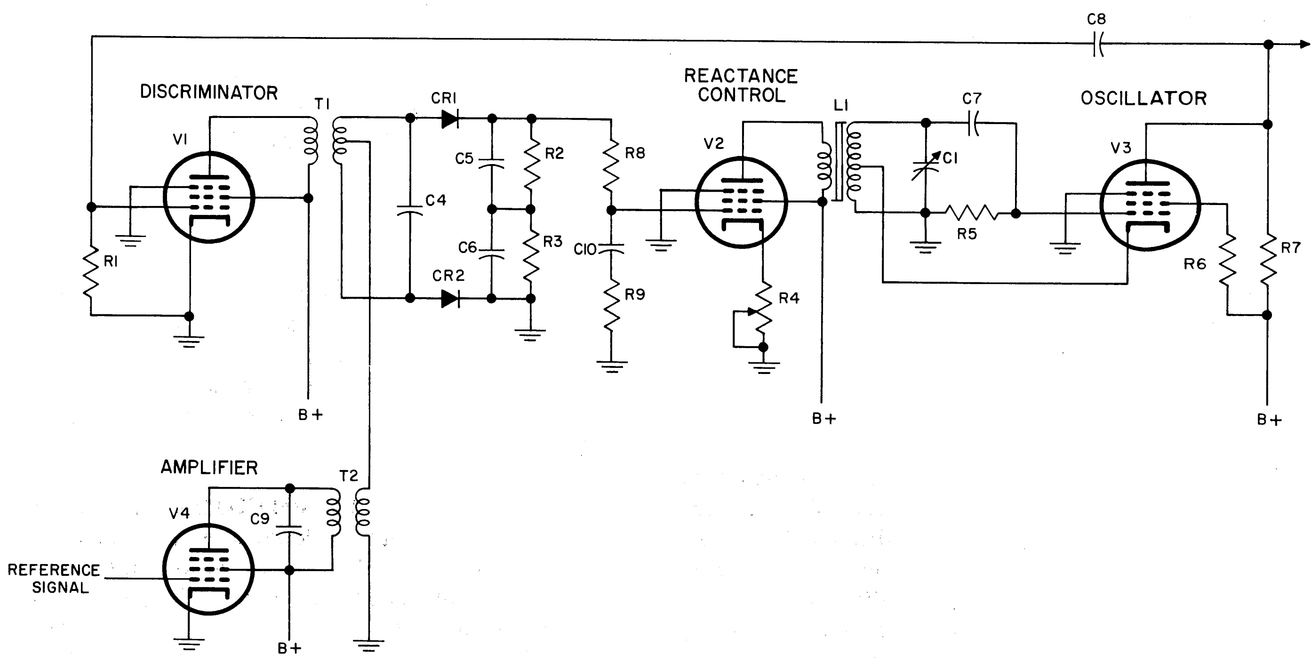


Figure 4-9. Simple Stabilized Master Oscillator with Phase Discriminator

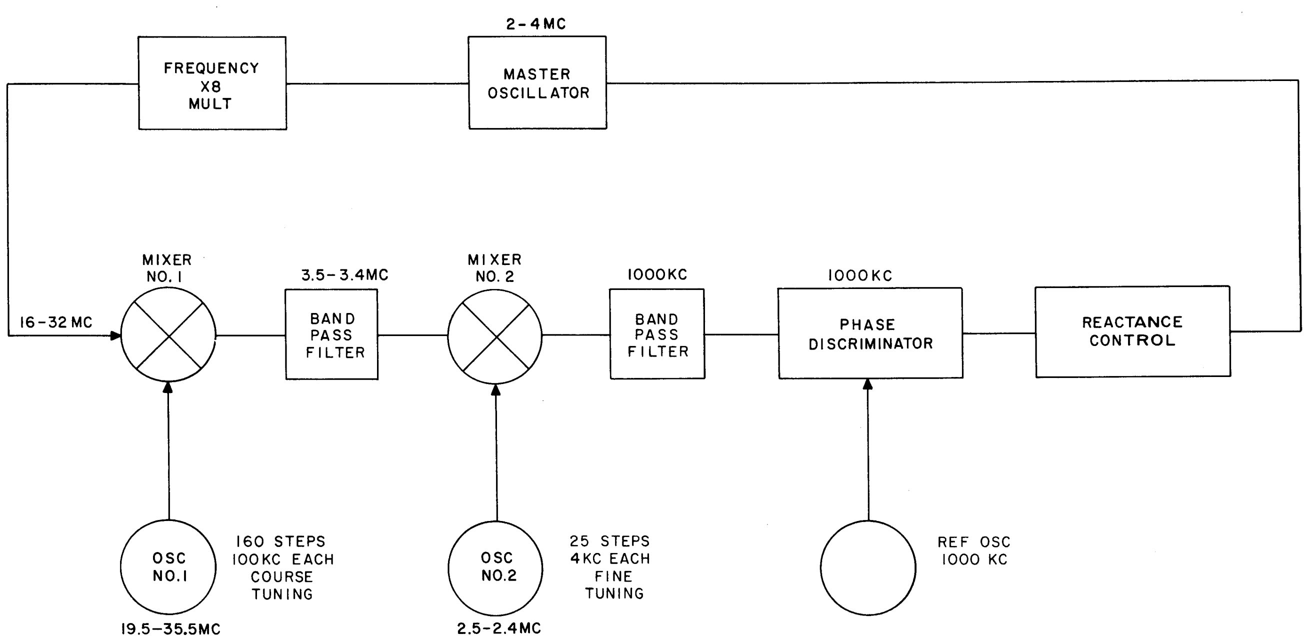


Figure 4-10. Block Diagram of Basic Stabilized Master Oscillator

the phase angle between the two voltages increases to provide the correcting voltage necessary to operate the reactance control. The stability of the system now is completely dependent on the stability of the reference oscillator. The stabilization loop is a feedback system and, as a result, careful attention must be paid to gain and phase shift if stable operation is to be obtained. If the gain at the frequency at which phase shift around the loop is 180° is unity, oscillation will result. The low-pass filter network in the grid of the reactance control tube provides the necessary control of gain to avoid oscillation by reducing the gain at the critical frequency.

d. MULTIPLE FREQUENCY SMO OPERATION

Although the stabilized master oscillator described is capable of operating on one frequency only, the circuit can be extended to operate on additional frequencies. To accomplish this, a double-mixer frequency translation system is designed to feed the discriminator (see figure 4-10). By this means, the reference frequency is translated upward in frequency to the range 16 to 32 megacycles. As long as oscillator two is fixed in frequency, the reference signal can be translated to frequencies separated 100 kilocycles between 16.0 and 32.0 megacycles, 16.0, 16.1, 16.2, etc. If the frequency of oscillator one is fixed and oscillator two is varied, the reference signal will be translated in steps of four kilocycles each over an interval of 96 kilocycles, (16,000, 16004, 16008, etc.). In this way the reference frequency can be translated to any one of 4000 frequencies between 16 and 32 megacycles, spaced four kilocycles apart.

The master oscillator operates from two to four megacycles, this range being best suited to covering the h-f band using both fundamental and harmonics. For synchronization with the reference, the master oscillator output frequency is multiplied by eight so that the master oscillator signal frequency range corresponds to the reference frequency range. Under these conditions the master oscillator fundamental output frequency will be stabilized on 1/2 kilocycle intervals over the range two to four megacycles. More channels can be synthesized by adding another mixer stage or by increasing the number of steps used at each mixer.

The accuracy of the stabilization obtained by the system described above depends on the accuracy of the frequencies used at the translating mixers. To obtain the greatest accuracy, all of these frequencies are derived from a single source; a standard reference oscillator of extremely high accuracy and having great stability.

The use of a phase error signal in the control loop insures that the residual error of the stabilized oscillator will be measured in terms of degrees of phase angle between controlled and reference oscillators rather than cycles of frequency difference if only a frequency discriminator were used.