Equalizing and Main Station Repeaters

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The equalizing and main station repeaters, together with the L-4 control center and command looping circuits, provide for the equalization and remote fault location in the L-4 system. The use of pre- and postequalization procedures requires virtually identical circuits at the sending and receiving main station repeaters, while abbreviated versions of the same equipment are placed in up to two line equalizing repeaters per main section. In most cases these equalizing stations occur at approximately every twenty-fifth repeater in a completed system.

The fault-locating circuits are distributed over the entire system and the control circuits required for their activation are located at the equalizing points.

I. INTRODUCTION

The equalizing repeater is the most complex of the family of L-4 line repeaters; at least one is required in any line section longer than about 50 miles. A maximum of two equalizing repeaters can be placed between main station repeaters, which have a maximum separation of about 150 miles. The equalizing repeater contains all of the circuits found in a regulating repeater and thus provides, in part, the same features: the automatic gain correction required to track the cable loss variations with temperature and the fixed equalization required to compensate for the systematic or average component of the line repeater design error.

The main additional function of the equalizing repeater is the adjustable loss required to compensate for the random component of design error, for the effect of temperature on the many line repeaters, and for the effects of aging. This is accomplished in the equalizing repeater by the A equalizer which includes six independently adjustable Bode-type equalizer networks whose several adjustable loss characteristics affect different parts of the L-4 transmission band. The loss settings of each equalizer network are established remotely from the L-4 control center (located at a nearby main station) and are maintained thereafter by the solid-state memory circuits which are a part of the repeater.[1] Figure 1 is a block diagram of the repeater.

The equalizing portion of the main station repeaters includes an A equalizer and a B equalizer. The two are similar but the B equalizer includes ten different adjustable Bode-type equalizer networks which function in narrower frequency bands than the A equalizer networks. In that the A equalizer provides a relatively coarse correction of the system response, the B equalizer provides a correspondingly finer correction. As in the equalizing repeater, logic and memory circuitry are required to permit the remote control of the equalizer settings.

In the main station repeaters (Figs. 2 and 3), the functions normally found in a regulating repeater are found in part, in the line transmitting repeater at the transmitting main station and in part in the line receiving repeater at the receiving main station. In conjunction with the pre-emphasis networks of the terminal equipment, this arrangement provides the desired level shaping to the signal as it is applied to the coaxial line. The transmitting portion includes the cable temperature preregulation while the receiving portion includes the cable temperature postregulation.[2]

The receiving main station repeater also includes a band-edge regulator which inserts pilot-actuated gain correction affecting the region below 3 MHz. The shape of this automatically applied gain correction is like that of the lowest frequency A equalizer shape and is intended to provide dynamic equalization of that part of the band during the interval between regulator equalizer adjustments.

The L-4 fault-locating system consists of monitoring oscillators located in each line repeater apparatus case; remotely controlled power supplies, switching, and logic circuits located at each equalizing station; and the control center, located at main stations. Each equalizing and main station repeater includes a dc-dc converter to to provide the power necessary to energize a series-connected group of the monitoring oscillators; a switching circuit to select which of the two groups of oscillators adjacent to the equalizing point shall be energized; and logic circuits to decode the commands transmitted from the control center. The fault-locating system as a whole is discussed in detail in Ref. 1.

To prevent fault-locating operations in a given control section (which may consist of up to two main sections) from interfering with like operations in other sections, the receiving main station re-

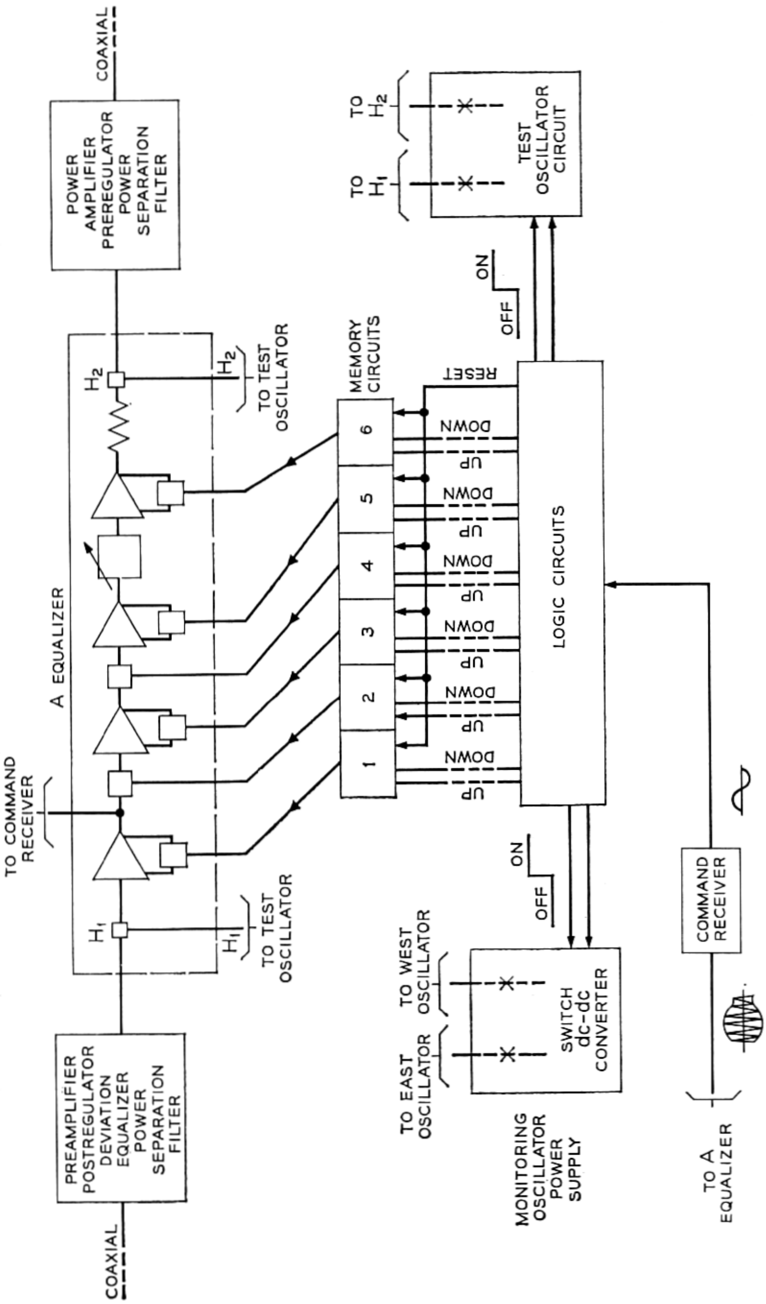

Fig. 1 — Functional block diagram of the equalizing repeater.

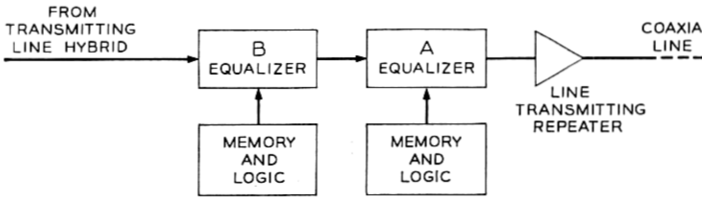

Fig. 2 — Block schematic diagram of the transmitting main station repeater.

peater provides for blocking the monitoring oscillator signals in the monitoring tone blocking circuit. In cases of two section control, this function is not supplied at the intermediate or power-feed station.

II. GENERAL FACTORS IN THE DESIGN OF THE L-4 EQUALIZING AND MAIN STATION REPEATERS

The equalization of the L-4 system involves three distinguishing characteristics:

(*i*) Bump shapes are used throughout.
(*ii*) Equalizer adjustments are made while the circuits are in service.
(*iii*) Line response is pre- and postequalized.

Considering the last of these features first, the use of partial pre-equalization and partial postequalization will, for a given response deviation, lessen the magnitude of the signal level deviation from nominal. If the nominal levels have been selected so as to minimize the loaded noise performance of the system, then any departure from these levels can only increase total system noise. Consequently, pre-

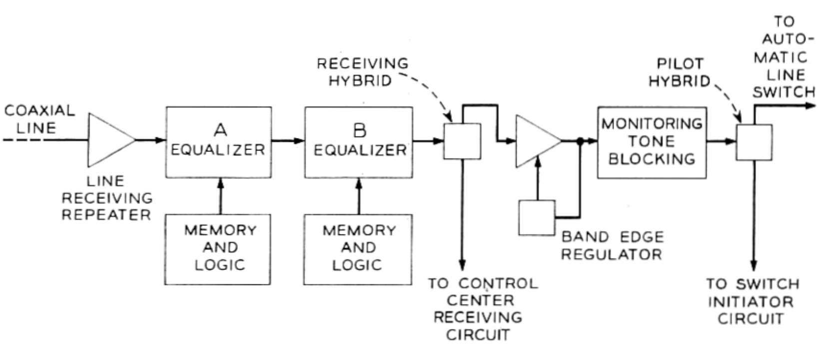

Fig. 3 — Block schematic diagram of the receiving main station repeater.

equalization can result in improved noise performance of the system. In systems limited by the load carrying capability of the repeaters, this feature can be used either to maximize the spacing of adjustable equalizers, to reduce the load requirements on the repeaters, or both.

In a system like L-4 where the noise performance is limited by modulation distortion and where the load capacity of the repeaters is not excessive, advantages in both areas are realized as a result of pre- and postequalization.

Given a section of modulation-limited system for which the accumulated misalignment is M_s (dB), and for which the nominal signal levels have been optimized with respect to total noise, the noise incurred in that section is increased by an amount determined by the method of equalization and by the relative importance of second- and third-order modulation distortion. If the total noise of the section is determined primarily by thermal and second order noise, the nominal system levels are selected so that the contribution from each of these sources is the same. Minimizing the noise in the misaligned condition requires that this relationship be maintained or, in other words, that both the thermal noise and second order noise incur equal penalties. This result is achieved if the signal levels are adjusted at the input to the section by $(M_s/2)$ dB, that is, if pre- and postequalization is applied in equal parts.

In general, the over-all penalty incurred in a section in which the noise is determined primarily by thermal noise and either voltage-adding or power-adding third order modulation noise will not be minimized by pre- or postequalization in equal parts. It can be shown, however (for moderate misalignment—up to about ± 5 dB), that pre- and postequalizing in equal parts incurs penalties which are trivially different from optimum.[4] Thus for sections in which the misalignment is in this range, the noise performance may be reoptimized by equal parts of pre- and postequalization whether the performance is limited by second order modulation distortion or by third order distortion.

This is the principle applied in the equalization of the L-4 response which, except in some cases for the lowest frequency supergroups, is usually misaligned between equalizing stations by considerably less than ± 5 dB. In fact, it will be later noted that the maximum adjustable range of the equalizer shapes is on the order of ± 4 dB and in most cases provides about a 2:1 ratio margin against anticipated needs.

The provision of accurate pre-equalization of relatively complex deviations requires a reverse channel or equivalent for the feedback of information on which the pre-equalizer settings may be based.

Fully adaptive equalization would require either the full-time surveillance of the channel to be equalized and full-time use of the reverse channel or a computer-like control system which would sample the channel at programmed intervals, and over the reverse channel would cause corresponding corrections in the equalizer settings.

In the latter case some kind of memory must be used to maintain the equalizer settings between samples and corrections. The L-4 equalization scheme corresponds in principle to the case in which the computer-like control system would sample the channel at programmed intervals, but in the present form cannot be programmed to sample automatically the coaxial line and cause the necessary corrections. The reverse channel in this case is the command band of a coaxial line transmitting in the opposite direction from the line being equalized.[1, 3] This single reverse channel is shared by all of the lines (up to 10 in the L-4 system) transmitting in the direction being equalized, as shown schematically in Fig. 4. The sampling and decision mechanism is found at the L-4 control center. Solid-state memory circuits maintain the equalizer settings between adjustments.

If the equalization procedures are to be implemented while the circuits are loaded and in service, it follows that the process of measuring the line response to determine what corrections, if any, are needed must not adversely affect the circuits in use. This precludes,

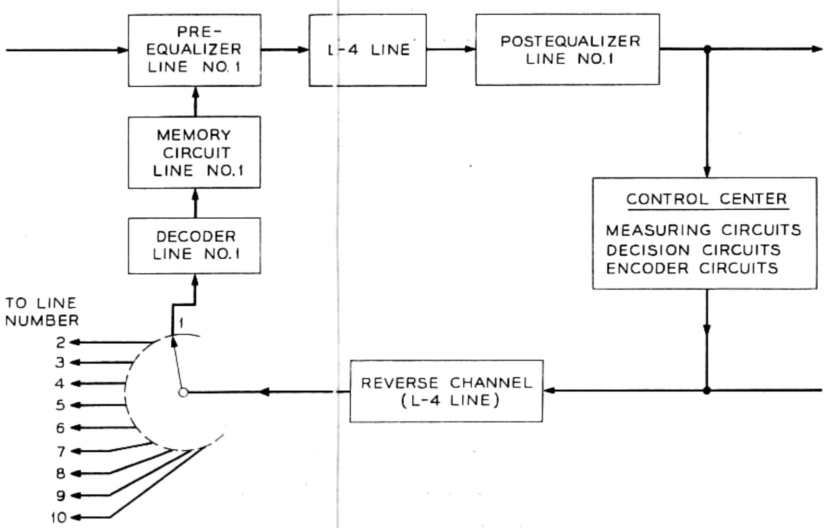

Fig. 4 — Functional schematic diagram of the L-4 equalizing system.

for example, using sweep techniques. However, the signals used to characterize system response must be separable from the message signals in the detection circuits. Consequently, the test signals associated with the adjustment of the A equalizers are located below mastergroup 1, between mastergroups and above mastergroup 6. As noted in Ref. 3, there is a 4 percent guard band between mastergroups. The test signals associated with the adjustment of the B equalizer are located above MG6 or within the mastergroups between the two submastergroups. Exceptions are the two lowest B test signals for which the test frequencies fall between adjacent supergroups of MG1. Guardbands between the submastergroups and supergroups are 56 and 8 kHz, respectively.

With this placement of the test signals across the transmission band, it is possible to realize practical filter designs which will in one case (control center detection process) separate the tones from the surrounding message power and in another case (at branching, dropping, and frogging points) block the test signals while passing the whole of the message spectrum.

The decision to use bump shape equalizers throughout the system is probably a bit more provocative than the other distinguishing features of the plan so far discussed. Obviously any of several approaches could provide the desired ultimate system response if the scheme were to use sufficiently complicated networks and adjustable shapes—and enough of them. The L-3 system, for example, uses 6 dynamic equalizers (each pilot-actuated and cause-associated), 15 cosine equalizers (including a flat term), and 5 bump equalizers (primarily to eliminate any unwanted effects of the cosine equalizer at the pilot frequencies of the dynamic equalizers). Bump shapes can be achieved by relatively simple Bode equalizer sections and offer attractive advantages over cosines with respect to realization and ease of adjustment. These features become particularly important in view of the desire to use both preequalization and in-service adjustment.

Preliminary calculations early in system development showed that a moderate number of bump shapes (between 10 and 20) would provide as good an equalized response as a corresponding number of cosine shapes. It further appeared that the bump shape approach would likely be superior in the final analysis when as many as possible of the bump shapes would be made cause-associated. Subsequent computer studies of the relative effectiveness of various combinations of adjustable shapes led to the selection of the family of 16 bumps shown in Fig. 5. Shapes 1–6 are located in the A equalizers while shapes 7–16 make up the B equalizer. At this time, however, only shape No. 1 may be characterized as cause-associated. As nearly as possible, this characteristic matches the loss variations with changing temperature of the many ferrite transformers located in the transmission path of the line repeaters.

III. EQUALIZING REPEATER

This section discusses the important factors involved in the design of the several distinct subassemblies which make up the equalizing repeater.

The regulating portion of an equalizing repeater is identical to the line regulating repeater except that access is provided to the output of the postregulating section and to the input of the preregulating section. This access is provided through high-voltage isolation transformers and permits the connection of the A equalizer between these points (Fig. 1).

3.1 A *Equalizer*

3.1.1 *General*

The A equalizer provides for the relatively coarse correction of the more complex deviations in system response which remain after the corrections applied by the regulating repeater. To the extent that the fixed deviation equalizers do not perfectly eliminate the systematic

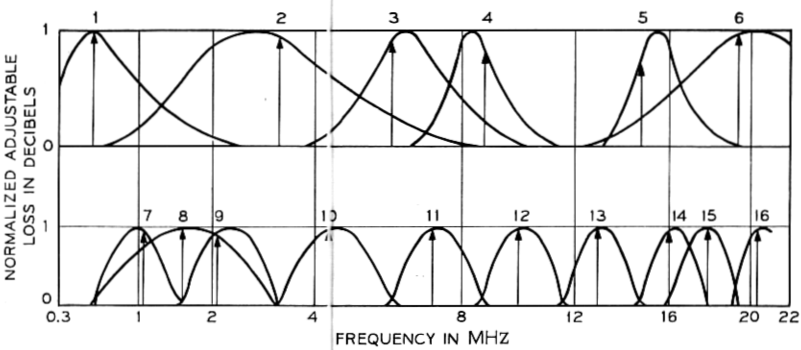

Fig. 5 — Normalized adjustable loss characteristics of the L-4 equalizer networks. The arrows denote the frequency of the test signals used as basis for adjustment.

repeater design error, the residual to be equalized will include a contribution from this source. To the extent that the latter becomes a significant part of the total residual, the resultant equalized response from main section to main section will tend to include like characteristics which will accumulate systematically along the system. It is therefore vital that the response to be compensated for by the equalizers include a minimum component of this sort.

The factors considered in Section II led to the specification of the equalizer shapes numbered 1–6 in Fig. 5 for the A equalizer. These are the relatively broad shapes required to make the necessary first-order correction which in turn permits the advantages with respect to signal-to-noise ratio and overload to be realized.

The main constituents of the A equalizer are shown in Fig. 6 and include four flat gain amplifiers, six adjustable Bode equalizer networks, and the elements and circuits required to permit remote control.

3.1.2 *Amplifier Design and Performance*

3.1.2.1 *General.* The equalizer amplifiers basically provide enough gain to compensate for the loss of the necessary adjustable equalizers. In addition, there is some loss associated with the circuits which permit both the coaxial line and the A equalizer to be interrogated as to response at the six A test frequencies. Finally, there is loss resulting from the trim equalizer network, which is required as a mop-up in order that the over-all A equalizer response in its reference state be as nearly as possible 0 dB throughout the L-4 band.

It is desirable, from considerations of noise and reliability, to minimize the number of amplifiers required to achieve this basic objective. This must also be balanced with the practicability of the resultant requirements on permissible noise, nonlinear distortion, and load capacity. A satisfactory compromise is the configuration of Fig. 6 wherein four of the adjustable Bode networks are incorporated in the feedback paths of four amplifiers, while the other two and the trim equalizer are connected between amplifiers.

Since the adjustable characteristics required of the A equalizer affect a fairly wide range of frequencies, it is particularly desirable that the amplifier configuration selected permit good isolation of the several equalizer networks to minimize interaction effects, and that this isolation be achieved with a minimum of loss. The configuration of Fig. 7 satisfies this requirement and is characterized by the following features:

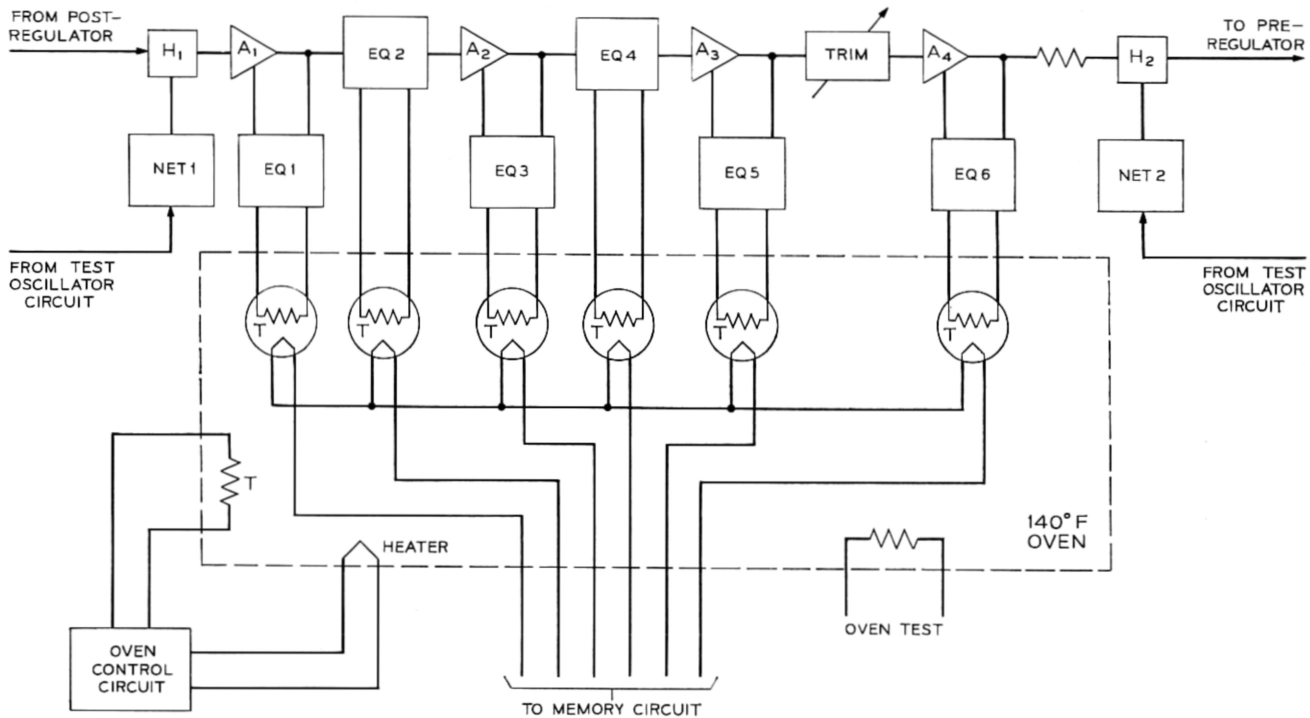

Fig. 6 — Block schematic diagram of the A equalizer. For clarity the two ovens and oven control circuits actually used are shown as one.

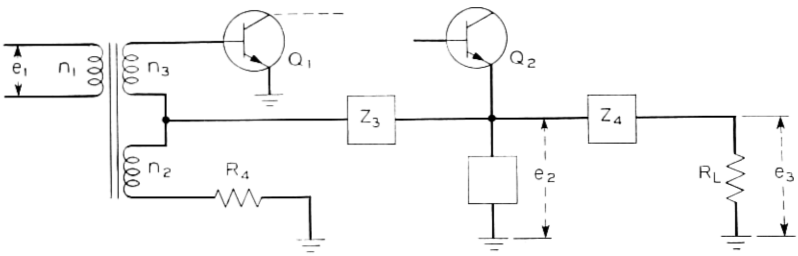

Fig. 7 — Simplified schematic diagram of the equalizer amplifier. Z_3 and Z_4 would normally be realized by the adjustable impedance of equalizer networks.

(*i*) The output impedance is approximately zero ohms and the voltage gain is essentially independent of load impedance.

(*ii*) The voltage gain is shown in the appendix to be

$$\frac{e_2}{e_1} \doteq \frac{n_3}{n_1}\left(1 + \frac{Z_3}{R_0}\right)$$

where $R_0 = n_3/(n_2 + n_3)R_4$. For $n_3 = n_2 = n_1$,

$$\frac{e_2}{e_1} \doteq 1 + \frac{Z_3}{R_g},$$

where R_g is the nominal resistance terminating the primary winding and in this case is 75Ω.

The loss associated with an equalizer Z_4 inserted in series between the output transistor and the load resistor, R_L, as shown in Fig. 8, is

$$\frac{e_2}{e_3} = 1 + \frac{Z_4}{R_L} = 1 + \frac{Z_4}{R_g}, \quad \text{if} \quad R_L = R_g .$$

Where the range required of the adjustable networks is similar, it is possible to design a family of like networks which operate at identical impedances and which require the same range of variable control resistance. All of the adjustable shapes could thus be achieved with virtually the same network and thermistor design.

Where greater or lesser range is required, this can be readily achieved by the specification of a different input hybrid transformer, one which can continue to provide the necessary load impedance to any series-connected networks while adjusting the β-circuit impedance at which the feedback network operates.

In a similar fashion the flat gain of the configuration can be adjusted without affecting Bode network performance, if desired, by specifying appropriate turns ratios on the transformer.

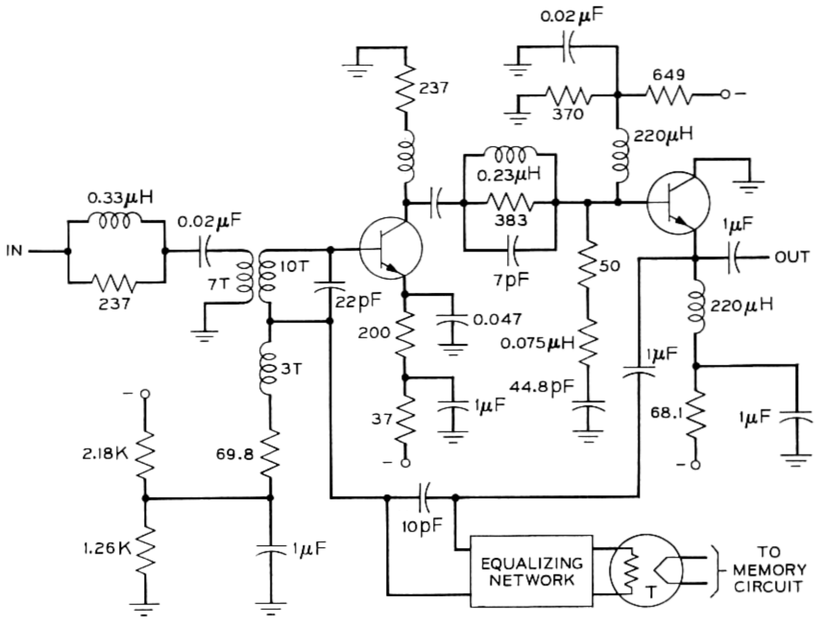

Fig. 8 — Schematic diagram of a typical equalizer amplifier. The circuit shown is that of A_4 in Fig. 6.

The configuration can be realized with a relatively simple two-stage design with common emitter input section and common collector output section, permitting excellent performance in respect to noise figure and linearity, respectively.

3.1.2.2 *Gain Considerations.* The overall voltage gain of the configuration of Fig. 7 is given by

$$\frac{e_3}{e_1} = \left(1 + \frac{Z_3}{R_g}\right)\left(1 + \frac{Z_4}{R_g}\right)^{-1},$$

where $R_0 = R_g$ and $n_3 = n_2 = n_1$; and $e_3/e_1 = 1$ if Z_3 and Z_4 assume equal values, which is very nearly the case for the Bode network designs used when each is in its reference state.

Consequently, a convenient building block of approximately zero dB gain (with the adjustable networks in the reference or "flat" state) can be readily achieved with this amplifier configuration by incorporating one equalizer network in the β-circuit, one equalizer network in series with the output transistor, and by specifying that $n_1 = n_2 =$

n_3. Under these conditions the equalizer networks will provide the same adjustable response capability whether connected in series with the output or connected in the β-circuit. As can be seen in Fig. 6 there are two such amplifier-network assemblies used in the A equalizer (A1–EQ2 and A2–EQ4).

The third amplifier of the A equalizer has an equalizer network only in the β-circuit and consequently provides a net voltage gain of

$$20 \log \left(1 + \frac{Z_3}{R_0}\right) \text{dB}.$$

As is described in subsequent sections, the value of Z_3 is determined, for operation with a particular R_0, according to the loss adjustment range required of the network and usually the wish to make that adjustment symmetric with respect to the reference or flat condition. In this case the value is approximately 93 ohms and, with the ability to vary the network control resistance between about 27 ohms and 665 ohms (using the indirectly heated thermistor), permits a loss variation at the network center frequency of about ± 4.0 to ± 4.5 dB. As a result, the gain of the amplifier A_3 of Fig. 6 is

$$20 \log \left(1 + \frac{93}{75}\right) = 7.0 \text{ dB},$$

and is approximately flat over the L-4 band.

The fourth amplifier in the string making up the A equalizer, A_4 of Fig. 6, is similar to A_3 in that the β-circuit alone includes an adjustable network. In this case it is the network having effect in the lowest regions of the L-4 message band and in the command and switching channels. There are two factors, however, which result in minor differences in its design. First, the adjustable range required of the low end equalizer network is greater than that required of any of the others—more nearly ± 6.0 dB than ± 4.0 dB. Second, some additional gain (beyond the 7 dB achieved from the circuit used in the other three amplifiers) is required to compensate for the total loss of the input and output connecting circuits and the trim equalizer. The flexibility of the selected configuration permits both of these goals to be achieved with a simple change of input transformer, all the while maintaining the standard over-all amplifier input impedance.

The same equalizer network design applies with an adjustment in the symmetry resistor to restore a symmetrical relationship between maximum and minimum loss and the reference loss. Selection of an input transformer for which $n_1 = 7$, $n_2 = 3$, and $n_3 = 10$, where

$$R_0 = \frac{n_3}{n_2 + n_3} R_4 = 49\Omega,$$

and

$$\frac{e_2}{e_1} = \frac{n_3}{n_1}\left(1 + \frac{Z_3}{R_0}\right) = 4.36,$$

provides a nominal gain of 12.8 dB with about ±6.0 dB adjustable range. The control resistance variation required by all of the networks is approximately 27 to 665 ohms, with reference or flat loss achieved when the network is terminated in 135 ohms. (A schematic for A_4 is shown in Fig. 8.)

3.1.2.3 *Noise Figure Considerations.* The noise figure of the amplifiers making up the A equalizer is not as significant to over-all system performance as that of some of the other line amplifiers, since A equalizer amplifiers are fewer and the transmission level within the A equalizer is not the lowest in the system. Nevertheless, it is necessary to minimize noise contributions from whatever source; a total A equalizer objective for noise figure less than 18 dB is satisfactory from the overall viewpoint. Fig. 9 shows the A equalizer constituents affecting noise figure and readily permits a satisfactory set of objectives for the individual amplifier noise figure to be developed. The symbol C in Fig. 9 is used to designate the negative of transmission level, or the transmission level expressed in dB below zero level.

The zero level noise contribution of the kth amplifier will be, in

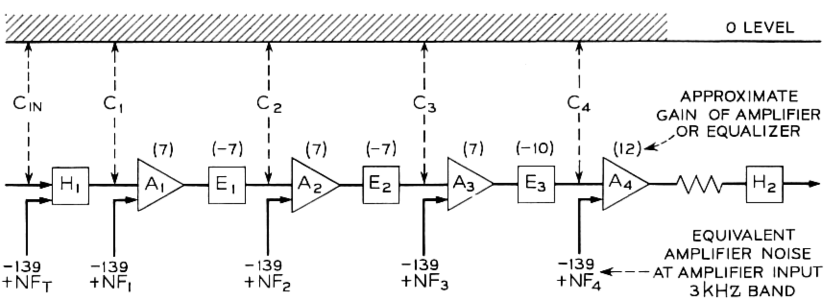

Fig. 9 — Block Diagram of the A equalizer for noise figure calculations. Indicated are the equivalent noise sources and the approximate amplifier and network gains.

a 3 kHz band:

$$P_k = -139 + NF_k + C_k \text{ dBm}.$$

The total noise contribution of the amplifiers making up the equalizer will be

$$P_{Nt} = \text{“}\sum_{k=1}^{4}\text{”} (-139 + NF_k + C_k) \text{ dBm} \tag{1}$$

where the “$\sum$” implies addition on a power basis.

The approximate nominal losses and gains are indicated on Fig. 9; it can be seen that, for these particular values,

$$C_1 \approx C_2 \approx C_3 \triangleq C.$$

If it is further assumed that $NF_1 = NF_2 = NF_3 = NF$ (which is not unreasonable, since the design of amplifiers 1 to 3 has been shown to be alike for other reasons) then (1) can be rewritten as:

$$\begin{aligned} P_{Nt} &= (-139 + NF + 10 \log 3 + C) \text{ “+” } (-139 + NF_4 + C_4) \\ &= -139 + [(NF + 10 \log 3 + C \text{ “+” } (NF_4 + C_4)]. \end{aligned} \tag{2}$$

It can be seen in Fig. 9 that C_4 is about 3 dB larger than C since the trimmer loss is about 3 dB larger than the loss of the series equalizer networks. If NF_4 can be realized at 3 dB lower than NF, then (2) can be simplified to

$$P_{Nt} = -139 + NF + 10 \log 4 + C \text{ dBm}. \tag{3}$$

In terms of the equivalent noise figure of the overall A equalizer,

$$P_{Nt} = -139 + NF_T + C_{IN} . \tag{4}$$

Equating P_{Nt} from (3) and (4) yields

$$NF_T = NF + 10 \log 4 + C - C_{IN} .$$

Since C–C_{IN} is just the loss of the input hybrid connecting circuit, L_H,

$$NF_T = NF + 10 \log 4 + L_H .$$

Thus

$$NF = NF_T - 10 \log 4 - L_H .$$

For $L_H = 1.5$ dB and letting $NF_T = 18$ dB,

$$NF = 18 - 6 - 1.5 = 10.5 \text{ dB} .$$

Recalling the assumption that the noise figure of the fourth amplifier would be 3 dB better than the others,

$$NF_4 = 10.5 - 3 = 7.5 \text{ dB}.$$

Consequently, satisfactory over-all noise figure performance may be achieved in the A equalizer if the configuration used in the first three slots realizes a noise figure of 10.5 dB or less and the configuration used in the fourth position, 7.5 dB or less. These are well within the capability of this configuration with the devices used.

The noise figure of the individual amplifier is determined primarily by the noise figure of the input transistor and the coupling loss of the input connection. Other considerations are the extent to which the input stage is mismatched with respect to noise figure and the extent of local feedback on the first stage.

With respect to local feedback, it can be shown that the effect of a resistor in the emitter of a common emitter transistor stage is entirely analogous to that of r_b' and that the effective noise figure of the stage, based on the equivalent circuit for noise shown in Fig. 10, becomes[5,6]

$$F \approx 1 + \frac{R_E}{R_g} + \frac{r_b'}{R_g} + \frac{r_e}{2R_g} + \frac{(1-\alpha_0)\left\{1 + \left[\frac{f}{(1-\alpha_0)^{\frac{1}{2}} f_\alpha}\right]^2 (R_g + R_E + r_b' + r_e)^2\right\}}{2\alpha_0 r_e R_g}. \tag{5}$$

(Apart from the loop gain considerations, an added factor favoring the common emitter input stage is the realization of the optimum

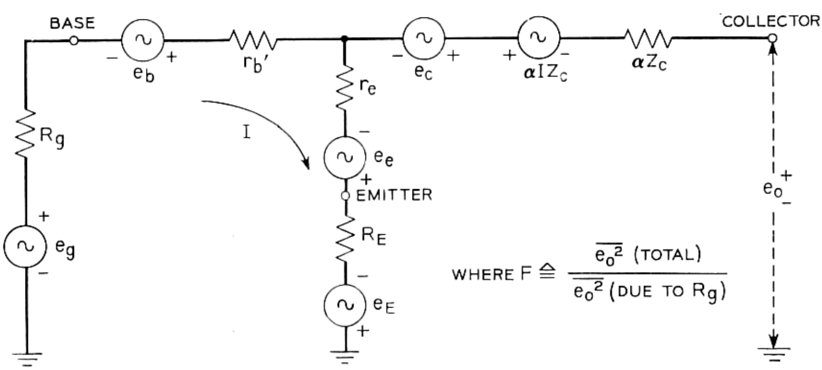

Fig. 10 — Equivalent circuit for noise figure calculation of a common emitter stage with series local feedback (R_E).

noise figure and maximum device gain at very nearly the same source impedance.)

Because of the lesser gain required of the amplifiers in the first three positions in the A equalizer, it is necessary and desirable in achieving a satisfactory loop gain response to apply series negative feedback to the input common emitter stage. From (5) it can be seen that this will degrade the effective noise figure of the stage to an extent which depends on the magnitude of R_E. Defining this degradation to be Δ_{RS} (in dB), the noise figure of the amplifier may be established by

$$NF = NF_{trans} + L_H + \Delta_{RS} , \tag{6}$$

where L_H is the hybrid transformer coupling loss and NF_{trans} is the device noise figure defined at the selected generator impedance.

In these first three amplifiers, the indicated $\mu\beta$ considerations have resulted in first stage emitter resistances corresponding to Δ_{RS} of approximately 1 dB. Since the hybrid transformers used in these positions are equal ratio, the hybrid loss, allowing 0.5 dB dissipation loss in the transformer, is approximately 3.5 dB. For over-all NF of 10.5 dB,

$$NF_{trans} = 10.5 - 1.0 - 3.5 = 6.0 \text{ dB}.$$

Thus the first stage may be biased at as large a current as possible at which the device noise figure is 6.0 dB or less.

The "largest" current is suggested since, in a configuration of the type selected, nonlinear distortion originating in the input or low level stage will generally not be negligible. Consequently, it is desirable to bias the first stage so that, while satisfying noise figure objectives, nonlinear distortion effects are minimized. As is described in greater detail in Ref. 2 this can usually be achieved by increasing the dc bias current, which of course will generally degrade the noise figure performance.

It has been shown that the fourth amplifier of the A equalizer must provide 5 to 6 dB more gain than the others and that this is achieved by connecting a different input transformer of turns ratio 7:10+3. The ideal loss of such a transformer in the path to the transistor is 1.1 dB; the dissipative loss of the hybrid (primarily caused by core loss) is approximately 0.4 dB. Therefore, the total loss to the signal in the path to the transistor is about 1.5 dB. The increased closed loop gain required of this amplifier makes it possible to achieve satisfactory open loop transmission with no local feedback whatever on the first stage. Thus $\Delta_{RS} = 0$. Consequently the over-all amplifier noise figure will be 7.5 dB or less if the transistor noise figure is 6.0 dB or less, the same requirement imposed on the first stage of the other three amplifiers. Figure 11 shows the typical noise figure of this amplifier.

3.1.2.4 *Other Considerations.* The linearity of the feedback amplifier depends primarily on the inherent linearity of the transistors used and on the nature and amount of feedback applied. The effective transistor linearity depends largely on bias conditions and on connecting impedances. If the selected configuration causes the output or power stage to be the primary source of nonlinear distortion, advantage can sometimes be realized by using a common collector output stage. The degree of improvement (relative to a common emitter stage, for example) depends largely on the particular device characteristics and operating conditions; 5 to 10 dB advantages might be expected under the right conditions. Since a common collector output stage has already been shown to be desirable in the convenient realization of the adjustable equalizer networks, this connection for the output stage was used throughout the A (and the B) equalizer.

Negative feedback is used in the equalizer amplifiers to reduce nonlinear distortion and to reduce sensitivity to variations in the parameters of the active devices. It has already been pointed out that the configuration selected provides an isolation between adjustable equalizer networks which permits their totally independent operation and adjustment. The problems encountered in the realization of a satisfactory and stable $\mu\beta$ transmission in the equalizer amplifiers are very similar to those described in detail for the preamplifier of the basic repeater in Ref. 2 and are not elaborated here.

Also like the preamplifier, the equalizer amplifiers have a hybrid transformer connected at the input which largely determines the

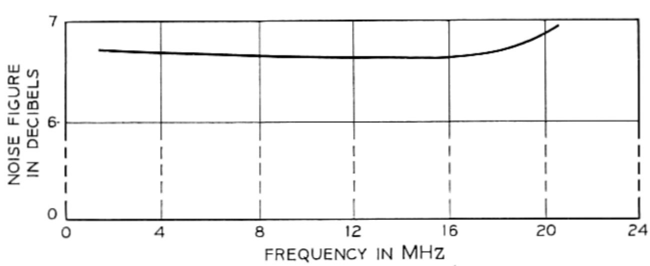

Fig. 11 — Typical noise figure of the equalizer amplifier A_4 of Fig. 6.

quality of the input impedance provided by the amplifier. The RLC network connected as shown in Fig. 8 is required to transform the "raw" impedance of the essential amplifier to that required for satisfactory and predictable performance. The capacitance is effective chiefly at low frequencies where it reduces the effect of the transformer mutual inductance, while the resistor-inductor pair provide a low Q compensation, effective primarily at high frequencies, for transformer inter- and intrawinding capacity.

3.1.3 *The Design of the Equalizer Networks*

3.1.3.1 *Bode Network Design.* The use of Bode networks (sometimes called Bode equalizers or Bode regulators) in transmission systems is not new.[7] One of the early applications was in the L-1 coaxial system.[8] The higher frequency range of the L-4 system introduces some unique problems resulting in design modifications. Before continuing, let us examine the basic relationships for Bode network design.

The three standard configurations using Bode networks are shown in Fig. 12. With R_0 as defined in Fig. 12 and with $Z_1Z_2 = R_0^2$, the insertion factor of all three configurations is

$$e^{\varphi} = 1 + \frac{Z_1}{R_0} = 1 + \frac{R_0}{Z_2}. \tag{7}$$

Normally the impedance Z_1 is realized as shown in Fig. 13(a); the impedance Z_2 is obtained as shown in Fig. 13(b). Equation (7) can be written

$$e^{\varphi} = 1 + \frac{1}{R_0(G_1 + Y_{1A})} \tag{8}$$

with

$$G_1 = 1/R_1, \qquad Y_{1A} = 1/Z_{1A}.$$

The corresponding insertion loss equation is

$$A = 20 \log_{10} | e^{\varphi} | = 20 \log_{10} \left| 1 + \frac{1}{R_0(G_1 + Y_{1A})} \right| \text{dB}. \tag{9}$$

By varying the termination shown in Fig. 13 between 0 and ∞, the loss A can be made to vary from $20 \log_{10} | 1 + R_1/R_0 |$ dB down to 0 dB with a characteristic shape determined by the shaping networks Z_A or Z_B. The variations will be symmetric if $R_0 = R_1R_A^2/(R_1^2 - R_A^2)$, resulting in a flat loss $A_0 = 10 \log_{10} | 1 + R_1/R_0 |$ dB.

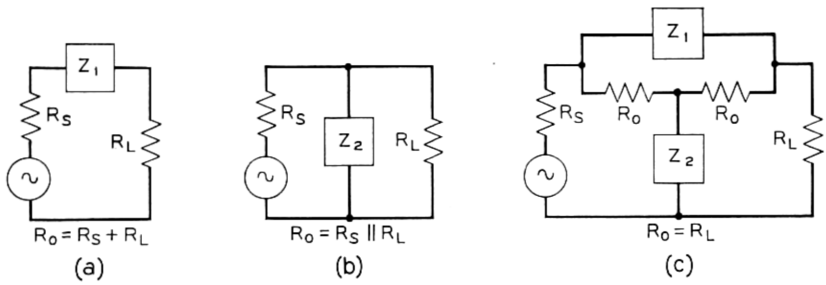

Fig. 12 — Basic equalizer network configurations: (a) series, (b) shunt, (c) bridged-T.

Equations (8) and (9) can be normalized so that the greatest loss variations are between −1 and +1 dB and the flat loss is 0 dB. Then charts can be used to relate G and B [where $Y_A = 1/Z_A$ (normalized) $= G + jB$] to the resulting normalized loss and phase. The network configuration N_A and the choice of G and B determine the ideal Bode network response.

The effect of the Bode network G parameter for the shape used in the A equalizer is evident from Fig. 14. A section with a G greater than 0.21 has no overshoot, but: (*i*) an undershoot remains at frequencies far removed from the desired response and (*ii*) the shape falls off too rapidly, resulting in ineffective equalization between the bump shape centers. (However, allowing a small loss where the response should ideally be zero permits the use of relatively high values of G). At low values of G the shape is reasonable between the crossovers, but a large overshoot can cause interference with adjacent shapes. The choice of G is thus a compromise. Values between 0.1 and 0.2 are used in the L-4 system equalizers.

In the design of L-4 A and B equalizer Bode networks, the bridged-T

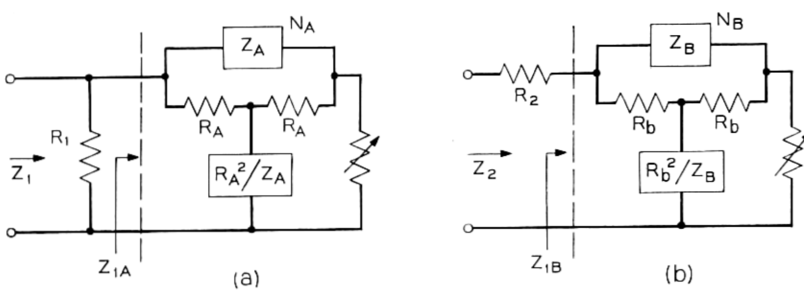

Fig. 13 — Realization of Z_1 and Z_2. (a) network Z_1 and (b) network Z_2.

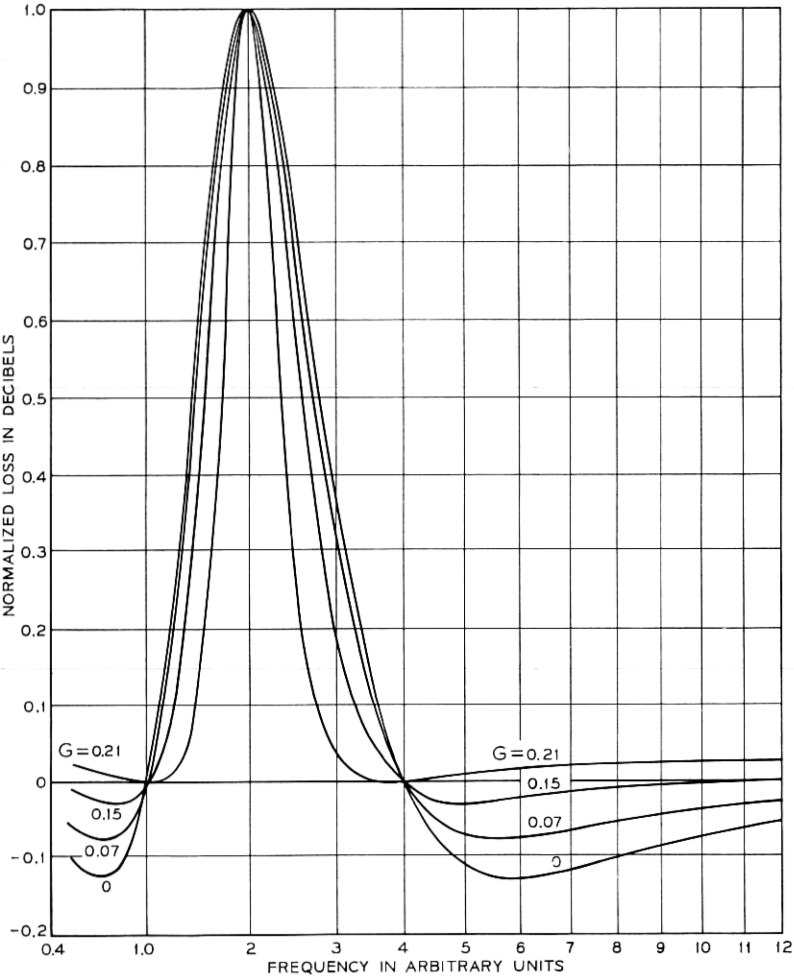

Fig. 14 — Effect of the Bode network parameter G on the response of the network.

configuration of Fig. 12(c) was eliminated from consideration by its complexity and by the undesirable necessity to provide two variable, tracking, inverse resistances terminating Z_1 and Z_2. The shunt arrangement was eliminated because the resulting impedance levels would require development of new thermistors or introduce major difficulties in amplifier design. Therefore, the series configuration (Fig. 15) is used for all of the A and B equalizer Bode networks.

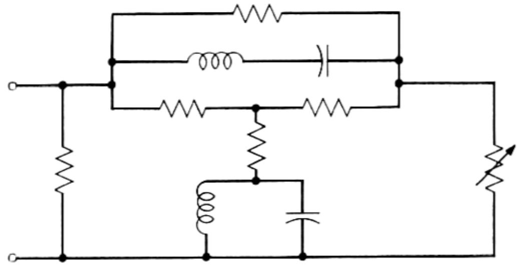

Fig. 15 — Ideal A equalizer Bode section.

For the A equalizer, the shaping network Z_A is a simple series resonance shunted by a resistor, resulting in the network Z_1 shown in Fig. 15. The variable resistance is supplied by a Western Electric 2A thermistor. The thermistor has a separate heater, substantially reducing signal coupling through the logic and memory circuitry. Thermistor characteristics at 140°F ambient temperatures vary as illustrated in Fig. 16. To maintain approximately equal loss changes in dB as the thermistor heater current is stepped by the memory, the linear portion of the characteristic is used as far as possible.

Realization of the Bode sections requires a deviation from the ideal parameters because of parasitics within the equalizer and impedance

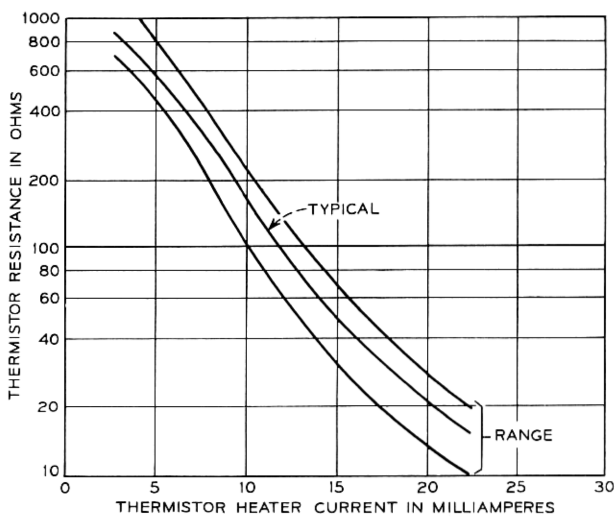

Fig. 16 — Thermistor R-I characteristics. Shown are the typical, maximum, and minimum characteristics.

interaction with the amplifier circuitry. The chief parasitics are the interwinding capacitance and inherent resistance of the inductors and the distributed capacitance and lead inductance associated with the thermistors. These undesired interactions produce a lowering of the realized G relative to the design G and introduce a distortion of the characteristic as shown in Fig. 17 for a feedback path Bode network. (The interamplifier Bode networks produce the same characteristic crossing shift, but the higher frequency loss response is decreasing rather than increasing.)

To overcome these difficulties, the component values were slightly altered based on laboratory measurements and a capacitance was placed in series with the thermistor leads (except for the highest and lowest frequency shapes, where the distortion is less of a problem). In addition, a capacitance was placed across the input of the Bode sections located in the amplifier feedback path.

3.1.3.2 *Trim Equalizer Design.* The amplifiers, transformers, and networks do not have a perfectly flat frequency response, and a fixed trim equalizer is required to provide an over-all flat nominal response for the A equalizer. The configuration for the A trim equalizer is shown in Fig. 18. The equalizer is composed of two bridged-T sections which provide loss peaks, one bridged-T section providing a loss valley, and a potentiometer for flat loss adjustment. The constant-resistance

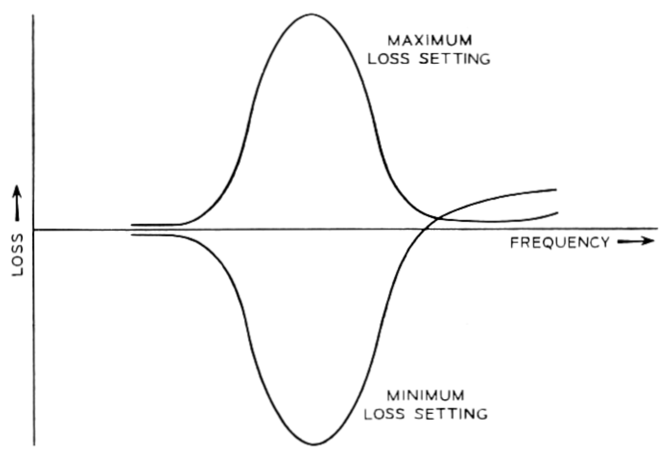

Fig. 17 — Distorted network response before compensation. The distortion results chiefly from circuit parasitics and has the effect of lowering the realized G relative to the design G.

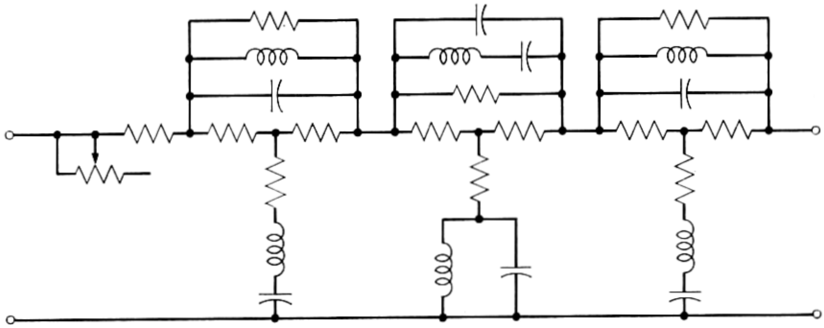

Fig. 18 — Configuration of the A trim equalizer.

bridged-T sections were designed with the assistance of specialized time-sharing computer routines and a digital computer general-purpose optimization program.[9]

The location of the trim equalizer between two amplifiers of the A equalizer renders its impedance relatively unimportant. Thus, the equalizer is not designed for high return loss. Because of the effect of parasitics, an extra capacitor is added across the bridge arm of the valley section. This capacitance resonates with the effective inductance of the series LC branch of the bridge arm, peaking the high-frequency side of the loss valley.

3.1.4 *Other Components of the* A *Equalizer*

The adjustable equalizer networks are controlled through the indirectly heated thermistor associated with each network. In order that these thermistors provide, for a given heater current, a predictable and constant termination to the network, it is necessary to establish a controlled environment. This is provided by placing the thermistors in an oven, the temperature of which is established and maintained by a proportional-control temperature-regulating circuit. The thermistors should be maintained at the lowest possible temperature consistent with operating environment, since this permits a maximum possible variation in thermistor resistance for a given variation in heater current. Consequently, the oven is maintained at approximately 140°F and provides a virtually unchanging environment for the thermistors between about 60°F and 140°F ambient temperatures. (The typical resistance heater current characteristic for the thermistors at 140°F was shown in Fig. 16.)

The input and output connecting circuits of the A equalizer permit the insertion of the test signals which are used at the remote control center to determine either the gain settings of the equalizer networks or the misalignment of the section of the system between equalizing stations. These, in Fig. 6, are designated H1-Net 1 and H2-Net 2, respectively. The loss-frequency characteristics of the two circuits are carefully specified and controlled so that the test signals originating in the test oscillator circuit are applied to the L-4 line at a transmission level of −20 dBm0. The input and output connecting circuits are thus designed so that a comparison of the test signal level measured at the equalizer output (or any point beyond, such as at the control center) when the test signals are applied first to Net 1 and then to Net 2 provides an accurate measure of the A equalizer gain at the test signal frequencies (denoted by the arrows on Fig. 5).

Correspondingly, a comparison at the control center of the received test signal level when applied first to Net 2 of an A equalizer and secondly to Net 1 of the A equalizer next closer to the control center provides an accurate measure of the response at the test signal frequencies of that section of the system between the equalizers. This will usually be a section including about 25 basic and regulating repeaters. The information gathered in this fashion is then used to determine the optimum settings of the several equalizer networks.[1]

3.2 *Equalizer Remote Control Circuits*

Equalizer settings are remotely controlled by the transmission from the L-4 control center of coded commands which at the equalizer location must be detected, decoded, and acted upon. These functions in the equalizing repeater involve: (*i*) the command receiver, which selects those commands from the line signal which are transmitted in the command channel assigned to that location, and which recovers the originally encoded audio signals; (*ii*) the logic circuit, which performs an analog-to-digital conversion of the command-receiver output and decodes the commands inherent in the signals received; (*iii*) the test oscillator circuits which provide the test signals used to measure the gain of the A equalizer and the misalignment of the cable sections between equalizers; (*iv*) the memory circuits which maintain the settings of the equalizer networks between adjustments; and (*v*) the monitoring oscillator power supply and switching circuit which provides, on command, the 15 mA dc required to energize a string of monitoring oscillators, and which connects this dc source to one of the two oscillator strings adjacent to the equalizing repeater.

The command receiver is shown in block form in Fig. 19. The input

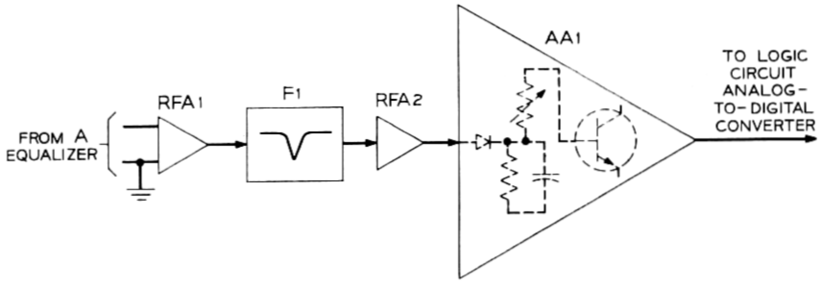

Fig. 19 — Block diagram of the command receiver. The amplifier AA1 includes the envelope detector and amplitude control.

signal to the receiver is bridged from the output of the first amplifier of the A equalizer. The combination of amplifiers and filter permit the receiver to be adjusted so that, with nominal input to the A equalizer, approximately 10V p-p is delivered to the logic circuit.

The logic circuit consists of an analog-to-digital converter and a series of gates and drivers. The analog-to-digital converter (Fig. 20) includes ten vibrating reed selectors and ten Schmitt trigger circuits. Each of the reed selectors has a resonant frequency which corresponds to one of the audio frequencies used by the control center to generate the various remote control system commands.

When the series-parallel connection of the selector windings, which forms the command receiver load, receives a signal of adequate amplitude at one of the these frequencies, the corresponding selector responds with intermittent closure of a pair of contacts at a rate equal to its resonant frequency.[10] The vibrating contact is connected in series with an RC charging circuit which in turn is connected in the base of the Schmitt trigger circuit. The presence of the particular audio frequency is thus detected by the reed selector and causes the operation of the trigger circuit which remains operated for the duration of the audio signal. Most of the control system commands are transmitted in bursts of approximately 300 ms duration and these commands correspondingly produce, at the analog-to-digital outputs, pulses of approximately the same length. (The only commands not falling into this category are those associated with test or monitoring oscillator turn-on which are continuous during the interval that these oscillators are "on.")

The outputs of the analog-to-digital converter associated with equalizer adjustment are connected to the several gates (Fig. 20).

Each gate is associated with a particular equalizer-adjust command and is connected to one of the six memory circuits. The equalizer-adjust commands advance (count-up) the count of the memory; retard (count-down) the count of the memory; or cause all of the memories to go to the 011111 state (reset).

Analog-to-digital converter outputs G and H are connected to driver circuits which in turn operate the relays K1 and K2, respectively, of Fig. 21. The contacts of these relays apply dc power to the test oscil-

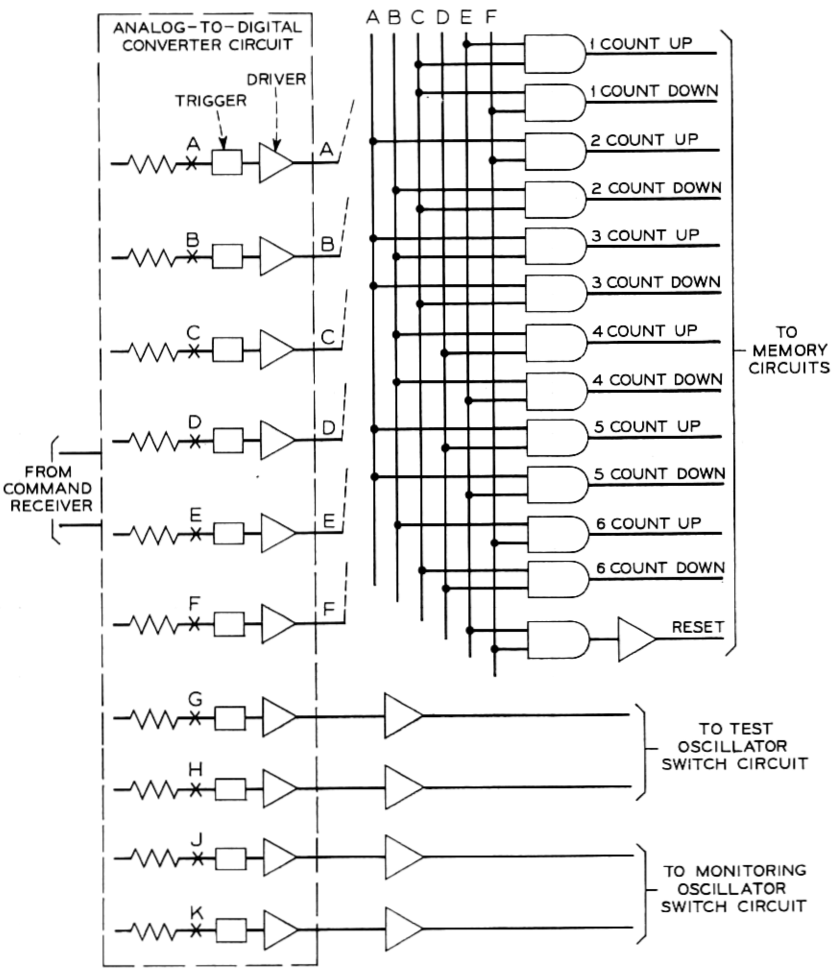

Fig. 20 — Block schematic of the A logic circuits.

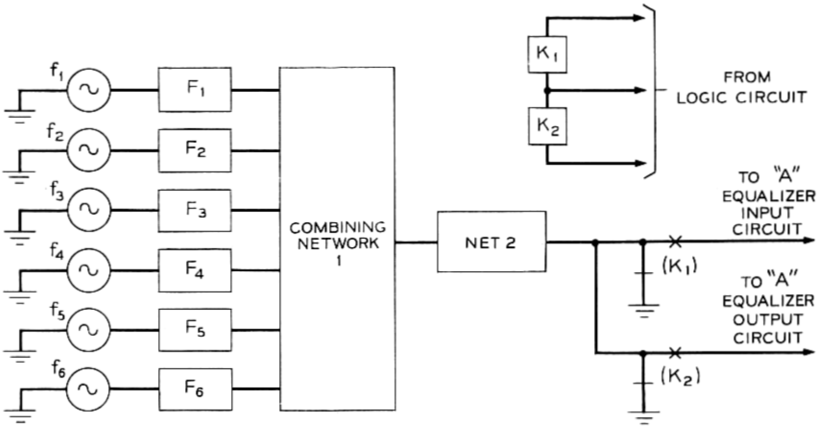

Fig. 21 — The A test oscillator circuit.

lators and connect the test oscillator signals either to the input (Net 1 of Fig. 6) or to the output (Net 2 of Fig. 6) of the A equalizer.

Outputs J and K are connected to circuits which, in a similar way, cause power to be applied to one or the other of the two adjacent groups of monitoring oscillators when the appropriate command is received.

The test oscillator circuit is shown in Fig. 21 and provides at a carefully controlled amplitude the six test signals which ultimately provide the basis for the settings of the six A equalizer networks. The frequencies of the test signals span the L-4 band and are indicated in Fig. 5 by the arrows associated with shapes 1 to 6. As can be seen, each is at or near the center-frequency of the associated "bump." The outputs of the six oscillators are individually filtered (F1 to F6) before the six signals are combined (combining network 1) and the proper level is established (Net 2). The combined signal is connected to the switching circuit consisting of K1 and K2 which, upon command, will apply power to the oscillators and connect the test signals either to the input or to the output of the A equalizer.

Associated with each adjustable equalizer network is a memory circuit which maintains the equalizer settings between adjustments. This is done by using the memory to establish and maintain the current supplied to the thermistor heater in the corresponding network. The L-4 equalizer memory is indicated in Fig. 22 and consists of a six-stage reversible binary counter which can established 64 different

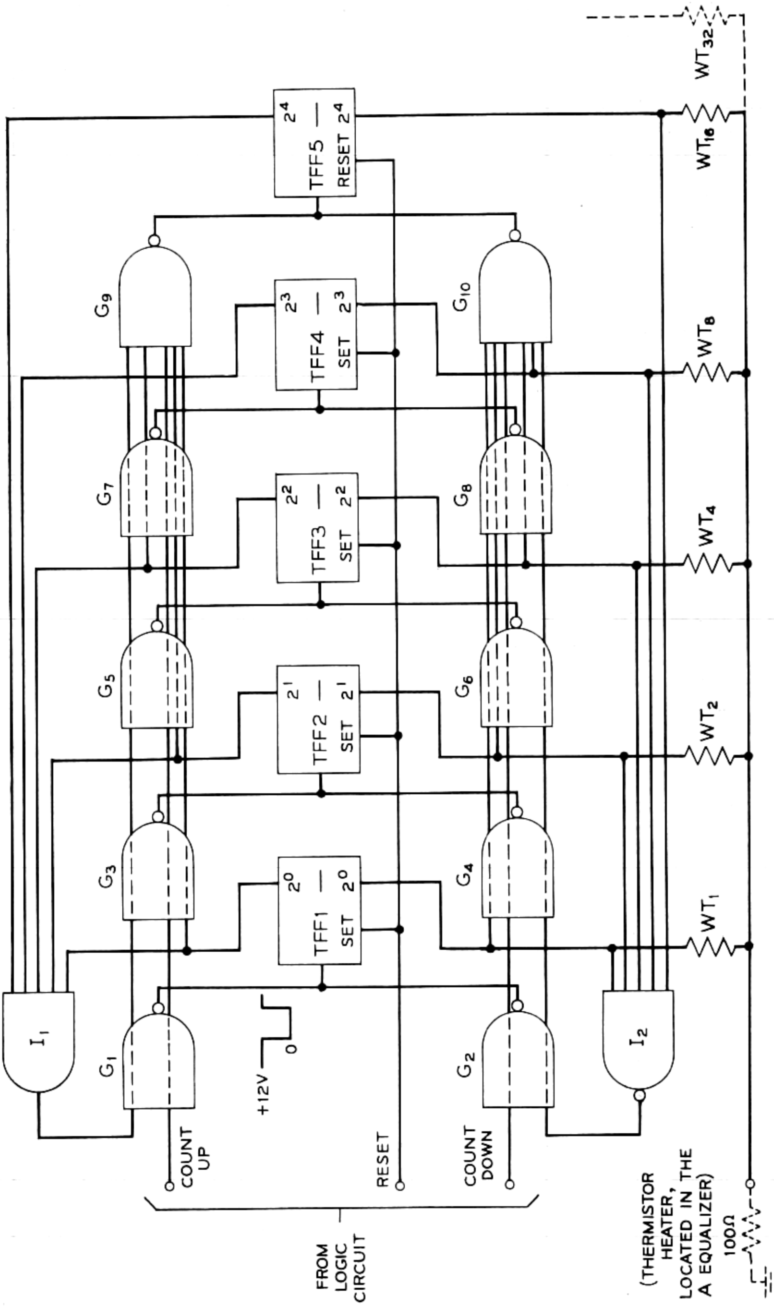

Fig. 22 — Memory circuit for the equalizers. This circuit is used throughout the system for the control of A and B equalizer settings.

values of heater current and consequently 64 different settings of equalizer network gain.

As the memory is counted by remote commands originating in the control center from the 000000 state to the 111111 state, the current supplied to the network thermister increases from minimum to maximum. Depending on whether the network involved is connected in series with the amplifiers of the A equalizer or connected in the β-circuit of the same amplifiers, the gain of the equalizer goes to maximum or minimum, respectively. In the simple or "uninhibited" binary counter one pulse beyond the 111111 state lies the 000000 state (and vice versa); such a change in this application would cause the corresponding equalizer network to go from one extreme gain setting to the other (which may be as much as 12 dB different at peak frequency). Consequently, over- and undercount inhibit are designed into the counter. Having counted up to the 111111 state or down to the 000000 state, further attempts to count in the same direction will produce no change in either the counter or the associated network. This is accomplished (Fig. 22) by the gates I1 and I2 which shut off the inputs to the counter associated with counting up and counting down, respectively.

The several equalizer bumps have adjustable range of approximately ± 4 or ± 6 dB. Thus the difference in the gain associated with consecutive states of the memory average about 0.1 to 0.2 dB. This places an ultimate limit on how close to ideal the response at the several test frequencies can be made.

The dc-dc converter used to power the monitoring oscillators controlled by a particular station is described in Ref. 11. The switching circuit associated with fault location is shown in Fig. 23. When the proper command has been received from the control center and decoded in the logic circuits, the 0.5A dc line current is switched to the dc-dc converter. The resultant 15 mA dc from the converter (at up to 260V) is connected to the group of monitoring oscillators either to the east or to the west of the equalizing station (depending on which command had been received). Each of these groups may include oscillators at up to fifteen repeater stations in addition to the equalizing station. A typical main section is divided into six such groups, two groups controlled by each of the two equalizing repeaters and one group controlled by each main repeater. The converter operates only when fault location is under way, and in the absence of one of the required commands the dc-dc converter input is short-circuited by the oscillator switch circuit as shown in Fig. 23.

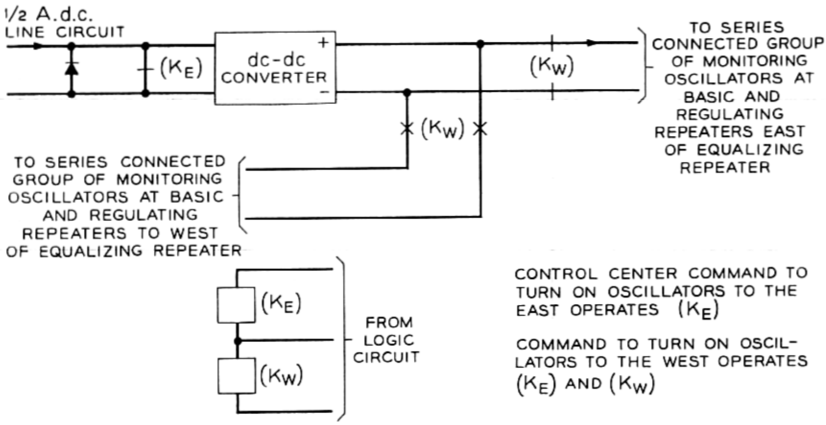

Fig. 23 — Monitoring oscillator power and switching circuit.

3.3 *Physical Design*

The entire L-4 equalizing repeater complex occupies the volume of two apparatus cases of the same size and shape used for the basic and regulating repeaters.[12] For a fully equipped Coax 20, there are 40 of these sealed pressurized apparatus cases which house the transmission equipment required at an equalizing station.

Because of the repetition in circuitry of the L-4 repeaters, the basic building block concept was carried to the physical design of the equalizing repeater. The same elements present in the regulating repeater appear again in the equalizing repeater with the addition of the A equalizer and the equalizer and fault-location control circuitry. Thus, the regulating portion of the equalizing repeater consists of an L-4 regulating repeater modified to distribute power to the other plug-in units.

The remaining parts of the equalizing repeater are separated into two types of equipment packages—large castings with over-all dimensions about 3.4 by 12 by 17 inches which occupy the central portion of the apparatus cases, and smaller, peripheral units filling spaces of about 2.5 by 6 by 15.5 inches along the sides of the larger units (see Fig. 24). Because of the series powering scheme for the L-4 line, all the circuits of the equalizing repeater are at high voltage with respect to sheath or earth ground. High voltage points have been made as inaccessible as possible and all electronic components, active and passive, are contained within epoxy-insulated cavities of the plug-in units.

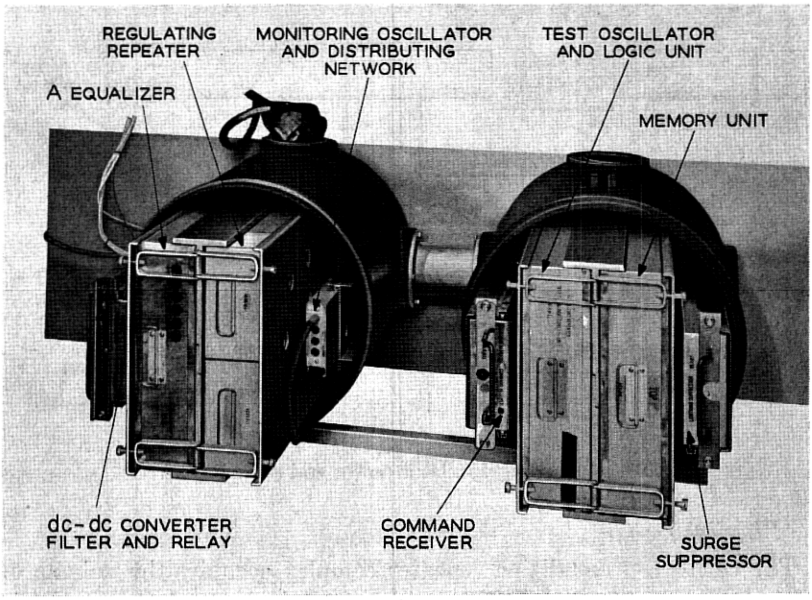

Fig. 24 — Equalizing repeater apparatus case. The left cabinet houses the transmission circuits; the right cabinet houses the remote control circuits.

The A equalizer assembly (Fig. 25) contains the equalizer amplifiers, Bode networks, thermistor ovens, temperature control networks and the regulating diodes which provide the several dc voltages required by these circuits and the control circuits. Because the lead lengths interconnecting the amplifiers and Bode networks are critical, the networks have been made an integral part of the amplifier assembly which uses an epoxy glass printed wiring board mounted in a cast aluminum housing. These are the characteristic die cast amplifier housings used throughout the L-4 designs where the bottom amplifier cover, containing the mounting studs for the amplifier, is bonded to the epoxy coated cavity in the main casting using an epoxy sheet adhesive.

The same bonding technique is used in the test oscillator and logic assembly to mount the six A test tone oscillators (see Fig. 26). The individual oscillator containers are bonded into position as close as possible to their respective filters. The array of cast ribs in the cavity of the main housing shields the small filters.

The logic circuitry, mounted in the test oscillator and logic assembly, uses a series of reed selectors which respond to the audio command tones from the main station control center. Since the conventional mounting arrangements of these vibrating reed selectors in sockets could not be adapted to the L-4 designs, the selectors were soldered on epoxy-glass printed wiring boards. Clamping arrangements and a sequential assembly method were developed to prevent relative motion between the selector's permalloy shell and its molded plastic base, and between its base and its terminal leads to the energizing winding. These expedients permit normal handling and manipulation of the selectors during shop assembly, testing and inspection.

The memory assembly houses six memory circuits on epoxy glass printed wiring circuit boards. The memories are mounted on standoffs in individual cavities formed in the main casting.

The command receiver (see Fig. 27) typifies the type of construction used in the peripheral units. They have fabricated housings, insulated with an epoxy coating; constituents are mounted by standoffs and by bonding. They are a single cavity deep, lighter than the larger cast type units, and have guide rails on their sides for mating with guides on the apparatus case chassis. Handle assemblies contain locking features for securing the units in place. During hardness

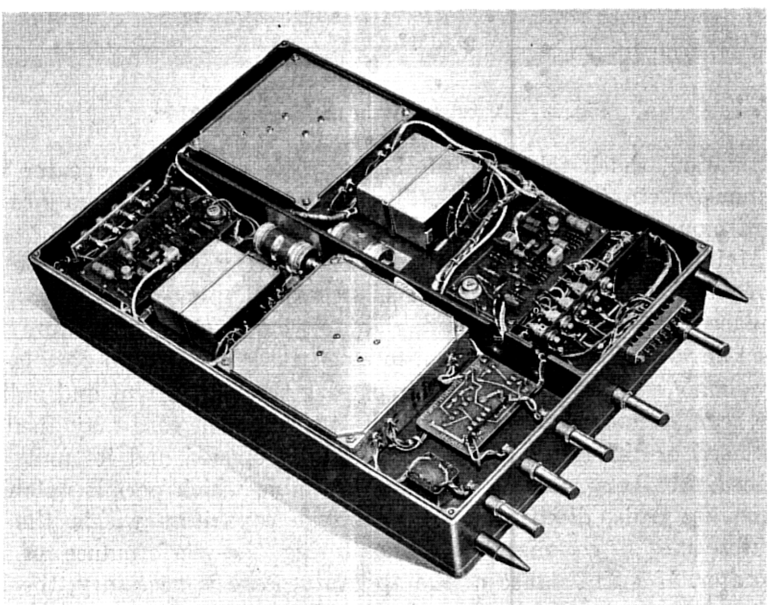

Fig. 25 — A equalizer assembly.

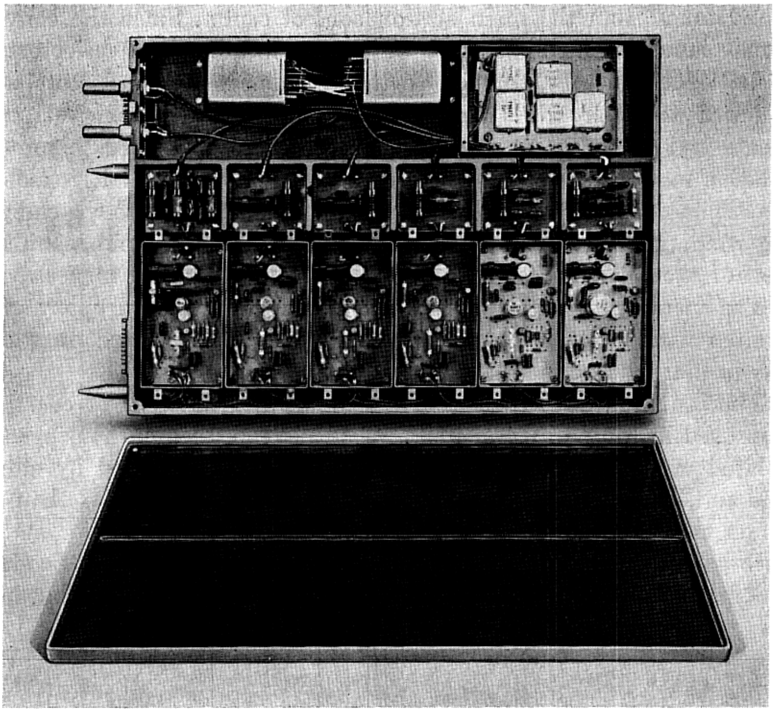

Fig. 26 — A test oscillator and logic assembly.

evaluation, shock tolerance of the complete equalizing repeater was demonstrated at the 50g level. Therefore, this equipment qualifies for hard-mounting in manholes.

Maintenance of equalizing repeaters is very similar to that for basic and regulating repeaters. If necessary, plug-in units can be replaced under power without risk to personnel. A procedure has been developed to enter the transmission case first, and to disable the equalizing repeater complex by bypassing the line current and pulling the regulating repeater. Units in the transmission case may then be replaced or the control case may then be opened and its units replaced. Auxiliary aids or tools are available which permit patching, removing pads, discharging high voltage capacitors within the repeater and A equalizer, and monitoring the performance of the repeater. If maintenance of the apparatus case is necessary, the line power is turned down so that the apparatus case chassis may be removed safely.

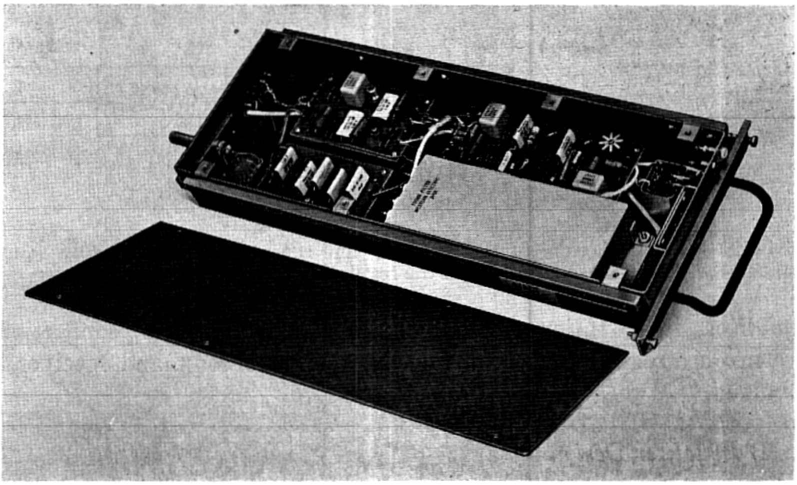

Fig. 27 — Command receiver assembly.

IV. MAIN STATION REPEATERS

The main station repeaters are made up of the several major elements indicated in Figs. 2 and 3. The line transmitting repeater (Fig. 28) and the line receiving repeater (Fig. 29) taken together perform the service of a single regulating repeater.[2]

The A equalizers of the main repeater are identical to those of the equalizing repeater in all essential respects, differing only in physical design and manner of powering. The remote control aspects of the main repeater differ from the equalizing repeater only in phyisical design and in the absence of a command receiver. As described in Ref. 1, the command receiver for the main repeater equalizers (both A and B) is a physical part of the command looping panel. In receiving

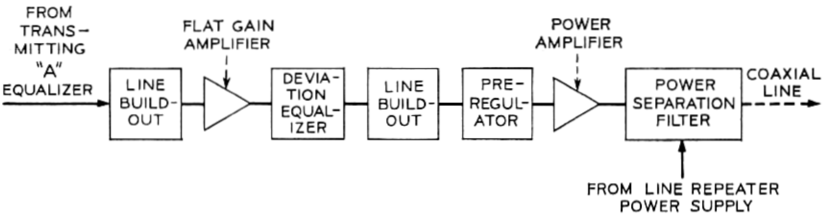

Fig. 28 — Block diagram of the transmitting line repeater. This is roughly equivalent to the preregulating portion of the regulating repeater.

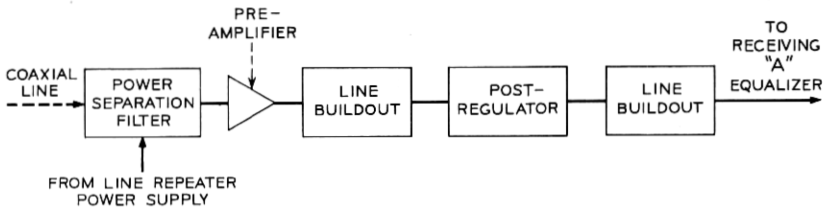

Fig. 29 — Block diagram of the receiving line repeater. This is roughly equivalent to the postregulating portion of the regulating repeater.

equalizers in a station which includes a control center, connections are made directly to the control center and no command receiver is involved.

4.1 B *Equalizer Design*

The design of the B equalizer and its associated control circuits in most ways closely parallels that of the A equalizer. This section concentrates on the areas of significant difference: (*i*) the equalizer network design and (*ii*) the manner in which the test signals used for B equalizer adjustment are applied. Figure 30 is a block diagram of the B equalizer.

4.1.1 *Design of the Equalizer Networks*

The B equalizer requirements differ somewhat from those of the A equalizer:

(*i*) The minimum desired loss range is ±3 dB.

(*ii*) Instead of six broad shapes, the B equalizer consists of ten narrow shapes.

(*iii*) To keep amplifiers at a minimum, it is desirable to replace the two-section-per-amplifier scheme used in the A equalizer with an arrangement allowing more sections per amplifier.

The first requirement eases the design of the B equalizer; the second and third requirements introduce new problems.

The four shapes near the center of the L-4 band are provided by Bode networks in the feedback paths of the amplifiers in the manner of the A equalizer. Each of the four networks includes a capacitor in series with the thermistor leads and another capacitor shunting the input to the network.

To conserve on amplifiers, the single bump series Bode network placed between the amplifiers of the A equalizer is replaced with a

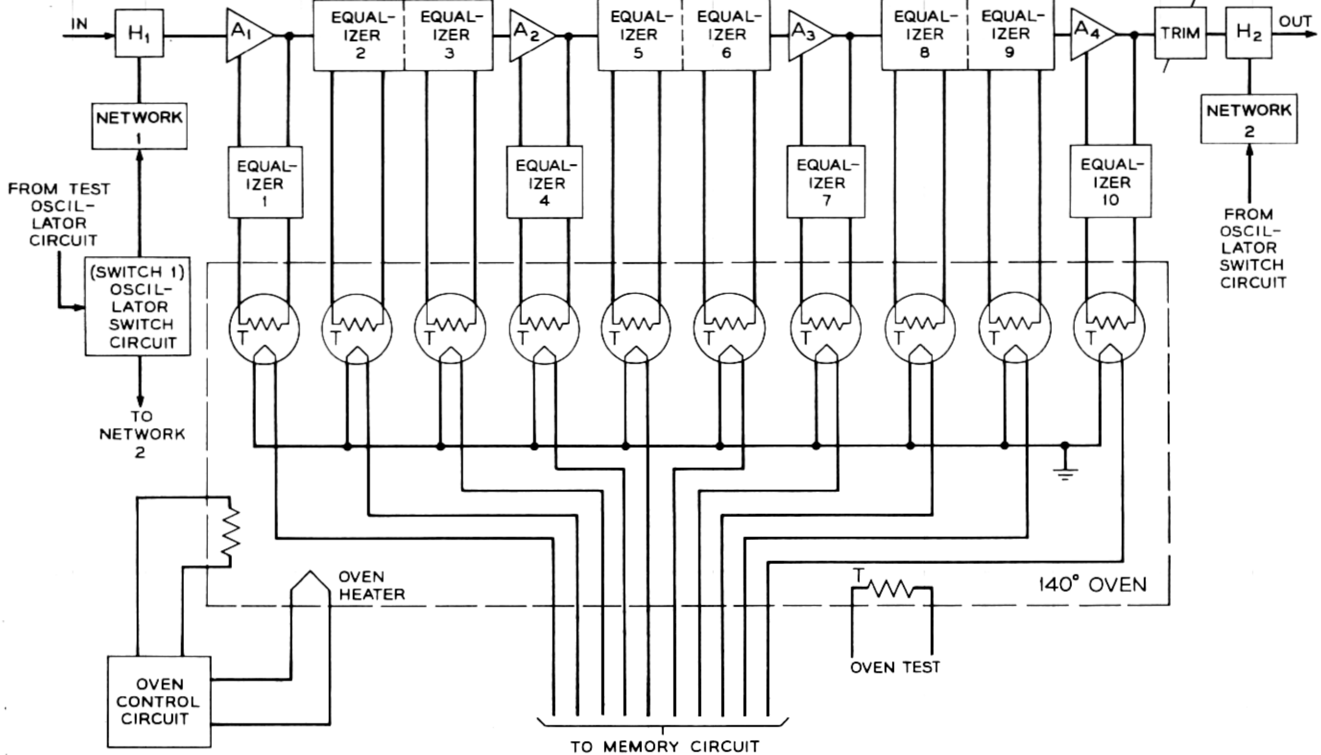

Fig. 30 — Block schematic of the B equalizer. For clarity only one oven and control circuit is shown. The B equalizer circuits are actually distributed among four plug-in modules and the rack-mounted shelf. Each module has its own oven and control circuit for the thermistors required by the equalizing networks in the module.

double-bump series configuration of the type described by Lundry.[8] As is illustrated in Fig. 31, the network consists of a frequency separation network and two Bode networks. One Bode network provides a shape near the low edge of the L-4 frequency spectrum, while the other network supplies a high frequency shape.

Resistor R_1 corresponds to the same resistor in Fig. 13(a). The frequency selective network is designed so that one branch is a low impedance and the other a high impedance at and above the effective frequency band of one Bode network as shown in Fig. 31(c). Between the effective ranges of the Bode networks, the impedances of the frequency selective networks are rapidly varying. These networks are inverse about R_2, which is also the nominal impedance at the input

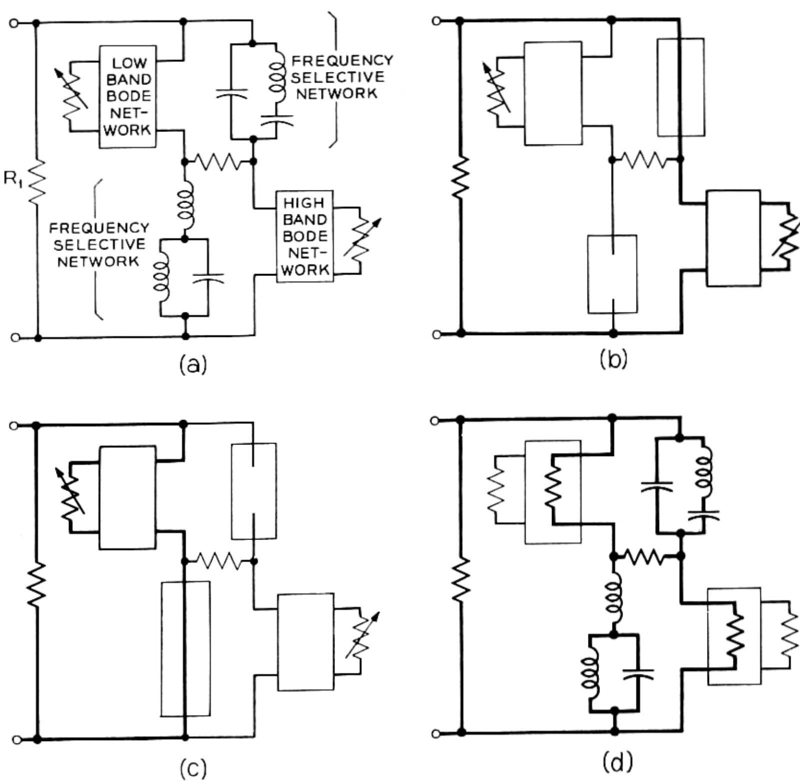

Fig. 31 — (a) Double-bump Bode network; (b) high frequency equivalent; (c) low frequency equivalent; (d) midband equivalent.

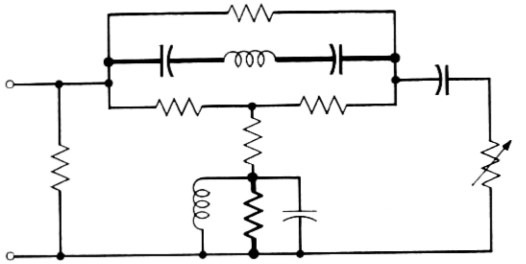

Fig. 32 — High frequency B equalizer Bode network.

of the Bode networks. Thus, in mid-range, the network is a properly terminated, constant-R, bridged-T section as shown in Fig. 31(d).

The high frequency networks, however, are modified in three ways as shown in Fig. 32. The first modification is to add a capacitor in series with the thermistor lead to remove the tilt and crossing variation in the characteristic. The second modification is to replace the capacitor in the bridge arm with two capacitors because the desired capacitance is small (4.65 to 12.45 pF). The third change consists of adding a resistor in parallel with the tank circuit in the shunt arm. The resistance serves a Q-balancing function. Above the center frequency of the bump shape, the tank circuit capacitor and the bridge network inductor predominate, but the capacitor has a considerably higher Q. Without the Q-balancing resistor, the Bode network nominally-flat shape is distorted as shown in Fig. 33. This distortion is

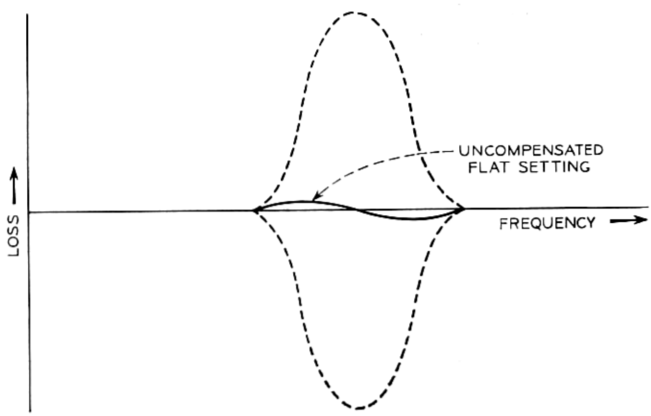

Fig. 33 — Effect of Q imbalance.

present in all of the A and B equalizer shapes, but is negligibly small except for the high-frequency B shapes where the uncompensated peak-to-peak distortion is about 0.3 dB.

4.1.2 *Trim Equalizer Design*

Just as a trim equalizer is needed to remove residual fixed deviations in the A equalizer, a similar equalizer is provided to flatten the response of the B equalizer. Both trim equalizers include one loss valley and two loss peak shaping sections and one level adjustment section. The configuration for the B trim equalizer is shown in Fig. 34. One resistor has been saved in each bridged-T section by performing a wye-T transformation on the bridge resistor and the T resistors and then combining the remaining two resistors in the shunt arm.

Because the trim equalizer is located at the output of the B equalizer, its return loss is important. Hence the simple potentiometer level adjustment of the A trim equalizer is replaced by a T-pad including a potentiometer.

4.1.3 B *Equalizer Test Signal Oscillators*

Unlike the A equalizers, all of the B equalizers in a particular main repeater setup—for a coax 20 this means up to ten receiving and ten transmitting B equalizers—share a single set of test signal oscillators which, on command from a control center, is connected to the B equalizer of the line being equalized. Since the transmitting and receiving equalizers are controlled by different control centers, and since each of these control centers should be able to equalize independently of the other, the test signals can be connected simultaneously to one transmitting and one receiving B equalizer.

The B test oscillator and oscillator-connecting circuits are shown schematically in Fig. 35. The control center command is directed to

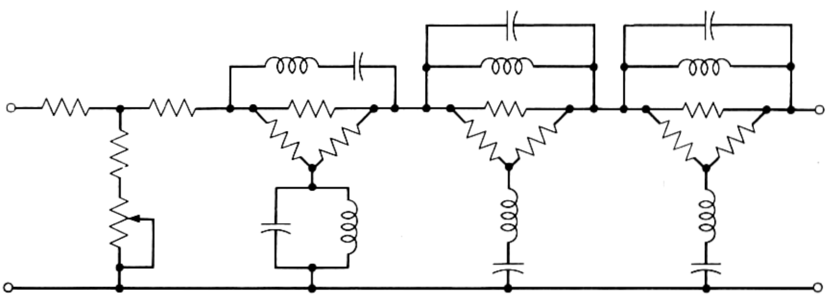

Fig. 34 — B trim equalizer.

the logic circuit of the B equalizer to be adjusted where the command is decoded. In the case of an oscillator turn-on command, the logic circuit establishes the dc voltage required to operate the oscillator switching circuit so long as that command continues to be received from the control center. The switch circuit (switch 1 of Fig. 30) establishes a path to either the input or the output of the B equalizer, depending on the command received, and operates relay K_1 or K_2 (Fig. 35) in the B oscillator and connecting circuit, depending on whether a transmitting or receiving B equalizer, respectively, is involved. (Not evident in Fig. 35 is the fact that operation of either K_1 or K_2 also applies dc power to the set of oscillators, the oscillators being normally in the OFF condition.)

Like the A test signals, the B test signals are applied to the system at -20 dBm0. This is accomplished by the careful control of the oscillator amplitudes and of the insertion loss of the input and output connecting networks (networks 1 and 2 of Fig. 30) located at the B equalizer.

4.2 *Band-Edge Regulator*

The role of the band-edge regulator in the L-4 system is the dynamic equalization of the lower edge of the spectrum during the interval between A and B equalizer adjustments. The temperature dependence of the system response in this part of the transmission band is appproximately three times greater than in any other part of the band. In the absence of the regulator, the equalizer adjustment interval would be wholly determined by these low end effects and would necessarily be shorter.

The design of the regulator loop follows very closely the design described in detail in Ref. 2 for the cable temperature regulator of the line regulating repeater. A block diagram of the regulator circuit is shown in Fig. 36.

4.3 *Monitoring Tone Blocking Circuit*

The monitoring tone blocking circuit is connected between the band-edge regulator and the automatic line switch in the receiving main station repeater bay only (Fig. 3).

This circuit provides for (*i*) flat gain required to establish proper system levels, (*ii*) the fixed equalization of the coaxial cable running from the receiving bay to the automatic line switch (located in the control connecting bay) and back, and (*iii*) blocking the monitoring tones used in fault location when this function is required.

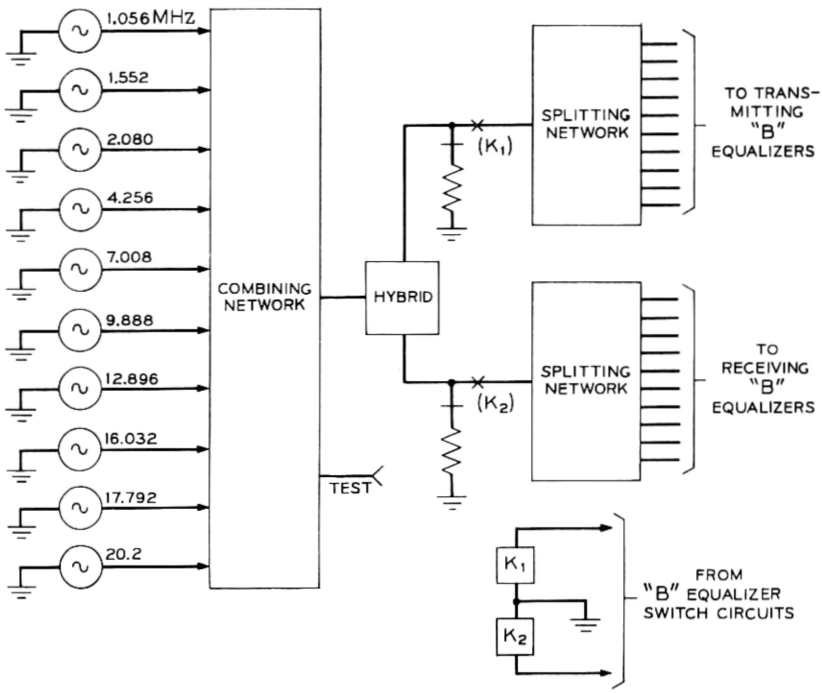

Fig. 35 — B test oscillator and oscillator connecting circuit.

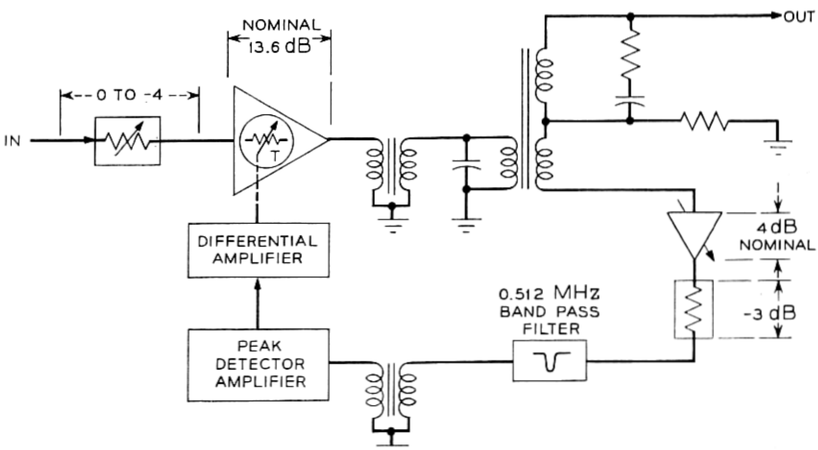

Fig. 36 — Block diagram of the band-edge regulator.

Figure 37 is a block diagram of the monitoring tone blocking circuit. The blocking filter option is exercised at those main stations having a control center, while the pad is used at power-feed stations. In the power-feed stations this permits fault-locating signals originating in the far section of a two-section control link to pass through the power-feed station and then to be observed at the control center at the receiving end of the near section.

The cable equalizer is selected from among a family of such equalizers which are available to compensate for the slope of the interconnecting cable losses. The selection depends on the length of cable to be equalized and is made to the nearest 25-foot multiple.

The nominal 15 dB flat gain amplifier is of the type used throughout the line connecting circuit and mastergroup multiplex. The gain of the amplifier is adjusted so that 12.5 dB of flat gain is provided between the output of the B equalizer and the block signal output jack of the line connecting circuit.[13] The gain of this circuit supplements the nominal gain of the band-edge regulator in achieving this goal.

4.4 *Physical Design*

Main station repeaters are the terminal elements of the L-4 repeatered line and are located in central offices. For hardened L-4 routes, these offices are underground buildings fully hardened to survive the designated overpressure.

Main station repeaters are designed for relay rack-type mounting on standard 23-inch, unequal flange, duct-type bays (11 feet, 6 inches high for most applications; 10 feet, 6 inches, and 9 feet high for offices with limited ceiling height). Two transmitting main station repeaters

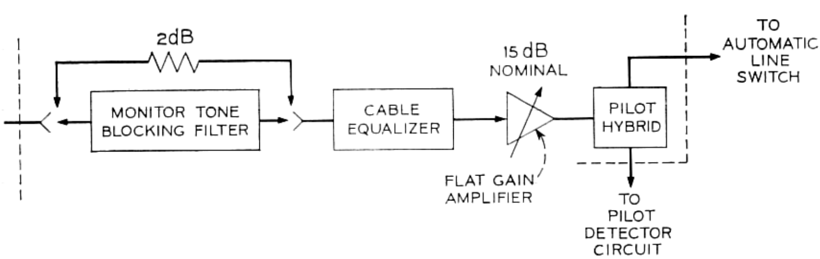

Fig. 37 — Block diagram of the monitoring tone blocking circuit. One of the pilot hybrid outputs is connected to the receiving line switch while the other goes to the switch initiating circuits.

are located in one transmitting bay while a single receiving main station repeater occupies a receiving bay.

Because the circuitry used in the line repeaters is required again in the main station repeaters, the concept of repetition in packaging arrangements was carried on to the physical design of the L-4 main station repeaters. Thus there are two distinct types of physical designs featured within the line bays—manhole-type packages, adapted for use on relay racks, and panel-type packages, designed specifically for relay rack mounting.

The line bays were styled to appear flush from the front. Panels and shelves are assembled on the rear small flanges of the 5-inch deep bay uprights and reach forward to match the closed duct formed in a bay lineup by the larger front flanges of the bay uprights. The equipment extends 10 inches to the rear of the bay framework for an overall depth of 15 inches excluding guard rails (see Fig. 38). Aisle space must be provided for access at the rear of the bays, making L-4 line bays unsuitable for back-to-back mounting. Equipment bay lineups are generated in multiples of four coaxials starting with the first receiving bay (for the first receiving coaxial) then a transmitting bay (for the first and second transmitting coaxial) and another receiving bay (for the second receiving coaxial). Equipment common to all of the coaxial lines in the cable is mounted in the control connecting bay, appearing typically in the middle of an L-4 equipment lineup. Thus, one Coax 20 requires a sixteen-bay equipment lineup comprising fifteen repeater bays and one control connecting bay. Provisions are

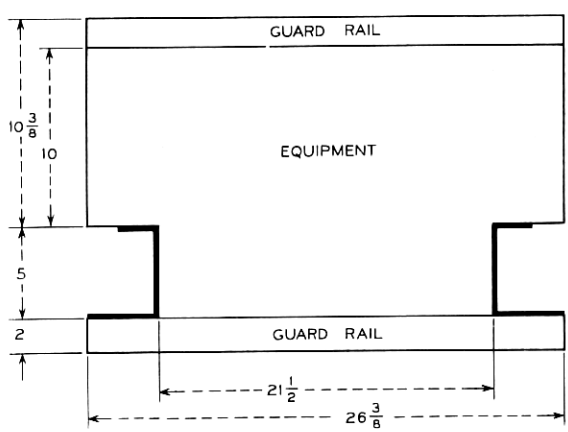

Fig. 38 — Plan view of a line bay.

made for shock isolating the bays by suspending them on shock mounts when conditions require. There was no special attempt to make the bay equipment rugged beyond a minimum 3g acceleration shock tolerance normally required for telephone equipment.

Typically the bays mount equipment in fixed panels, sliding shelves and panels with sliding drawers depending on the degree of access required for installation or maintenance. Wherever possible, the panels and shelves plug in to the local cable in the bay ducts.

The panels and shelves use light construction extensively. They are fabricated from 0.060 inch aluminum sheet and welded together using a generous number of ribs, struts, and stiffeners. The end results are bays equipped with sturdy, lightweight, compliant assemblies aesthetically pleasing because of structural simplicity.

4.4.1 *Transmitting Main Station Repeater*

Figure 39 shows the line transmitting bay equipment arrangement. The power separation filter (one per coaxial) at the top of the bay is shelf-mounted (the Fig. 40) and contains the filters and blocking capacitor needed to combine power and signal for transmission over the line without adversely affecting the line transmitting repeater. Access to the line is by solid dielectric coaxial connection to the cable terminal located in front of the bay lineup. RG 213/U cable, in rigid conduit or rigid raceway, is used for the power run from the high voltage dc-dc converter in the power room. Flexible conduit covers the power cable on the short run from the rigid raceway to the power separation filter where the power cable is hard wired by the installer. Solid dielectric insulation, metal shield plus outer insulation for the power cable, and the run in conduit are safety features to protect personnel and equipment. The power separation filter is so designed that inadvertent access to dangerous voltages is virtually impossible.

The power separation filter at the top of the bay is the only place where high voltage appears in the bay. For personnel safety, the equipment in the bay is not powered from the high voltage line but uses dc-dc converters powered from −24V battery to supply a quiet, regulated −25V source for distribution over the bay. Four converters are plugged into the rear of the fuse panel (see Fig. 41). Fuses are arranged in fuse blocks with four separate buses to provide A- and B-battery power to the equipment for the two coaxial cables in the bay. Equipment for the odd transmitting coaxial cable is powered from the two A buses and the equipment for the even transmitting coaxial cable is powered from the two B buses. Decentralized filter capacitors

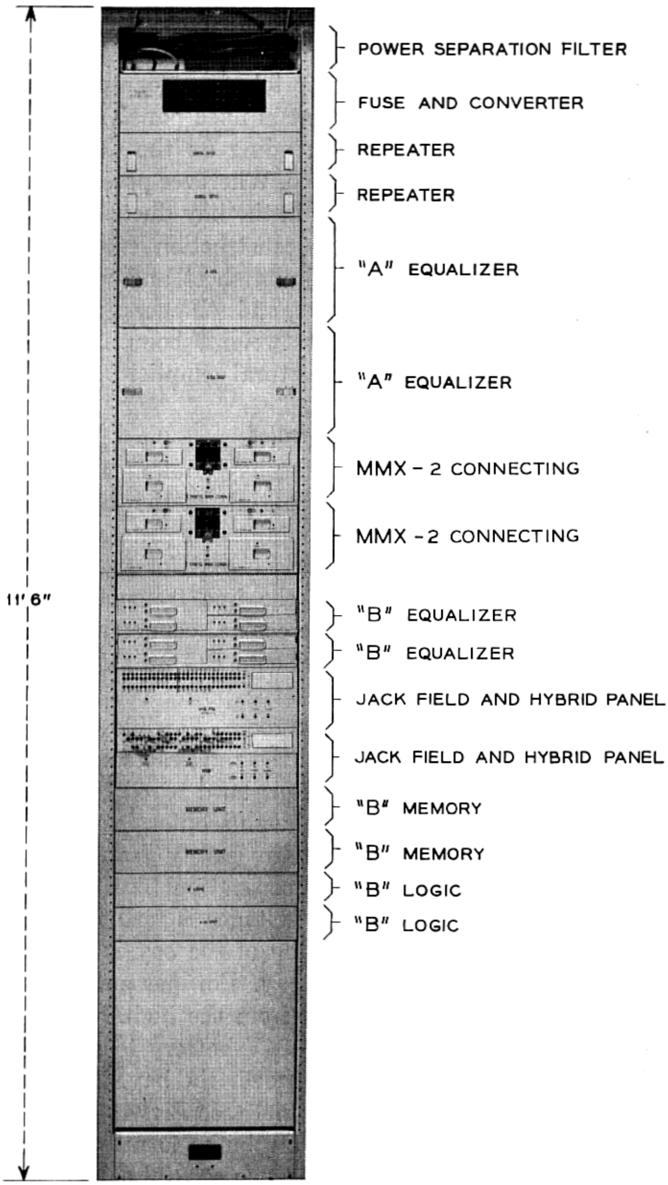

Fig. 39 — Transmitting bay equipment arrangement.

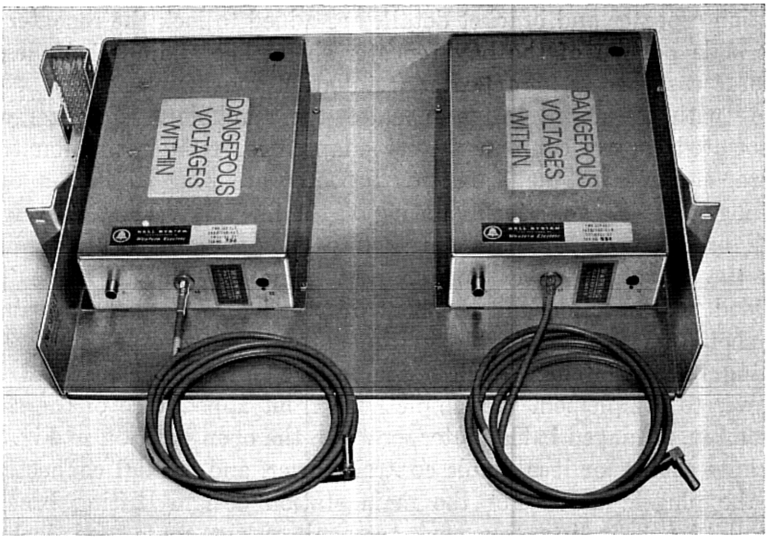

Fig. 40 — Transmitting bay—power separation filter shelf.

and the fuse alarm relay printed circuit board are also mounted in the fuse panel. The decentralized filter coil is mounted on top of the bay framework on standard mounting plate details. The dc distribution from −24V battery is made from the main power board in the office directly to the line bays.

The line transmitting repeater shelves (one per coaxial) are below the fuse panel to minimize the lead lengths to the power separation filter. The manhole regulating repeater casting is used for the main

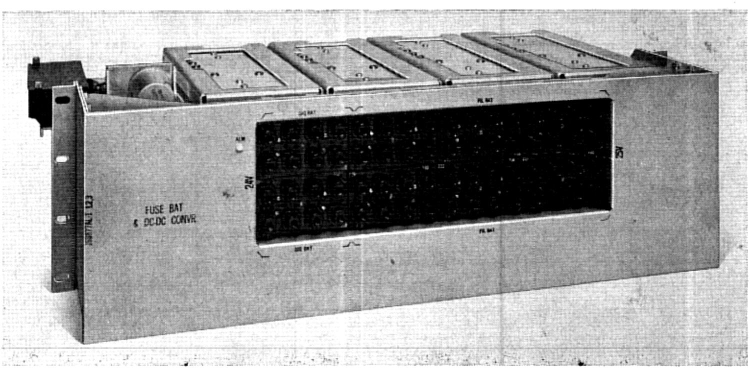

Fig. 41 — Fuse panel and converter assembly.

station repeater and bracket details are added to lock the repeater on the slide portion of the bay repeater shelf. The sliding shelf design affords easy access for repeater installation and maintenance.

As with the main station repeater, the manhole A equalizer and associated control equipment were adapted for relay rack mounting. Here, elements of the equalizing repeater are plugged into a deep sliding shelf (Fig. 42) for mounting on the line bays. The lightweight, well braced, welded aluminum shelf carries the ball bearing slides for the movable drawer portion that holds the plug-in units. The welded "hat" section and the bent over end flange which contribute to shelf stiffness are visible in the bottom center of Fig. 42. The spring release latching devices are recessed in the faceplate of the drawer to complement the simple flush front appearance of the shelf assembly. A hinged baffle plate, shown in the open position in Fig. 42, permits access for local cable control, power, and coaxial connections to the plug-in units. For the main station designs, lifting bracket details for easy insertion and removal of the units and locking bracket details for anchoring the units on the sliding shelf are added to the manhole design castings. These units are not coated internally with the high voltage epoxy insulation.

The B equalizer (Fig. 43) is a relay rack mounted aluminum panel-

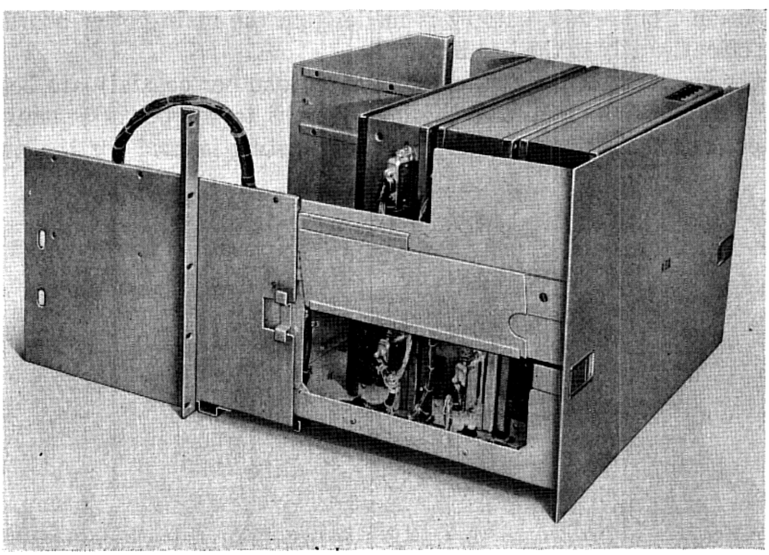

Fig. 42 — A equalizer shelf assembly.

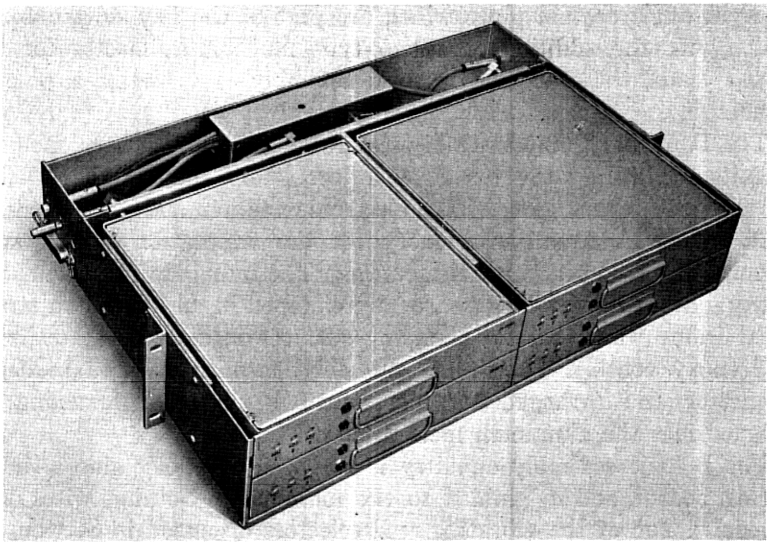

Fig. 43 — B equalizer assembly.

type design. The circuitry is similar to that of the A equalizer and for convenience in performing test and maintenance, the amplifiers, thermistor ovens, oven control networks, and equalizer networks have been divided in an array of four removable, slide-type, plug-in drawers. Small Bell System coaxial plugs, equipped with teflon guide bushings, are rigidly fixed to the drawer and mate with smaller right angle coaxial jacks mounted on floating funnel-type phenolic guide blocks at the base of the B equalizer mounting shelf. Power and control connections are made via a multipin connector assembly which has the necessary float for mating and provides the drawer retaining feature by way of a split spring guide pin arrangement. The amplifiers have their bottom cover welded to the base of the removable drawer.

Equalizer networks, located outside of the amplifier housings, and oven control networks are contained on epoxy glass printed wiring boards mounted on standoffs in the bottoms of the drawers. The top drawers have shields and dust covers which fasten to small floating angle brackets located on the sides of the drawers. Gain adjustments and test points are accessible at the faceplates of the drawers.

The base of the B equalizer mounting shelf houses the shielded combining-hybrid network assembly. Its coaxial leads are terminated in small coaxial jacks mounted at the sides of the shelf for access to right angle coaxial plugs which are part of the bay duct cabling. Thus, with the addition of a lock-type multipin connector for the power leads, the B equalizer shelf assembly is virtually a plug-in panel.

The B memory unit assembly (Fig. 44) contains the ten memory circuits controlling the ten B equalizer bump shapes. This design represents a repackaging of the electronic counter and gate circuitry used in the A equalizer memory for the adaptation of ten such circuits to main station panel mounting. The individual, double sided, epoxy glass printed wiring boards are clamped in an aluminum structural frame which has its clamping surfaces insulated by anodizing and epoxy coating. The frame assembly, terminated in a multipin connector and arranged for mechanical keying and fastening, is plugged into the aluminum memory panel housing.

The B logic assembly circuitry is mounted on epoxy glass printed wiring boards and assembled to the main panel housing with rigid standoffs. Ten of the vibrating reed selectors discussed in Section 3.3 are mounted on a printed wiring board and held by clamps similar to those designed for the A equalizer logic.

4.4.2 *Elements of Line Connecting—Transmitting Bay*

Elements of the L-4 line connecting circuits mounted in the transmitting main station repeater bay consist of the transmitting MMX-2 connecting assembly and the transmitting jack field panel assembly.

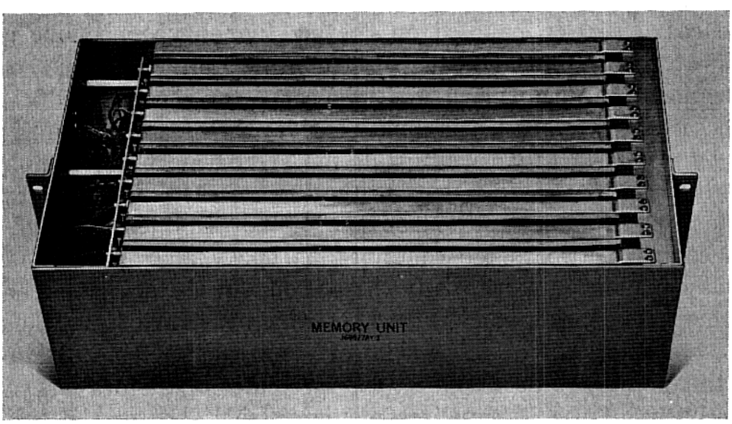

Fig. 44 — B memory assembly.

The former accomplishes the master-group adding function while the latter provides for pilot insertion and the connections from the control center, branching equipment, and receiving equipment.

The transmitting MMX-2 connecting assemblies, one for each coaxial cable, are located below the A equalizer shelves in the transmitting bay (Fig. 39). The MMX-2 connecting unit contains active circuits and is not protected by the line protection switching system. Therefore, this unit has two parallel transmission paths, each of which is monitored by a 512 kHz detector which controls a coaxial switch. The coaxial switch, accessible from the front, is located in the top center of the panel. The switch mounting, a die cast aluminum housing, forms an integral part of the panel assembly and, by virtue of epoxy adhesive bonding, contributes to the structural strength and rigidity of the panel by acting as the main strut in the center span of the assembly.

The active circuits of the two parallel paths are housed in plug-in drawer assemblies inserted from the front on each side of the coaxial switch. There are two sets of drawers consisting of the pilot detector and the pre-emphasis module per set. The drawer fronts have a recessed handle and access to the potentiometer adjustment. The elements within the pilot detector drawer are assembled much in the same way as are the elements within the modules of the MMX-2 Bay.[13] This results in minimum lead lengths between can elements without adverse effect of manufacturing tolerance buildups among the three elements being assembled. Small path selector switches and miniature indicating lamps are mounted in the front face of the main panel.

The center of operational activity on the transmitting bay is the transmitting jack field panel assembly (one per coaxial cable) located at shoulder level in the bay, convenient for people to reach. The hybrid panel and jack field combination contains the line amplifier, the hybrid networks, the line pilot adjust mounting assembly, the combining network printed wiring board assembly, cable equalizer, coaxial connectors, and test access points required for the L-4 line connecting functions.

The shelf provides front face access to the gain adjustment for the line amplifier and level adjustment for the L-4 line pilots. The hybrid networks, on epoxy glass printed wiring boards, are contained in can assemblies for shielding. Connections to the shelf are via small coaxial jacks on both sides of the shelf for signal leads and via a lock-type multipin connector for power leads.

4.4.3 *Receiving Main Station Repeater*

Figure 45 shows the line receiving bay equipment arrangement. The bay contains the repeater and line connecting equipment for one receiving coaxial cable. The type of construction is similar to the transmitting main station repeater bay.

The power separation filter at the top of the bay shares space on its mounting shelf with fault location equipment for main station repeaters as shown in Fig. 46. The oscillator, in the center of the shelf, appears in every other receiving bay and supplies monitoring tones to the main station repeaters of four coaxial cables. The dc-dc converter on the right powers the monitoring oscillator loop adjacent to the main station. Oscillator assembly and converter are the same plug-in units used in the manholes and are adapted for shelf mounting.

The fuse panel is similar to that in the transmitting bay but uses three A buses and one B bus to power the bay equipment. Two A buses power the repeater equipment associated with the one receiving coaxial cable appearing in the bay while the remaining A and B buses feed redundant power for the line connecting equipment which is not protected by the line protection switching system.

As in the transmitting bay, the receiving main station repeater uses the manhole regulating repeater casting with keyed line build-out positions and mounts in the sliding drawer below the fuse panel.

The A and B equalizer equipment is identical to that included in the transmitting bay (Figs. 42, 43, and 44).

Figure 47 shows the band-edge regulator assembly. This type of construction is also used for the monitoring tone blocking shelf and other shelves of the line connecting assembly.

4.4.4 *Elements of Line Connecting—Receiving Bay*

The balance of the panels on the receiving bay comprise the L-4 line connecting, performing mastergroup blocking, branching, and dropping as well as tone blocking, and pilot pickoff, and providing control center receiving connections and access points for in-service testing and maintenance.

The receiving MMX-2 connecting assembly, located below the A equalizer (Fig. 45), is the counterpart of the transmitting MMX-2 connecting assembly discussed earlier and substitutes the de-emphasis module plug-in drawers (featuring the same redundancy and construction) for the pre-emphasis module.

As in the transmitting bay, the center of operational activity on

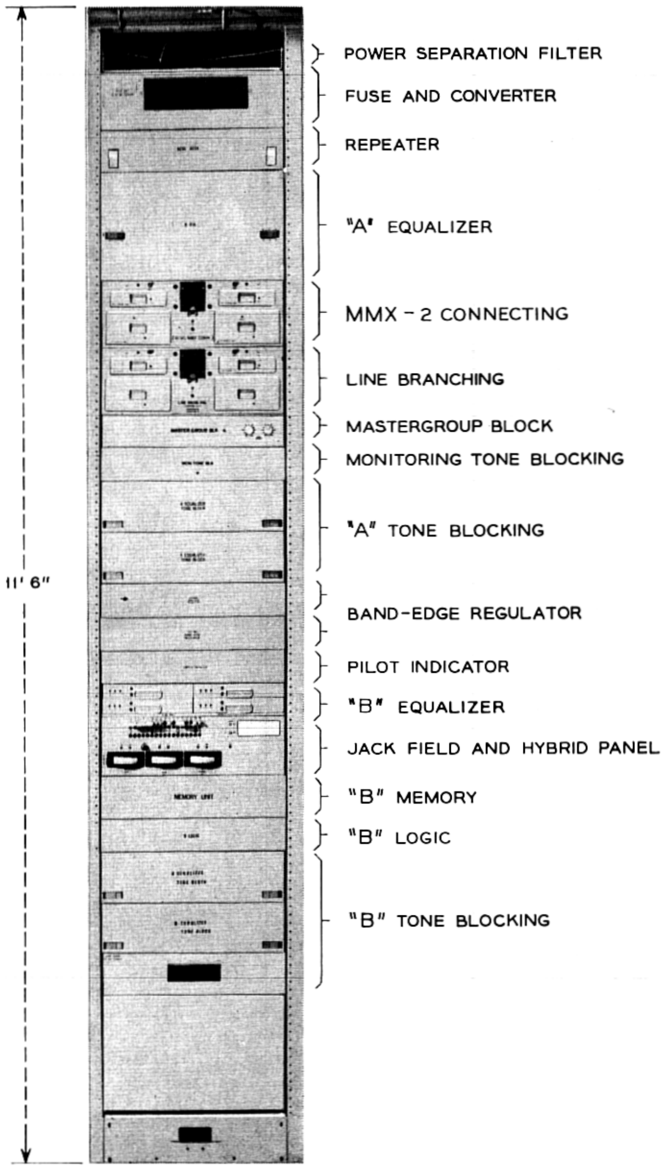

Fig. 45 — Receiving bay equipment arrangement.

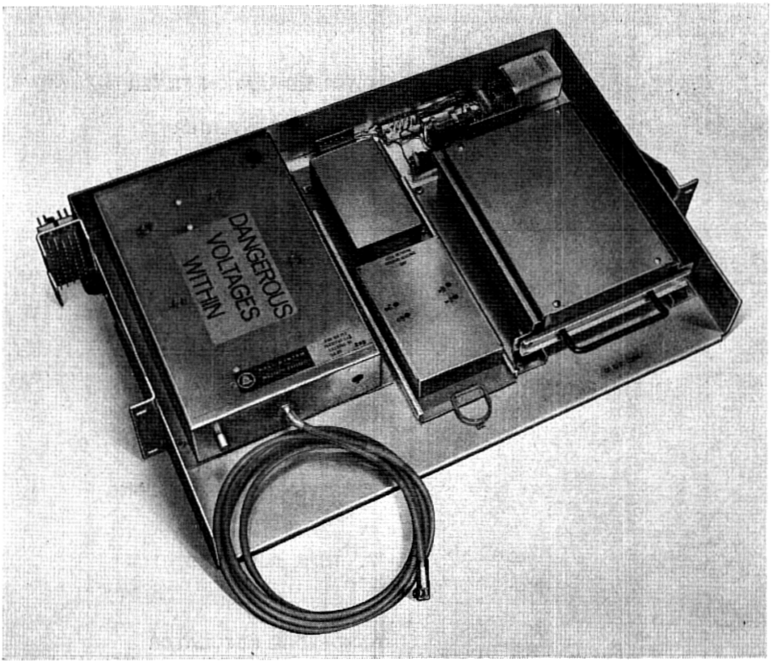

Fig. 46 — Receiving bay—power separation and converter shelf.

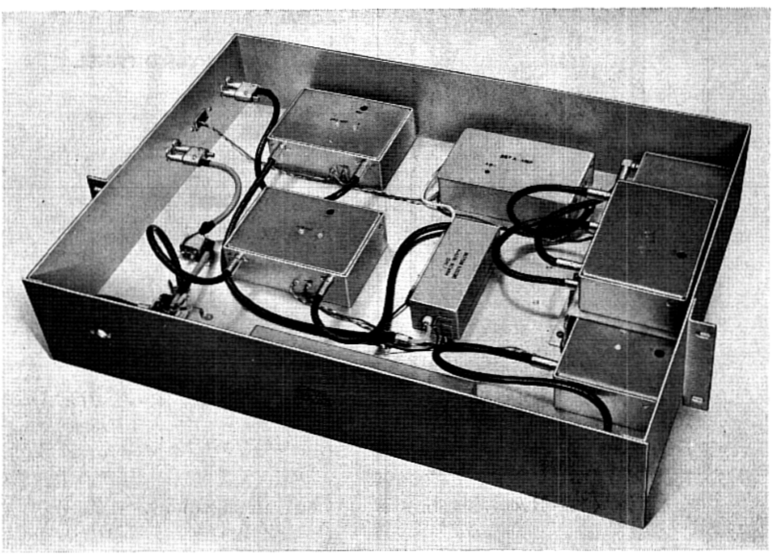

Fig. 47 — Band-edge regulator.

the receiving bay is the receiving jack field and the hybrid and meter panel located at shoulder level in the bay for access. The hybrid panel, in addition to containing the receiving counterparts of the transmitting hybrid panel, includes elements of the line protection switching system switch initiator circuitry. The indicating meters for the continuous L-4 line pilots are mounted in the front of the panel. The line amplifier faces the rear of the panel and gain adjustments are made from the back of the bay.

The intermix of line connecting elements with main station line repeater elements on the bay yields an orderly composite of shelves individually designed to the same ground rules and results in a simple, flush-front, uniform bay appearance which typifies L-4 equipment. Blank shelves and blank panels are available to fill spaces in the bay when circuit or function options eliminate the need for certain equipment. It is intended that packaged bays be shipped from the factory, fully equipped, wired, and tested for ease and efficiency in field installation.

4.4.5 *Control Connecting Bay*

Certain functional elements of the L-4 system are common to all twenty lines in a cable. In the past there has been a tendency to let this type of equipment be handled as miscellaneous in an office. The decision was made early to consolidate this common equipment into an orderly array on a dedicated bay. The L-4 control connecting bay thus fills the roll of the miscellaneous bay, yet offers the many advantages of a shop-assembled, shop-wired, and shop-tested bay. The L-4 bay design philosophy applying to the line bays was followed closely as is illustrated in Fig. 48.

The B test oscillator unit and the test oscillator connector unit are located directly below the fuse panel. The test oscillator unit contains ten plug-in crystal oscillators which are mounted on epoxy-glass printed wiring boards, are enclosed in shielded can assemblies, and are accessible from the rear of the panel. The hybrid combining network is contained on an epoxy-glass printed wiring board mounted on stand-offs in the front part of the shelf cavity. The oscillator connecting unit uses two such hybrid networks similarly mounted in the front of its shelf. These fan out the single test oscillator unit output to two sets of ten coaxial jacks for plug and coaxial cord connection to the B equalizers in the line bays.

The coaxial switches used in the line protection switching system

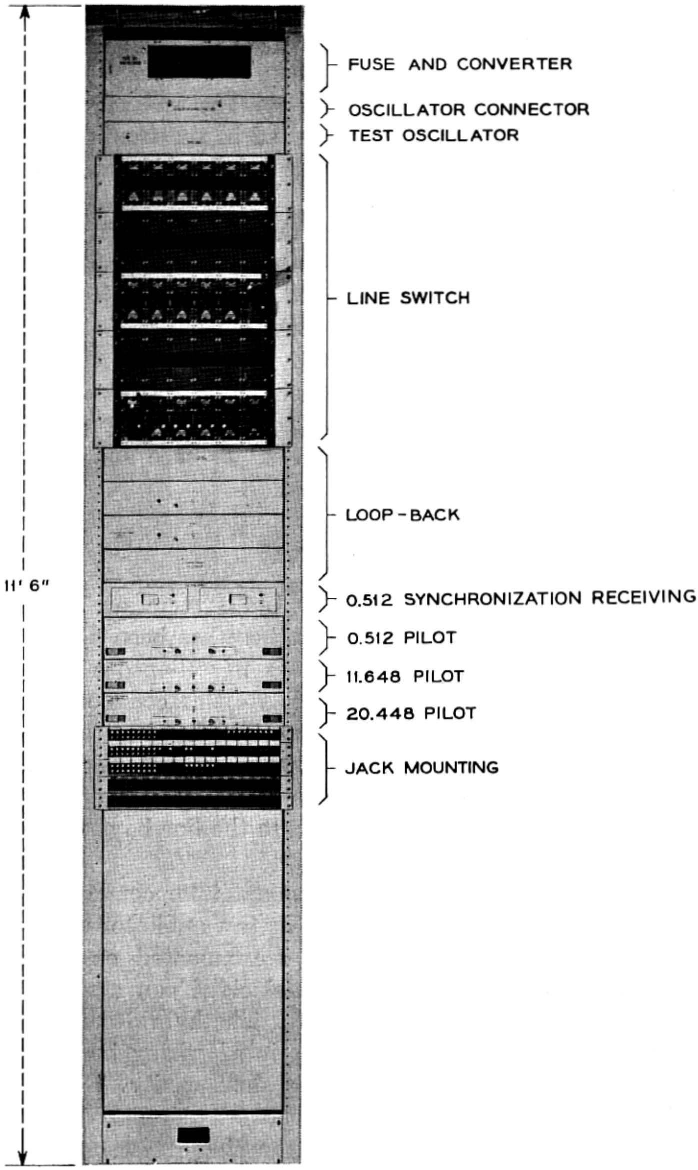

Fig. 48 — Control connecting bay equipment arrangement.

are mounted below the test oscillator and connecting units. The switches plug into die cast aluminum switch mountings which are assembled on panels intended for use in the 19-inch-wide bays used for the L-3 carrier system. In L-3, these switch panels were mounted as miscellaneous.

In L-4, which is initially using a modification of the L-3 line protection switching system, these switch panels are adapted for use on the 23-inch-wide control connecting bay. The jack field associated with the switch array is located at the bottom of the equipped portion of the bay. Again, the jack strips are those used on the L-3 bays and were adapted for use in L-4. Mounted on the jack strips are the indicating lamps, which portray the status of the switches, and the test jacks and switch keys used to check and control the switch modes.

The four panels located below the switch field provide the command looping function of the remote control system and the receiving line connections to the local remote control center. The loop-back portion consists of three shelves which, because of the need for hard wiring among the shelves, are joined on mounting bars to closely associate the individual shelves during the assembly, test, and other operations in the shop. For good control of the wiring within and among the three shelves, local cable designs are used featuring prescribed slack to permit backing off of any one shelf from the rear of the bay for maintenance.

The 512 kHz synchronization receiving assembly is located below the loop-back equipment. It is a four-inch high panel arranged to mount two plug-in modules. The left drawer contains the working circuit; the right drawer is a dead spare conveniently stored in the event that replacement of the working unit becomes necessary. Instantaneous replacement is not a design criterion since the primary frequency generator can run unsynchronized over relatively short intervals, affording adequate time to replace the working module in the event of a trouble. The design principle applying to the drawer modules is similar to that used on the modules of the MMX-2 connecting panels. The input connection from the receiving bay is through a small coaxial jack that mates with a plug connection on the fixed shelf. The connections to the primary frequency generator and battery are via a multipin connector engagement to protect the pins on the module while stored and to hold it in place on the shelf.

Space between the switch jack field and the 512 kHz synchronization receiving assembly is occupied by the L-4 pilot originating equipment. The top unit in this array is the 512 kHz pilot stabilization and distribution assembly. (Fig. 49). This unit receives the 512 kHz pilot from two taps on the distribution bus associated with the primary frequency generator in an office and limits and filters the signals in two independent paths. The outputs of these two paths are fed through differential detector and automatic switching equipment so that failure of the working path will bring about an automatic switch to the standby path.

A distribution network provides ten outputs to feed the ten transmitting coaxials of a route and ten outputs to feed the transmitting MMX-2 connector equipment. The apparatus associated with the dual signal paths is mounted in the sliding drawer. A local cable harness was designed to connect the apparatus to the distribution buses located at the rear of the shelf. Slack in the harness together with appropriate clamping allows the laced cable to twist freely without causing cable flexing and fatigue when moving the sliding drawer. Connections to the distribution bus are hard wired for running into the cable ducts of the bay uprights. Indicating lamps and a test jack position are recessed in the drawer faceplate which also contains miniature rotary switches for manual control and selection of signal paths.

The remaining two panels (Fig. 48) constituting the pilot originating equipment are the 11.648 and 20.448 MHz pilot generator and distribution assemblies. Both units are four inches high and provide dual oscillators with differential detection and automatic switching equipment so that failure of the working oscillator will bring about a switch to the standby. The distribution networks provide ten outputs to feed pilots to the ten transmitting coaxial cables of an L-4 route. The apparatus for these dual pilot sources is housed in the cavities of sliding drawer assemblies as was done with the 512 kHz pilot stabilization and distribution assembly (Fig. 49). An added feature with these pilot generators is the use of plug-in printed wiring board arrangements for the alarm circuits. Small printed wiring boards slide within guide-brackets mounted perpendicular to the main drawer cavity and contain multipin connectors which mate with connectors in the drawer. The L-4 pilot generators resemble the master-group pilot generator designed for the L-4 mastergroup multiplex bay.

Thus, the role of an L-4 miscellaneous bay is effectively filled by the packaged control connecting bay shipped as a unit from the shop. Although the bay presents a wide assortment of equipment which cuts across such various functional entities of the L-4 system as the main repeater, the line protection switching system, the control center

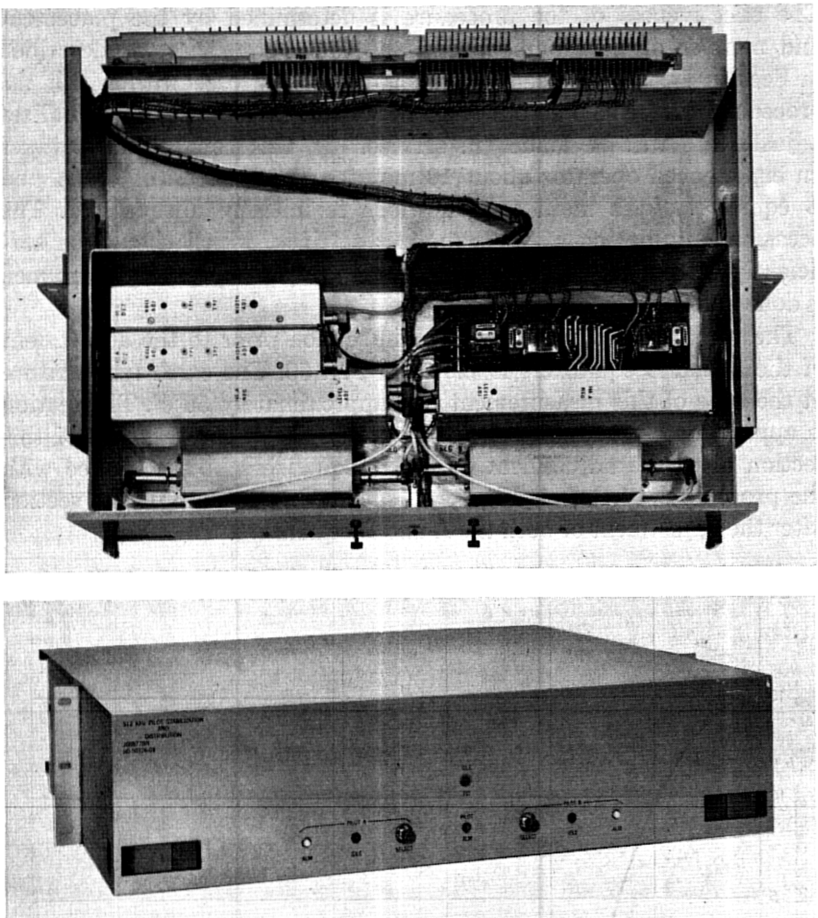

Fig. 49 — 512 kHz pilot stabilization and distribution unit. Top view (top) and front view.

operation, and the pilot generator, the over-all concepts as established for L-4 main station bay physical designs were satisfied.

V. OVER-ALL OPERATION OF THE EQUALIZERS

The procedures followed to determine the proper settings for the A and B equalizers are covered in detail in Ref. 1. It is apparent that the process amounts to adjusting the equalizers so that the response error at the 16 A and B test frequencies is as near 0 dB as possible.

The effectiveness of the procedure is determined by the placement and number of the "bumps" and the test frequencies, as described in Section II. It has been emphasized that the ease with which the procedure can be carried out is an important factor and that equalizer adjustments will be made "in service." In this connection, it takes an experienced operator about 10 minutes to adjust all of the A and B equalizers in a main section which is initially unequalized. The occasional up-dating of the equalizer settings, which should be sufficiently infrequent to place little burden on the operating personnel, is done in a fraction of this time.

The response of a typical L-4 main section prior to the adjustment of the A and B equalizers is shown in Fig. 50. The earth temperature at the time of this measurement was approximately 50°F. The section is approximately 145 miles long. Figure 51 shows the response of this section after the adjustment of the A equalizers in accordance with the procedures of Ref. 1. Figure 52 shows the response of the section after the adjustment of both the A and B equalizers.

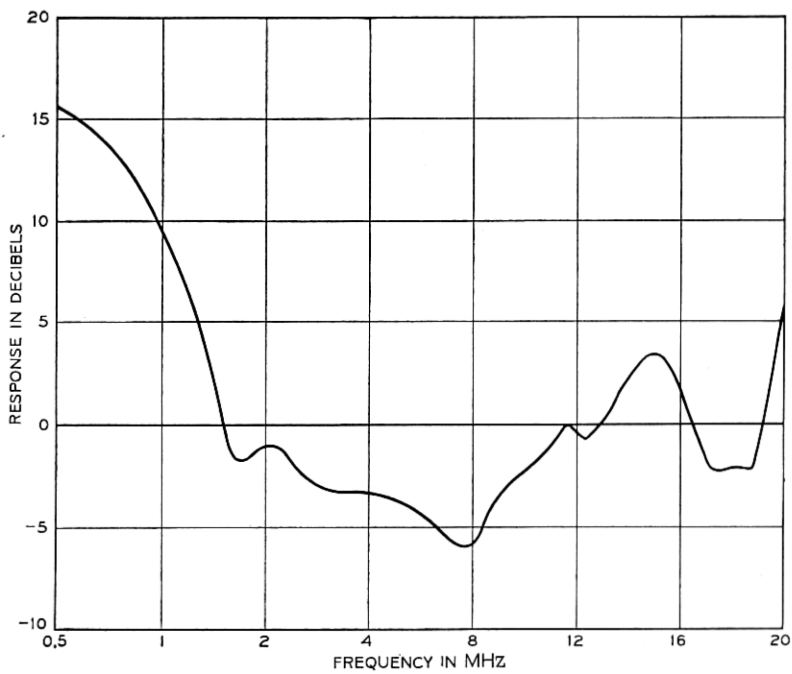

Fig. 50 — Response of L-4 main section before equalizer adjustment.

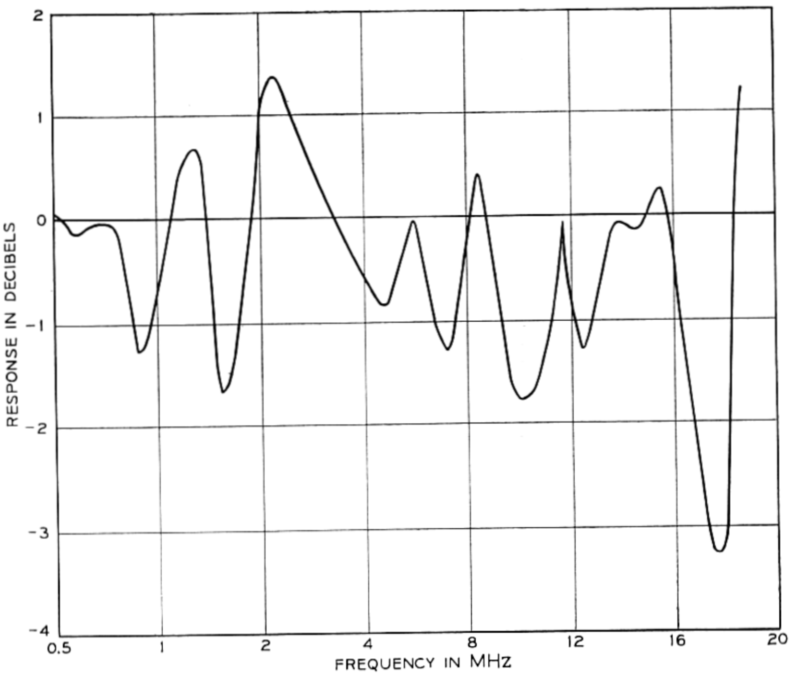

Fig. 51 — Response of L-4 main section after the adjustment of the *A* equalizers.

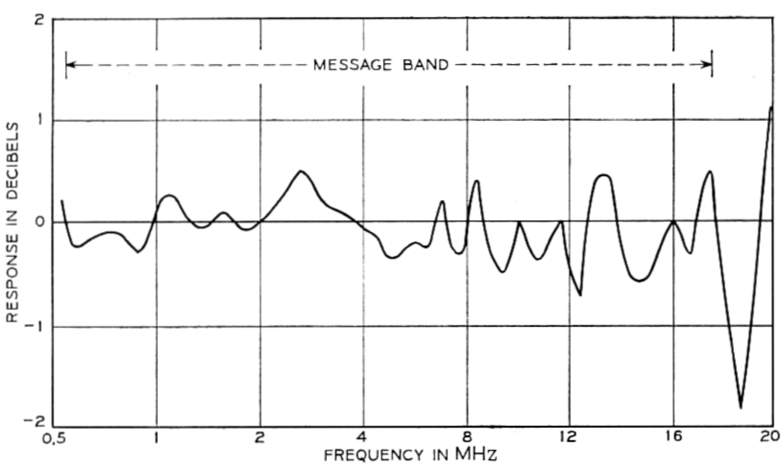

Fig. 52 — Response of L-4 main section after the adjustment of the A and B equalizers.

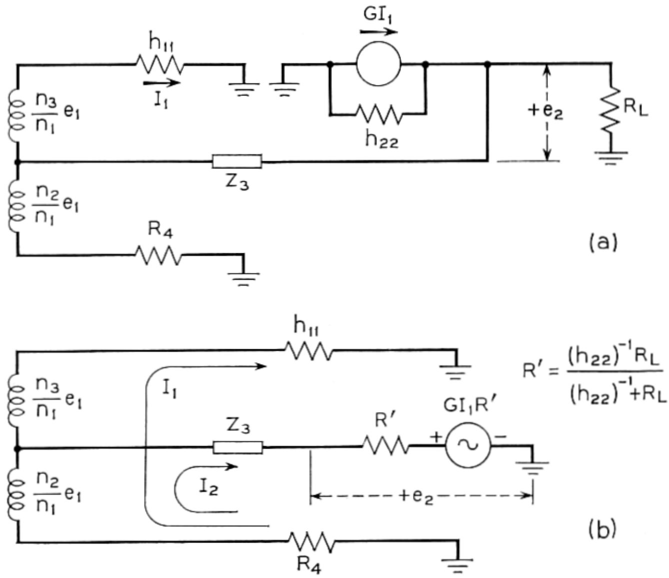

Fig. 53 — Simplified versions of Fig. 7.

APPENDIX

Approximate Gain of the Equalizer Amplifiers

Figure 7 shows the hybrid feedback amplifier configuration used throughout the A and B equalizers. Figures 53(a) and (b) are simplified versions of the circuit of Fig. 7 permitting convenient analysis.

From Fig. 53(a)

$$e_2 = (GI_1 + I_2)\, R'$$

and

$$\begin{bmatrix} \dfrac{n_3 + n_2}{n_1} e_1 \\ \\ \dfrac{n_2}{n_1} e_1 \end{bmatrix} = \begin{bmatrix} h_{11} + R_4 & R_4 \\ R_4 + GR' & Z_3 + R_4 + R' \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$I_1 = \frac{\dfrac{n_2 + n_3}{n_1} e_1 (Z_3 + R_4 + R') - \dfrac{n_2}{n_1} e_1 R_4}{(h_{11} + R_4)(Z_3 + R_4 + R') - (R_4 + GR')R_4} ;$$

$$I_2 = \frac{\frac{n_2}{n_1} e_1(h_{11} + R_4) - \frac{n_2 + n_3}{n_1} e_1(R_4 + GR')}{(h_{11} + R_4)(Z_3 + R_4 + R') - (R_4 + GR')R_4}.$$

Thus

$$\frac{e_2}{e_1} = R' \frac{G\frac{n_2+n_3}{n_1}(Z_3+R_4+R') - G\frac{n_2}{n_1}R_4 + \frac{n_2}{n_1}(h_{11}+R_4) - \frac{n_2+n_3}{n_1}(R_4+GR')}{(h_{11}+R_4)(Z_3+R_4+R') - R_4(R_4+GR')}$$

$$\left.\frac{e_2}{e_1}\right|_{G\to\infty} \to \frac{\frac{n_2 + n_3}{n_1}(Z_3 + R_4) - \frac{n_2}{n_1}R_4}{-R_4}$$

$$= \frac{n_2}{n_1} - \frac{n_2 + n_3}{n_1}\left(1 + \frac{Z_3}{R_4}\right),$$

$$\left|\frac{e_2}{e_1}\right| = \frac{n_3}{n_1}\left(1 + \frac{n_2 + n_3}{n_3}\frac{Z_3}{R_4}\right)$$

$$= \frac{n_3}{n_1}\left[1 + \frac{Z_3}{\frac{n_3}{n_2 + n_3}R_4}\right].$$

Let $n_3 / (n_2 + n_3) R_4 = R_0$; notice that R_0 is equivalent to the parallel combination of the terminations required by windings n_3 and n_2 for hybrid balance if R_4 is the nominal termination for the winding to which it is connected. Then,

$$\frac{e_2}{e_1} = \frac{n_3}{n_1}\left(1 + \frac{Z_3}{R_0}\right).$$

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