SPEECH COMPRESSION AND EXPANSION USING MATCHED THERMISTORS

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1960

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Date thesis is presented 19 April 1960

Typed by Janette Crane

ACKNOWLEDGMENT

This thesis is dedicated to the people who made it possible: Professor A. L. Albert, Major Professor; Professor Louis N. Stone, head of the Electrical Engineering Department; Mr. Chaskin of International Telephone and Telegraph Laboratories; Dr. Moore of Bell Telephone Laboratories; and my wife.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF FIGURES (CONTINUED)

SPEECH COMPRESSION AND EXPANSION USING MATCHED THERMISTORS

INTRODUCTION

Since its beginning, telephone service has seen continuous improvement. Today the public expects complete satisfaction. Many devices have been developed to keep telephone service up to the public's expectations. One of these devices compresses and expands the electrical speech signals to improve transmission by reducing interfering signals.

In transmitting speech electrically, the voltages and currents on a transmission channel vary in accordance with the actual speech waves. These electric signal variations must be transmitted to the called subscriber's telephone receiver in a relatively undistorted form, free from unwanted extraneous signals. For long-distance calls, there are many paths where unwanted electric signals may enter the speech channel. Induced noise may reduce the intelligibility of the message. Crosstalk, which often is considered a form of noise, is not only bothersome from the interference standpoint, but also may violate the requirement of secrecy of transmission.

A method of reducing the effects of noise (including crosstalk) is speech volume compression at the transmitting carrier terminal, and expansion at the receiving terminal. The compressor at the transmitting end reduces the signal intensity range by increasing the weak signals and decreasing the strong signals. This allows weak signals to override the noise in the transmission medium. Conversely, the expandor at the receiving end re-establishes the original volume range. By using the first syllable of "compressor" and the last two syllables of "expandor", the word "compandor" was coined to describe the complete unit.

Because the number of required telephone circuits is increasing rapidly, more and more speech channels must be in close proximity for long distances. This increases the possibility of crosstalk between channels. Hence, the need for compandors on these channels has increased tremendously and their application is limited only by cost considerations. It is important that the cost of compandors is reduced. This investigation explores the possibility of using matched thermistors* as the key elements of a simple, inexpensive compandor.

* Thermistors are temperature sensitive resistors, which make use of the large temperature coefficients of resistivity of semiconductors.

EARLY HISTORY OF THE COMPANDOR

The introduction of noise and crosstalk into a telephone channel depends on the quality of the transmission medium. An important consideration for good transmission is the logarithm of the signal-to-noise power ratio. This is because of the logarithmic nature of the response of the human hearing mechanism. Because a high ratio of signal-to-noise power is of importance, speech transmission can be improved either by strengthening the signal or by reducing the noise in the circuit used for transmission. The term noise, as just used, includes crosstalk.

There are two limits on the range of speech volume which a system is capable of transmitting. The upper limit is determined by the overload capacity for which equipment such as the transmitting amplifiers and the repeaters in the line are designed. The lower limit is determined by the amount of noise interference entering the message-circuit. These two limits were taken into consideration early by manufacturers for improvements in design of telephone carrier systems. Linear amplifiers with sufficient overload capacity were built. Circuit noise was reduced. Cables with lesser crosstalk coupling between pairs were manufactured. These and other advancements allowed the increased application of carrier systems to long toll telephone circuits even before the invention of compandors.

In contrast to wire-line service, in radio telephony the noise characteristics of the transmission medium are largely beyond control. Therefore, it is not surprising that the compandor found its first application on inter-continental radio links.

Before the invention of the compandor, only one method was in use to reduce the range of signal intensities on radio circuits. An operator, with the aid of a volume-level indicator, adjusted the speech volume to a constant value just below the transmitter load capacity.

There are three causes for the large variation in signal intensities arriving at the transmitter by wire line. Differences among speakers and differences in line losses are two causes that together account for a 40 db. variation. Differences in speech amplitudes for a given talker is a third cause that accounts for another 30 db variation in signal intensity. An operator can compensate only for slowly varying quantities. He can, therefore, compensate only for the differences among speakers and differences in line losses, and thus, reduce the initial variations of signal intensities from 70 db to 30 db.

To override noise, it would be desirable always to send at maximum transmitter power output capacity. This would require eliminating the remaining 30 db of volume range. However, a device which could do this would destroy some of the information that is contained in the speech (7). To supplement the manual adjustment, the first compandor was installed in 1932 on the New York-London long-wave radio telephone circuit which reduced the remaining 30 db volume range to 15 db at the transmitter and which restored the original range at the receiver. The use of the compandor on this radio circuit increased the time when the circuit was usable by a significant amount (14).

As explained earlier, compandors also would be very useful on noisy wire lines. But a telephone channel equipped with a compandor needs a compressor and an expandor at each terminal, and the original compandor filled five feet of relay rack. Consequently, the large size and high cost prohibited the use of compandors on telephone wire lines for about eight years.

The first applications of compandors to telephone cable carrier systems were made in 1941 on the Charlotte-Miami and the Charlotte-West Palm Beach routes (5). By that time, the size of the compandor terminal had been reduced to fill only 15 inches of a standard relay rack. The reduced size of the compandor made it practical for use on toll carrier systems, and by 1946 over a hundred carrier-circuit compandors were in use.

BACKGROUND STUDY TO REACH CONCLUSIONS ON THE DESIGN REQUIREMENTS OF COMPANDORS

The Choice of Compression Law

One basic requirement of a compandor system is that its overall response must be linear. In other words, within its overload capabilities, its average output power must be directly proportional to its input power. The plot on logarithmic co-ordinates of input power vs. output power of a compressor is called its compression characteristic. Lawton (12) states that within reasonable limits any shape of compression characteristic is effective, but for ease of specification and matching, a straight-line characteristic on logarithmic co-ordinates is usually followed.

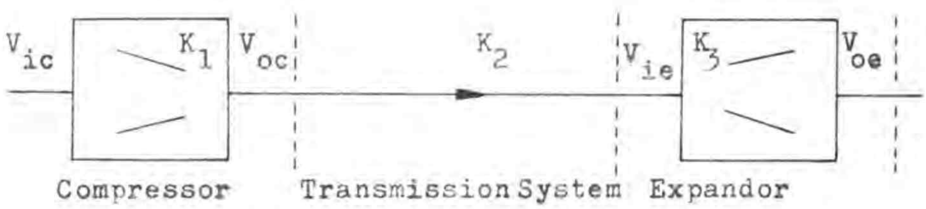


Fig. 1. A Compandor System Considered in One Direction of Transmission Only

The following symbols are used in the succeeding equations:

V_{ic}, V_{ic}' = Compressor input voltages

V_{oc}, V_{oc}' = Compressor output voltages

V_{ie}, V_{ie}' = Expandor input voltages

V_{oe}, V_{oe}' = Expandor output voltages

From Figure 1, the compression and expansion equations are

$$(1) \quad V_{oc} = K_1 V_{ic}^{1/n}$$

$$(2) \quad V_{oe} = K_3 V_{ie}^{n}$$

where K_1 and K_3 are the linear loss factors of compressor and expandor. The exponent 1/n is called the compression ratio. The reason for adopting this name is indicated by the following:

Consider a new input voltage, V_{ic}',

$$(3) \quad V_{ic}' = XV_{ic}$$

$$(4) \quad V_{oc}' = K_1 (XV_{ic})^{1/n}$$

Dividing Equation 4 by Equation 1, $\frac{V_{oc}'}{V_{oc}} = X^{1/n}$ or, in logarithmic form

$$(5) \quad 20 \log \frac{V_{oc}'}{V_{oc}} = 1/n\left[20 \log X\right] = 1/n\left[20 \log \frac{V_{ic}'}{V_{ic}}\right]$$

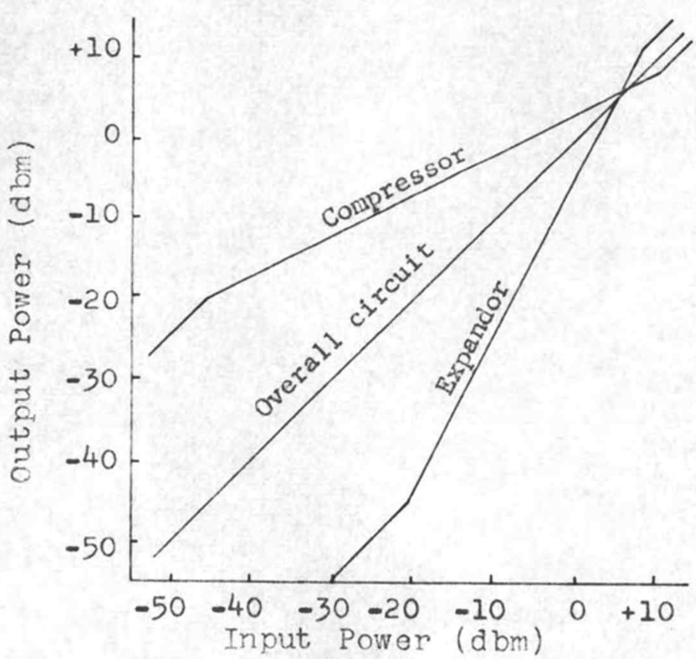


Fig. 2. Input and Output Characteristics of a Compandor

For most compandors, a compression ratio of 1/2 is chosen, which means that a 6 db increase in input will cause only a 3 db increase in output (see Equation 5). As Equation 2 shows, the expansion law should be the exact inverse of the compression law (Figure 2).

Then, since n = 2, and

$$(6) \quad V_{ie} = K_2 V_{oc}$$

where K_2 is the linear loss factor of the speech channel. For n = 2 placed into Equation 2, V_{oe} is

$$(7a) \quad V_{oe} = K_3 (V_{ie})^2$$

Equation 6 substituted into Equation 7a becomes

$$(7b) \quad V_{oe} = K_3 (K_2 V_{oc})^2 = K_3 K_2^2 V_{oc}^2$$

Equation 1 substituted into Equation 7b becomes

$$V_{oe} = K_3 K_2^2 (K_1 V_{ic}^{\frac{1}{2}})^2$$

$$(7c) \quad V_{oe} = K_3 K_2^2 K_1^2 V_{ic}$$

or, by dividing both sides by V_{ic} and taking the logarithms

$$(7) \quad 20 \log \frac{V_{oe}}{V_{ic}} = 2(20 \log K_1) + 2(20 \log K_2) + 20 \log K_3$$

In words, Equation 7 states that a 1 db change in the transmission loss (20 log K_2) will cause a 2 db output change (2[20 log K_2]). Hence, channel gain regulation is more critical for channels with compandors than for those without compandors. Also, if the channel response was flat within 3 db before applying compandors, the channel will have a 6 db variation after applying them. The effect on a typical channel response is shown in Figure 3.

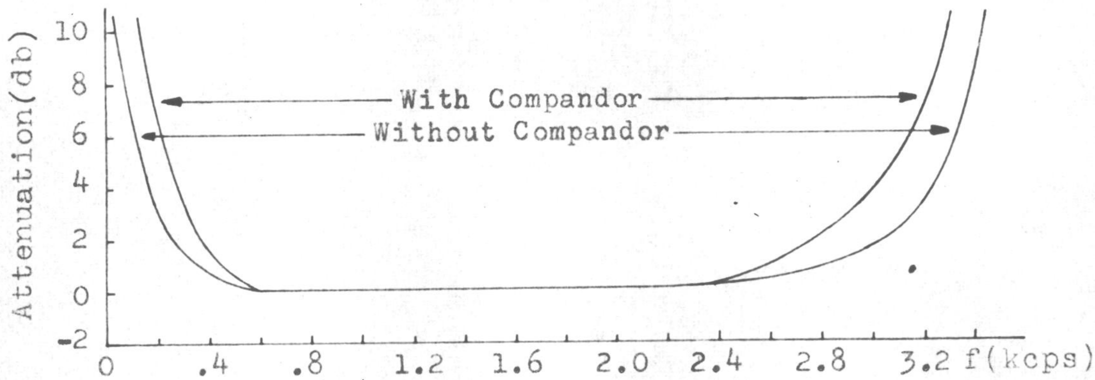


Fig. 3. Channel Frequency Attenuation
Characteristics with and without Compandor

This, however, is largely only an apparent disadvantage since Figure 3 is a response curve to single frequency tones. As voice signals are of complex wave shape, the most powerful frequency, the fundamental, will essentially control the compandor gain, resulting effectively in a high-frequency response identical to that without compandor.

Realization of the Design Objective with the Conventional Compandor

Before a new design can be undertaken, the design objectives must be clearly in mind. The study of existing circuits will help accomplish this.

Figure 4 shows a block diagram of a compandor terminal. The incoming signal power from the two-wire line is split

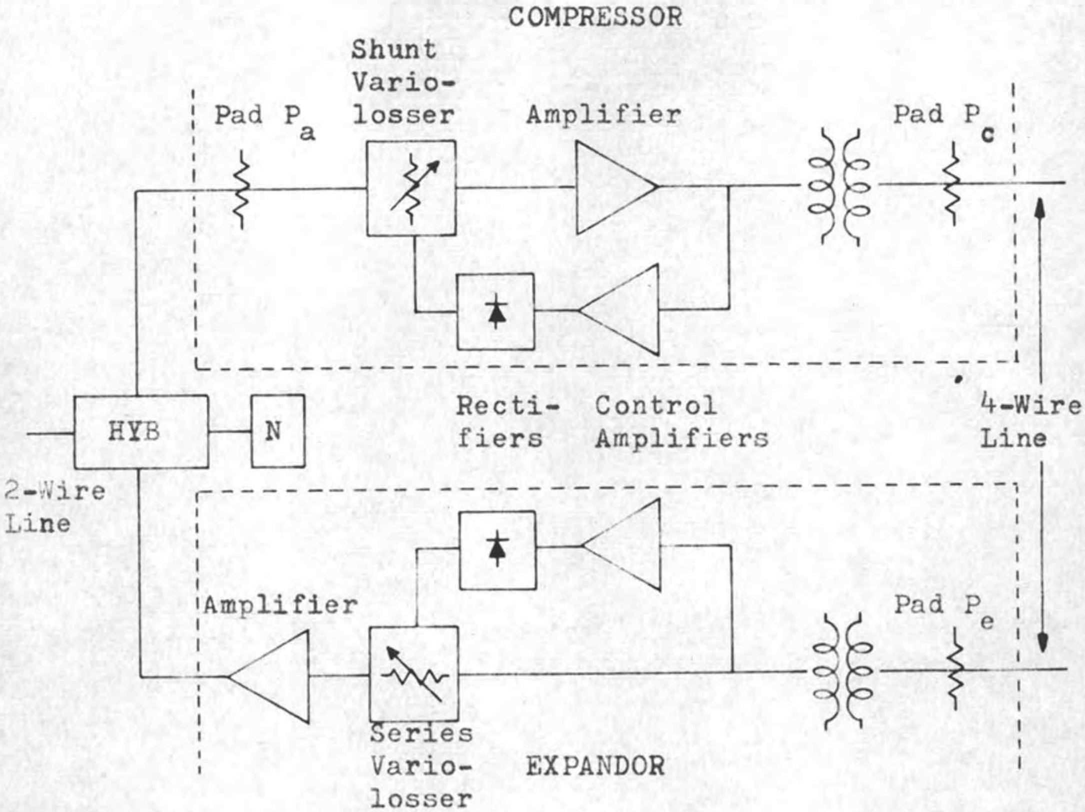


Fig. 4. A Compandor at One End of a 4-Wire Telephone Circuit

equally in the hybrid coil. One-half of the power is dissipated in the output of the expandor amplifier. The rest of the signal is attenuated in the Pad P_a before it enters the shunt vario-losser of Figure 4. As will be seen later, P_a is required to decrease the signal sufficiently to prevent harmonic distortion by the vario-losser. The compressed and attenuated signal now enters a high-gain amplifier which restores the necessary transmission level. In a feedback loop, a small amount of the compressor output power is amplified and rectified to control the vario-losser. Under steady-state conditions a 6 db increase in input increases the attentuation of the vario-losser by 3 db.

The expandor works in a similar fashion. The only differences are that forward-acting control is used instead of backward-acting control: that is, the input of the control amplifier is connected to the input of the expandor circuit instead of being connected to its output. Also, the vario-losser is now a series attenuator, the loss of which is decreased with increase in received signal. In the expandor, the gain savings of a backward-acting circuit cannot be used since this would allow the voice energy from the two-wire line to operate the expandor vario-losser.

Vario-losser Circuits Using Copper-oxide Varistors

The principles of different vario-losser circuits, which are used in conventional compandors, have been described by Bennett and Doba (2). The most common series and shunt type circuits are shown in Figures 5 and 6.

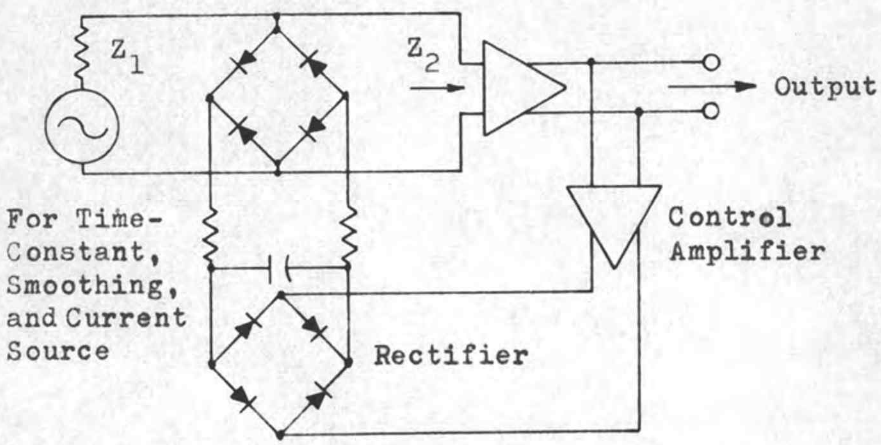


Fig. 5. Shunt-type Backward-acting Vario-losser

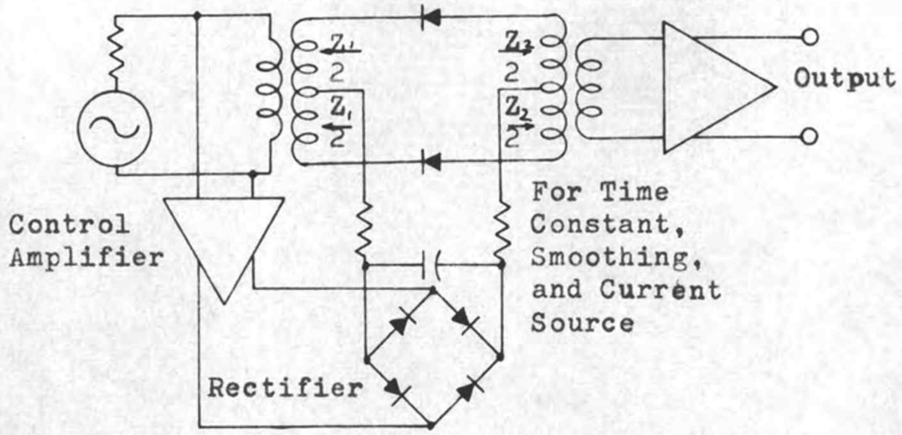


Fig. 6. Series-type Forward-acting Vario-losser

Since varistors have approximately an exponential current-voltage relationship, careful analysis of these circuits shows that they are especially suited for 2:1 compression and expansion ratios. These ratios are, however, not exact for all levels, because of the following approximations that had to be made in their derivation.

1) The varistor characteristics follow truly an exponential law.
2) They are biased by a current source.
3) Their impedances are at all times low as compared to the source and load impedance.

Within these limitations the derivations will hold true also when germanium or silicon diodes are used in place of the copper-oxide varistors. Later it will be shown that for the thermistor vario-losser no such approximations need to be made.

Response Times of the Syllabic Compandor

In the preceding sections, the properties of the compandor have been described in terms of steady-state testing power. However, during speech transmission, the losses of the vario-lossers are changing with time, at a syllabic rate. The time rate of loss variations are determined by the speech envelope and by the attack and recovery times of the compandor. Attack time is the interval required, after sudden application of a steady testing signal, for the gain of the compressor or expandor to reach substantially its final value. Recovery time is the analogous interval after the interruption of a steady testing signal (5). Expressed in a different way, the response time of the syllabic compandor is defined as the time required to change the insertion loss of a vario-losser to 90 per cent of its final value when a sudden change in power input occurs.

A long attack time of the compressor would allow loud initial syllables to overload succeeding amplifiers. This means that the beginning of loud syllables would be distorted. A long recovery time would permit the background noise to be heard, with gradually diminishing volume, when a strong signal was removed. Short attack and recovery times would cause abrupt changes of the speech wave form by the compressor. This type of change adds harmonics to the original waves. The harmonics generated by the compressor contain information of the original speech wave. Therefore, they must be transmitted to enable the expandor to restore the original signal, which means that a fast acting compandor would require a transmission bandwidth up to three times the original speech bandwidth. For this reason, compromise response times have to be used in the design of compandors.

Lawton (12) states that the ear cannot detect the effects of attack times less than 70 milliseconds and release times of less than 100 to 300 milliseconds. These would be the extreme allowable operating times if only one compandor was used in a transmission path. Carter (5) mentions that talking tests established that for a single compandor, attack times of the order of 10 milliseconds and recovery times of the order of 50 milliseconds gave satisfactory quality on good toll telephone circuits. These last two operating times will be used as design objectives because they allow two or three compandors in tandem without objectionable speech distortion.

It will be shown later that the thermistor compandor has varying operating times dependent on signal levels and the time rate of change of the signal levels. Operating times of conventional compandors show a similar dependence on the absolute signal levels and the rate of change of the signal levels. The capacitors in the vario-lossers (see Figures 5 and 6) charge in parallel with, but discharge through, the varying resistance of the vario-losser diodes.

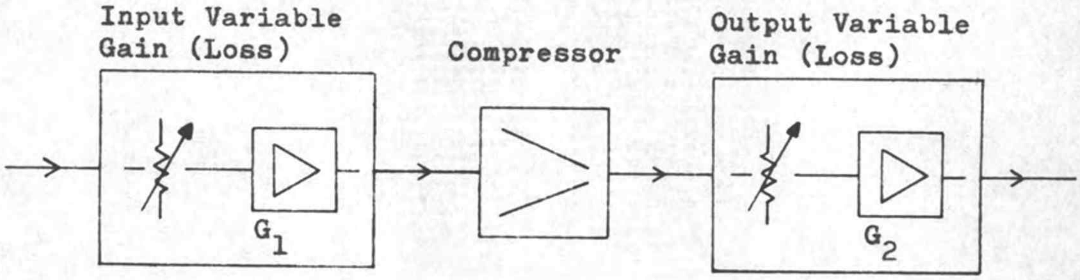
To have a completely distortionless reproduction of the signal after expansion, the transient change in the compressor insertion loss must be completely cancelled by a matched transient change in the expandor insertion gain during the entire period of the transient. However, according to Paulaitis (16), there is no possible way of designing the expandor vario-losser circuit, now used in practice, to have both the exact inverse transient response and the exact inverse steady-state gain response of the compressor. In modern compandors, usually the accurate matching of the steady-state gain response is considered most important. Thus, in vario-lossers now in use, it is usually only attempted to produce accurate compression and expansion ratios (4). As will be seen later, no such compromise solution is required for the thermistor compandor.

<u>Compandor Control Range</u>

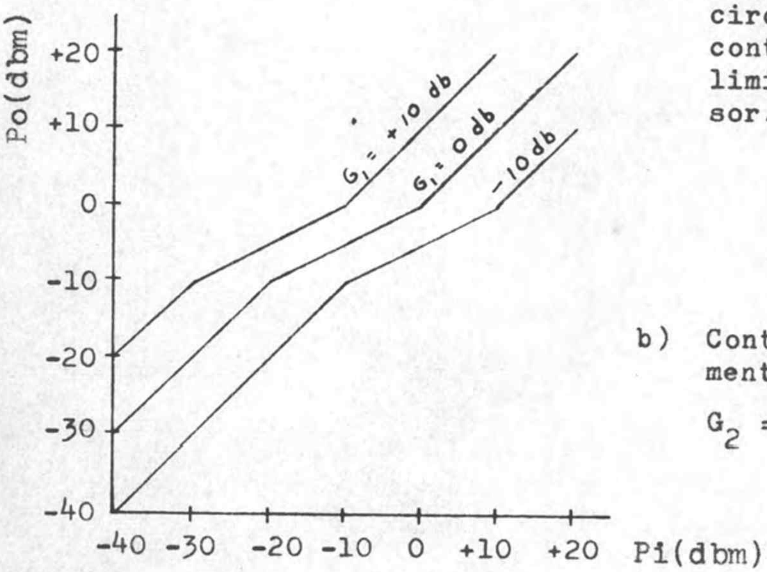
For any practical design, compandors are limited as to the input range they can accept and the output range they can provide. Therefore, in compandor design, the following definitions summarized from an article by Wright are useful (23).

The _control range_ is the difference between the maximum and minimum inputs over which a device functions in a specific nonlinear manner. The values dividing the controlled range from the uncontrolled ranges may be referred to as the "_control points_". A control point can be moved as desired over a wide range by connecting a repeater or attenuator in tandem with the compressor or expandor. This is illustrated in Figure 7 for a limited range compressor.

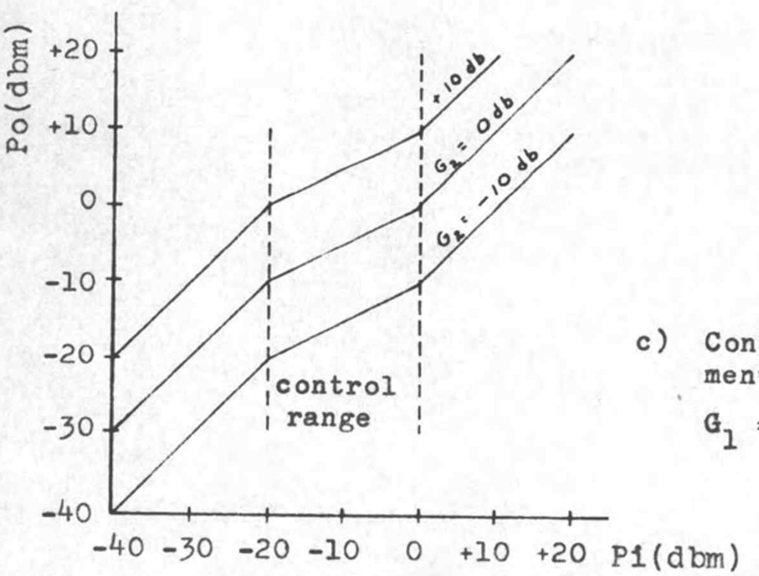
The above discussion of "range" concludes the general considerations for compandor design. In the following section, the need in a particular field for an inexpensive, small compandor will be explained.



a) Block diagram of a circuit to adjust the control points of a limited range compressor.



b) Control point adjustment by changing G_1.
$G_2 = 0 =$ constant



c) Control point adjustment by changing G_2.
$G_1 = 0 =$ constant

Fig. 7 Moving the Control Points of a Limited Range Compressor by Means of Attenuators and Amplifiers.

THE NEED FOR AN INEXPENSIVE, SMALL COMPANDOR

Ordinarily, in engineering work, preliminary specifications are written for a device after the need for such a device has been established. Determining design specifications for a compandor is application engineering and not within the scope of this investigation.

During previous work at International Telephone and Telegraph Laboratories, the writer became aware of the need for a simple, inexpensive, and small compandor. This proposed compandor is to be used on exchange carrier channels where a noise reduction of not more than 15 db is needed.

Exchange carrier systems are a new development within the telephone carrier field. These carrier systems are designed for economical operation on extremely short lines, that is for use on exchange telephone lines as distinguished from toll, or long-distance, circuits. Until recently all speech channels between central offices within a given exchange consisted of metallic pairs of wires operated on a voice-frequency basis. Exchange carrier systems now are used to provide additional speech channels over existing cable pairs, and at a cost lower than the needed channels could be obtained by installing additional new cable. For long-distance, or toll-system carrier, bridging thousands of miles, terminal equipment comprises only a small part of the cost of a system. The larger portion of the cost is in the open-wire, or cable, and the repeater facilities. For exchange carriers the situation is reversed, and it becomes necessary to save on the cost of the terminal equipment.

At first glance, it seems unnecessary to use compandors on carrier systems that only cover a distance of five to twenty miles. However, it must be remembered that the exchange carrier systems will transmit over cable lines that have originally been designed only for voice-frequency operation. Crosstalk attenuation for carrier frequencies is, therefore, much lower on exchange cables than on toll-telephone cables, and compandors will be needed on a number of channels with a large amount of crosstalk and noise.

In the investigations described in the following pages, it will be shown that an inexpensive compandor giving sufficient noise and crosstalk reduction can be designed using matched thermistors. To do this, the theory of the thermistor compandor will first be developed mathematically and then confirmed experimentally. Later, important design criteria will be investigated. Furthermore, thermistor theory will be studied with the aim of specifying thermistors with suitable operating times and sensitivity. Finally, recommendations will be made on how to incorporate the compandor into an actual system.

THERMISTOR COMPANDOR THEORY AND EXPERIMENTS

General Theory of the Compandor Circuit

In this section the general theory of the compandor circuit will be discussed. It will be noticed that nowhere in this section will thermistor properties be mentioned. In fact, it will be shown that under certain conditions the overall response of the circuit is independent of thermistor properties. Consider the circuit shown in Figure 8.

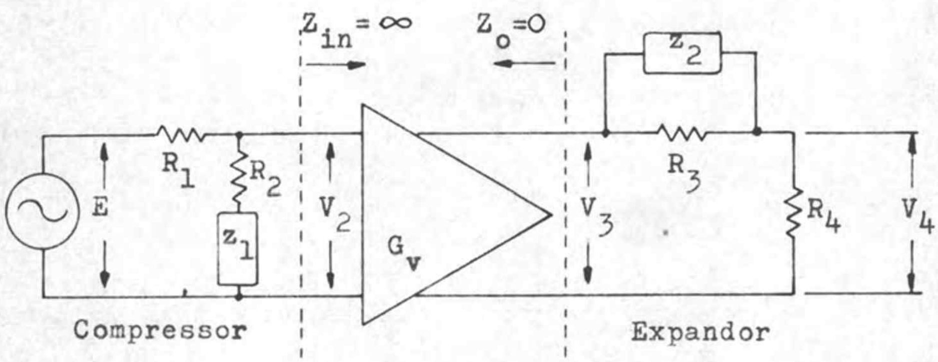


Fig. 8. Simplified Compandor Circuit

To make the overall circuit response independent of the circuit elements z, the following relations among circuit elements must hold true.

(1) $z_1 = z_2 = z$

where z is a linear or nonlinear impedance element.

(2) $R_3 = R_1 + R_2$

(3) $R_4 = R_2(1+\frac{R_2}{R_1})$

Also, the voltage transfer characteristic of the ideal voltage amplifier must be

$$(4)\quad \frac{V_3}{V_2} = G_v = 1 + \frac{R_2}{R_1}$$

Now it can be proved that the output voltage, V_4, is not a function of z.

Directly from Figure 8, the following three equations can be written.

$$(5)\quad \frac{V_2}{E} = \frac{R_2 + z}{R_1 + R_2 + z}$$

$$(6)\quad \frac{V_3}{V_2} = 1 + \frac{R_2}{R_1}$$

$$(7)\quad \frac{V_4}{V_3} = \frac{R_4}{\frac{R_3 z}{R_3 + z} + R_4}$$

Multiplying the left sides of Equations 5, 6, and 7 results in the overall voltage transfer ratio of the circuit, $(\frac{V_4}{E})$. Multiplying the right sides, and substituting Equations 2 and 3 into the product to eliminate the variables R_3 and R_4, the following result is obtained after some algebraic manipulations.

$$(8)\quad \frac{V_4}{E} = \frac{R_2}{R_1}$$

As already mentioned, Equation 8 shows that the resulting voltage ratio is independent of z when identical elements for z are used. To help visualize the result, the voltage transfer ratio $\frac{V_4}{E}$ will be calculated directly for the extreme values of z. If

$$z_1 = z_2 = \infty \text{ ohms (open circuits).}$$

Then, from Figure 8

$$(9) \quad V_2 = E$$

$$(10) \quad V_3 = V_2 G_v = E(1 + \frac{R_2}{R_1})$$

$$\frac{V_4}{E} = \frac{V_3}{E}\,\frac{R_4}{R_3+R_4} = (1 + \frac{R_2}{R_1})\frac{R_2(1 + \frac{R_2}{R_1})}{R_1+R_2+R_2(1 + \frac{R_2}{R_1})}$$

Simplified

$$(11) \quad \frac{V_4}{E} = \frac{R_2}{R_1}$$

which agrees with Equation 8. Or, if $z_1 = z_2 = 0$

$$(12) \quad \frac{V_2}{E} = \frac{R_2}{R_1+R_2}$$

$$(13) \quad \frac{V_3}{V_2} = (1 + \frac{R_2}{R_1})$$

$$(14) \quad \frac{V_4}{V_3} = 1$$

Therefore,

$$(15) \quad \frac{V_4}{E} = \frac{R_2}{R_1+R_2}(1 + \frac{R_2}{R_1}) = \frac{R_2}{R_1}$$

which is also identical with Equation 8.

If linear elements are employed at z_1 and z_2, it can be seen that the amplifier voltage transfer ratio is not critical. For instance, if capacitors are used, V_2 becomes a function of frequency ($V_2 = f(f)$) as shown in Figure 9.

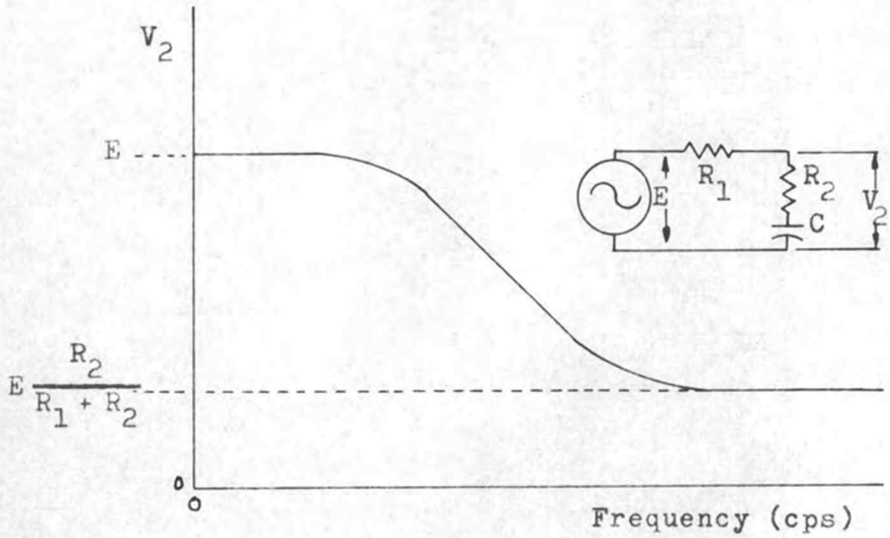


Fig. 9. Frequency Response of the Compressor Circuit for Constant Input Voltage if a Linear Capacitor is used for the z Component.

With an amplifier gain as given in Equation 4, Equation 8 still holds true. With some other gain, G_V', the system voltage transfer ratio changes to

$$(16) \quad \frac{V_4}{E_v} = \frac{R_2 \, G_V'}{R_1(1 + \frac{R_2}{R_1})} = \frac{R_2}{R_1+R_2} \, G_V'$$

In other words, the system will still have an output-input voltage transfer ratio independent of frequency. The fact that reactive elements do not change the gain linearity of the overall circuit response may be useful for the final design of a thermistor compandor if it becomes necessary to isolate direct current from the thermistor.

The question arises, why is a particular voltage transfer ratio of the ideal amplifier required, even though, for linear elements, the amplifier gain is not critical? For matched, nonlinear elements to behave identically, the currents through them and the voltages across them must be equal at any instant of time. The main function of the amplifier is to provide z_2, at all times, with a voltage identical to that existing across z_1. It will now be shown that currents and voltages in z_1 and z_2 are equal at all times. Directly from Figure 8 and Equation 1, the voltage across z_1 is

$$(17) \quad V_{z_1} = E \frac{z}{R_1+R_2+z}$$

From Figure 8 and Equations 5, 6, and 8, the voltage across z_2 is

$$V_{z_2} = V_3 - V_4 = E \left(\frac{R_2+ z}{R_1+R_2+z}\right)\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}$$

which, after some algebraic manipulation, becomes

$$(18) \quad V_{z_2} = E \frac{z}{R_1+R_2+z}$$

Hence, comparing Equations 17 and 18

$$(19) \quad V_{z_2} = V_{z_1}$$

The voltages across the nonlinear elements z_1 and z_2 are equal at all times. The equality of currents in z_1 and z_2 follows from Ohm's Law and Equation 19.

The companding action of the above circuit has not yet been considered. This action depends entirely on the characteristics of the elements z_1 and z_2. For instance, the circuit in Figure 8 has been used previously in instantaneous compandor design, but not for the type of compandor now under investigation. For the elements z, pairs of high conductance germanium diodes were used by the writer in previous work at International Telephone and Telegraphy Laboratories (See Figure 10).

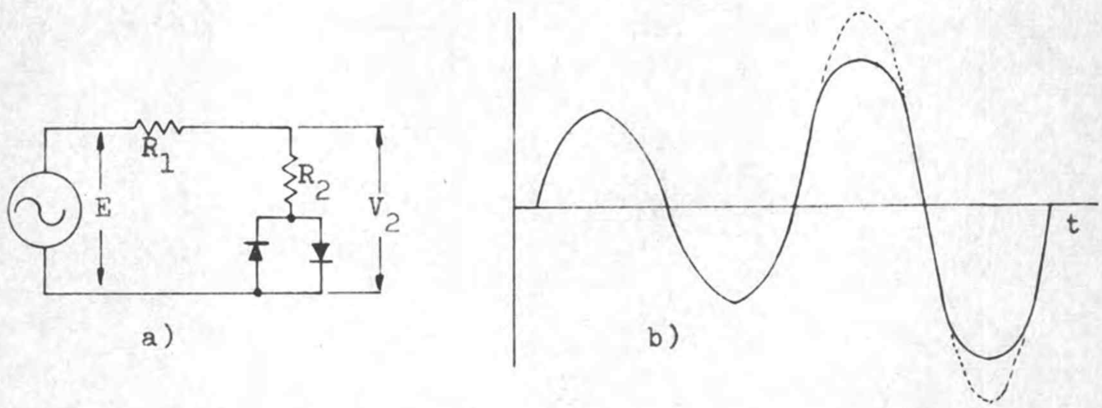


Fig. 10. a) Simplified Instantaneous Compressor Circuit Using Matched Diodes.
b) Output Wave Forms for Different Input Power Levels (Sine Wave Input).

When a wideband linear system is used between compressor and expandor, the instantaneous compandor has practically an undistorted output (second and third harmonics more than 40 db below the fundamental). However, at high levels of transmission, the transmitted waveform consists of a number of strong harmonics. Therefore, a bandwidth of at least 12 kilocycles is required to enable the expandor to reproduce the higher voice frequencies with tolerable distortions.

The two major contributions of this investigation consist of: (1) The realization that the circuit equations do not only hold for instantaneously varying nonlinear resistances such as diodes, but also for time delayed varying circuit elements such as thermistors. (2) The experimental verification, which is discussed later, shows that the above circuit may be useful for the design of an essentially distortionless syllabic compandor with its inherent smaller bandwidth requirement.

Graphical Determination of the Compressor Gain Characteristic

In the last section it has been shown that the expandor circuit has the exact inverse response of the compressor circuit. Therefore, only the desired compressor gain characteristic need be determined, as will be done in this section.

In Figure 11, a steady-state thermistor response is shown. When a current, I_{th}, flows through the thermistor, the voltage drop across R_2 will be $I_{th}R_2$. Adding the thermistor voltage and the voltage drop through R_2, the combined characteristic, also shown in Figure 11, can be drawn. This, then, is a graph of the compressor output voltages for different thermistor currents.

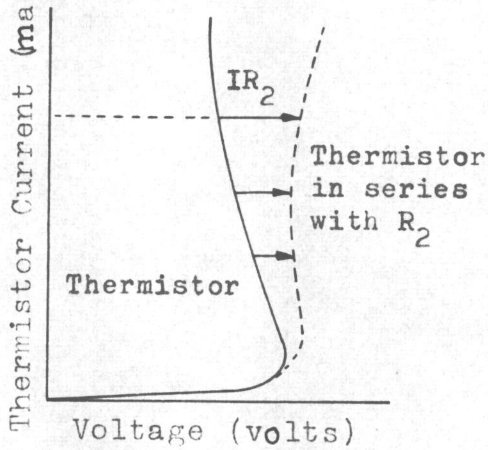


Fig. 11. Steady State Response of a Thermistor Alone and in Series with Resistor R_2.

The next step towards finding the overall compressor response is shown in Figure 12. A loadline drawn with the slope, $-\frac{1}{R_1}$, intersects the curve of compressor current vs. compressor output voltage. The point of intersection is the graphical solution of the linear equation,

$$(20) \quad I_1R_1+V_2 = E$$

and the nonlinear equation,

$$(21) \quad V_2 = f(I_1)$$

This solution assumes that the thermistor temperature stays constant during a cycle of an applied speech wave. Hence, the thermistor must have a long thermal time constant as compared to the half-period of the lowest frequency to be compressed. This requirement will be treated in more detail in the next section on thermistors.

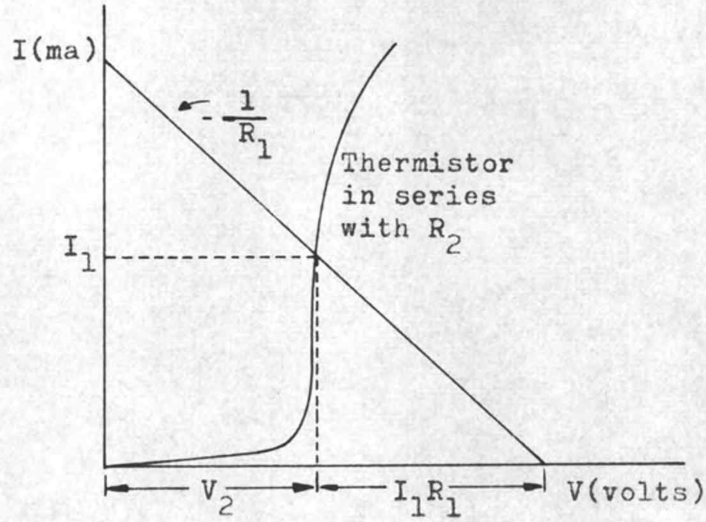


Fig. 12. Graphical Determination of V_2 vs. E.

Drawing parallel load lines of the same slope allows the determination of the complete steady-state response. It is customary to draw steady-state responses of compandors with decibel scales. Therefore, plotting the curve, V_2 vs. E, on log-log paper and dividing each decade into 20 equal divisions will result in the desired steady-state compressor response, $20 \log_{10} V_2$ vs. $20 \log_{10} E$ (see Figure 13).

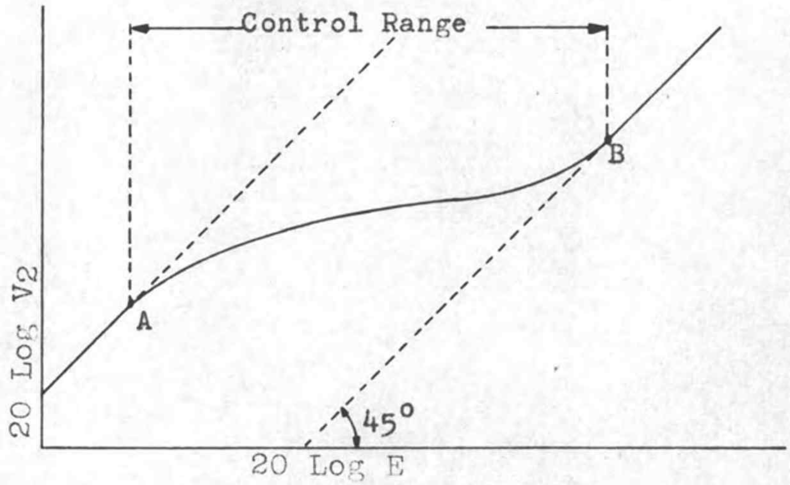


Fig. 13. Compressor Response.

In an actual system the positions of the control points (A and B in Figure 13) have to be chosen in comparison to some reference power level. This amounts to a relabeling of the coordinates of Figure 13 in a decibel scale. The resulting figure, which is then similar to Figure 2, page 6, is the compressor characteristic.

Figure 2 shows a control range of 55 db, or a difference in gain of 27.5 db for the lowest and the highest level within the limits of the control range. As listener evaluation tests of compandors have established, the above mentioned difference in gain is equal to the crosstalk advantage. This is true only if the noise power is below the lower control point of the expandor.

The crosstalk advantage of a thermistor compandor is limited to a lower value as the following example will show. A thermistor resistance may vary in the limit from

(22) $R_{th} \gg R_1$

when no signal is applied, to

(23) $R_{th_1} \ll R_2$

when a strong signal is applied, and after a new steady-state resistance has been reached. Then, from Figure 8, the difference of gain is

$$20 \log \frac{E}{E\left[\frac{R_2}{R_1}\right]} = 20 \log \frac{R_1}{R_2} \text{ decibels}$$

which is limited by the restricted choice for R_1 and R_2, as will be seen later. In a practical case (R_1 = 1200 ohms and R_2 = 120 ohms), the gain difference will be 20 log 10 = 20 db. In an actual design, without the approximations of Equations 22 and 23, a 15 db gain difference can be expected.

At this point it is useful to introduce two new technical terms, "full-range compandor" and "limited-range compandor" (15). The compandors now in use on toll lines are full-range compandors. In effect, they compress and expand over the full range of incoming voice signals. In contrast, the proposed thermistor compandor is a limited-range compandor. The limited range compandor vario-lossers do not act on low-level inputs and, therefore, cannot possibly distort low-level signals. This is advantageous because distortion of a low-level signal decreases its intelligibility more than an equal percentage distortion of a high-level signal.

In Figure 14, input and output characteristics of both a full-range compandor and a thermistor compandor are drawn. It will be seen that while the thermistor compandor is not as effective as the full-range compandor for low noise levels (A' vs. A in Figure 14), it is more effective at high levels of noise (B' vs. B in Figure 14).

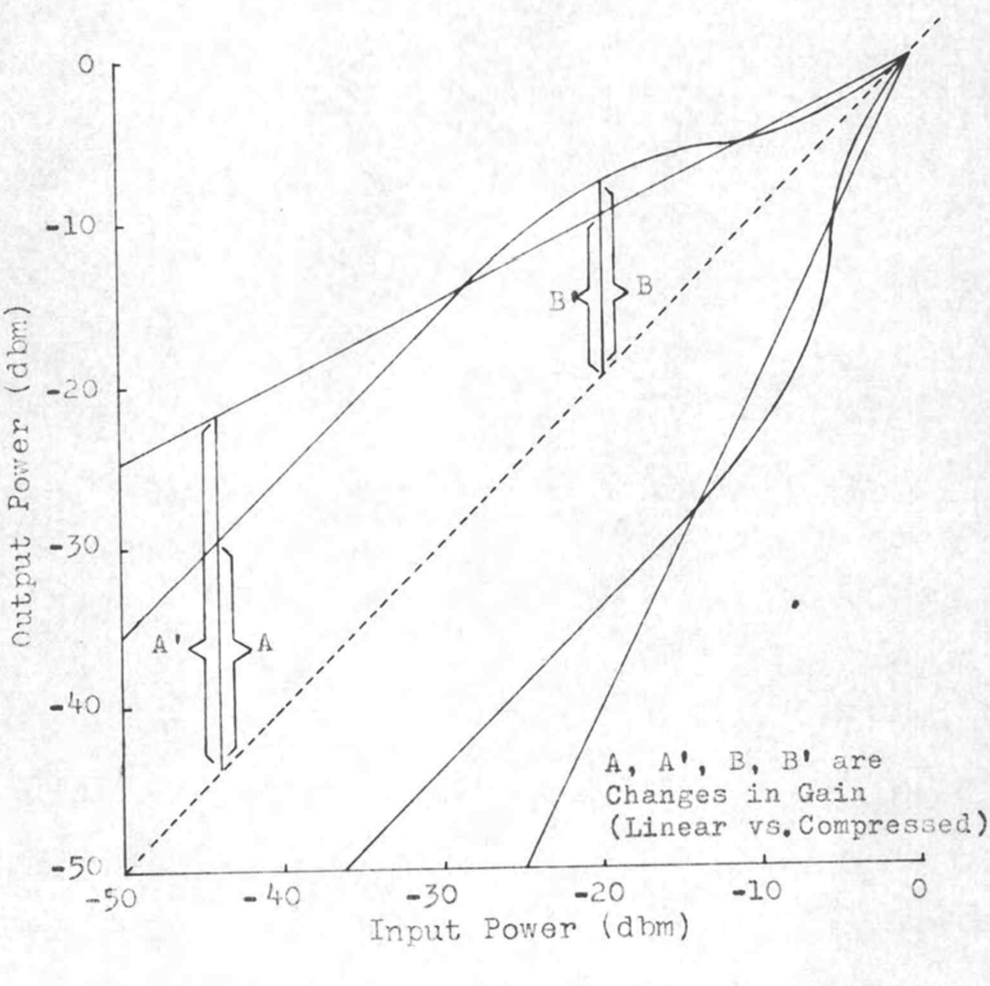


Fig. 14. Input and Output Characteristics for a Full-range Compandor and a Thermistor Compandor.

Experimental Verification of Thermistor Compandor Theory

In a preceding section it has been mentioned that compandor attack and recovery times in the order of 10 and 50 milliseconds are desirable. However, for the verification of the thermistor compandor theory, it is not necessary to have these operating times. The important consideration is to have matched thermistor elements. The Bell Telephone Laboratories supplied six sensitive Western Electric 34 A matched thermistors for this project. Without this help the investigation might not have been possible.

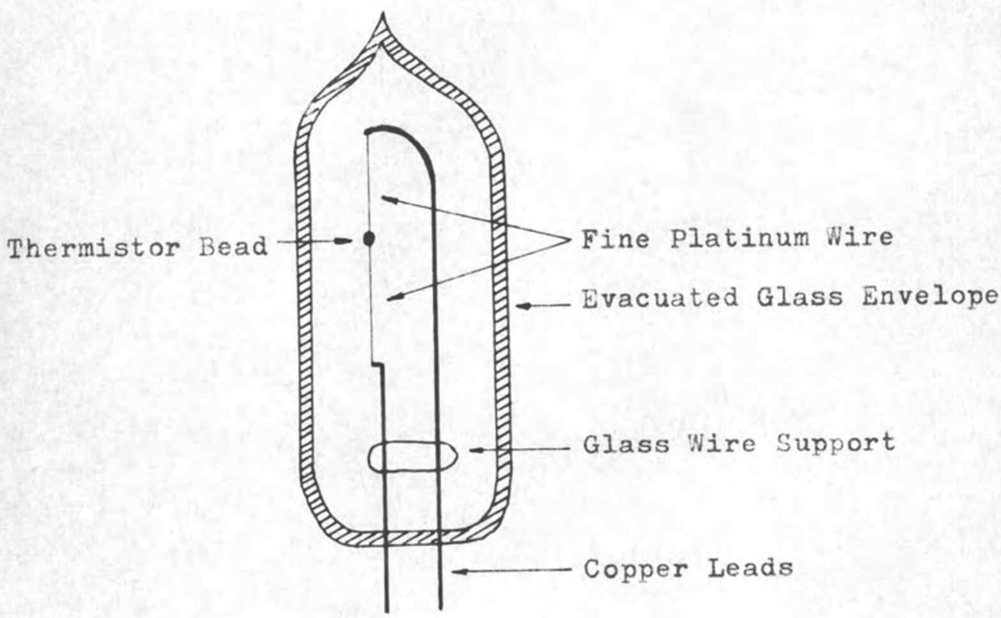


Fig. 15. Western Electric 34 A
Thermistor Construction.

WE 34 A thermistors are bead-type thermistors encapsulated in an evacuated glass envelope. This makes these thermistors very sensitive by reducing the heat loss to the atmosphere, but it gives them a long thermal time constant. After the power which heats the thermistor is removed, it may take nearly a minute before the thermistor returns to room temperature and its correspondingly high resistance. This fact would make the WE 34 A thermistor unsuitable for speech compression on actual telephone circuits. However, it does not make it unsuited for checking the theory.

In preparation for actual compandor measurements, the steady-state current vs. voltage characteristics of the six WE 34 A thermistors were measured. They were so similar that only one curve for one thermistor is shown in Figure 16. However, the equality of single-frequency steady-state characteristics does not imply that the transient responses of the thermistors must also be alike. A photograph was taken of the transient response of each of the six thermistors. The photographs were enlarged and the upper halves of the traces were superimposed to determine variations. The resulting graph is shown in Figure 17. The figure cannot easily be interpreted quantitatively. It was drawn only to show the small transient response differences of the six thermistors. The limits shown in Figure 17 are partially due to differences in cold and hot resistances of the different thermistors, but the actual shapes of the curves are more complicated functions of the

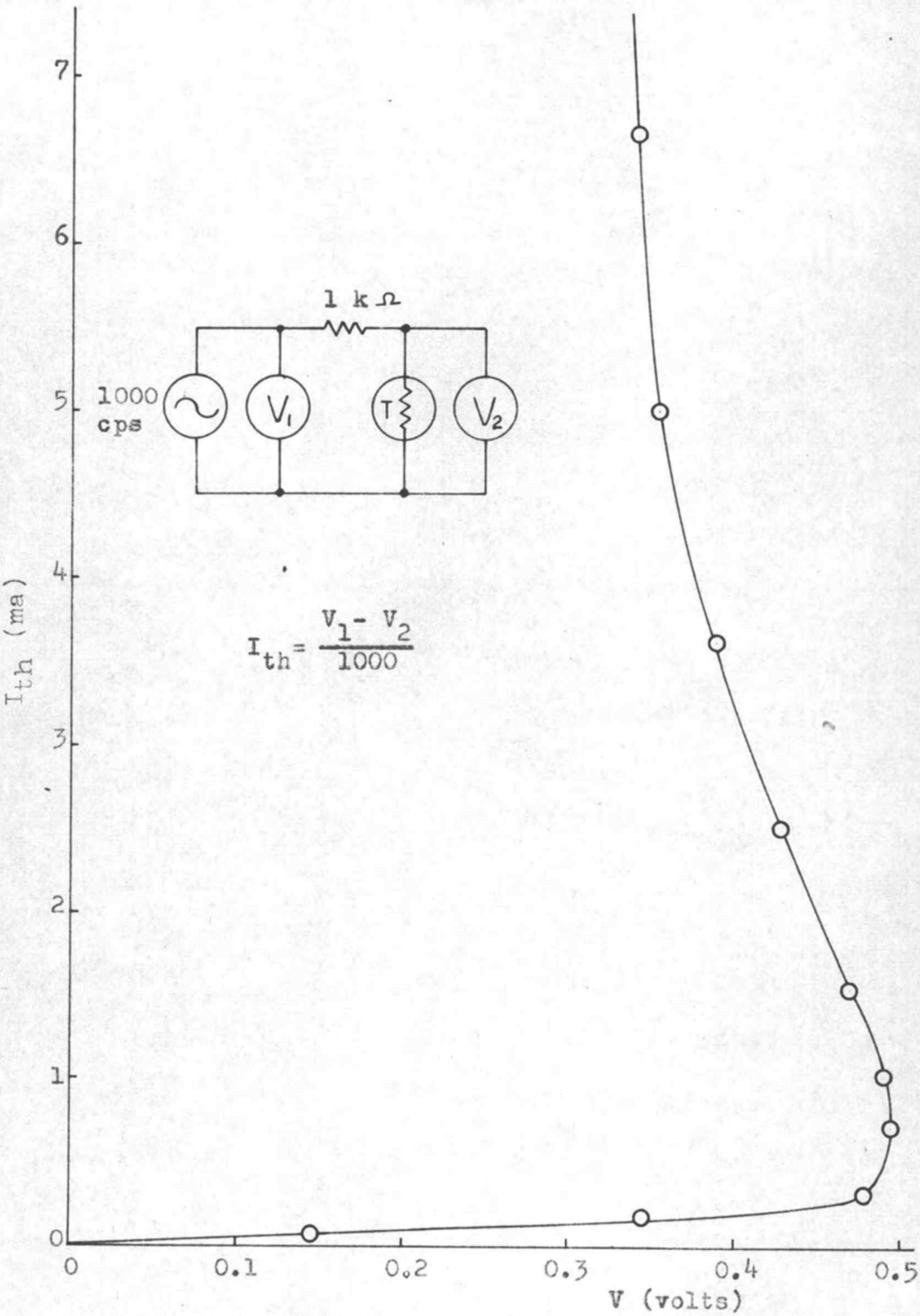


Fig. 16. Steady state characteristic of a WE 34 A Thermistor .

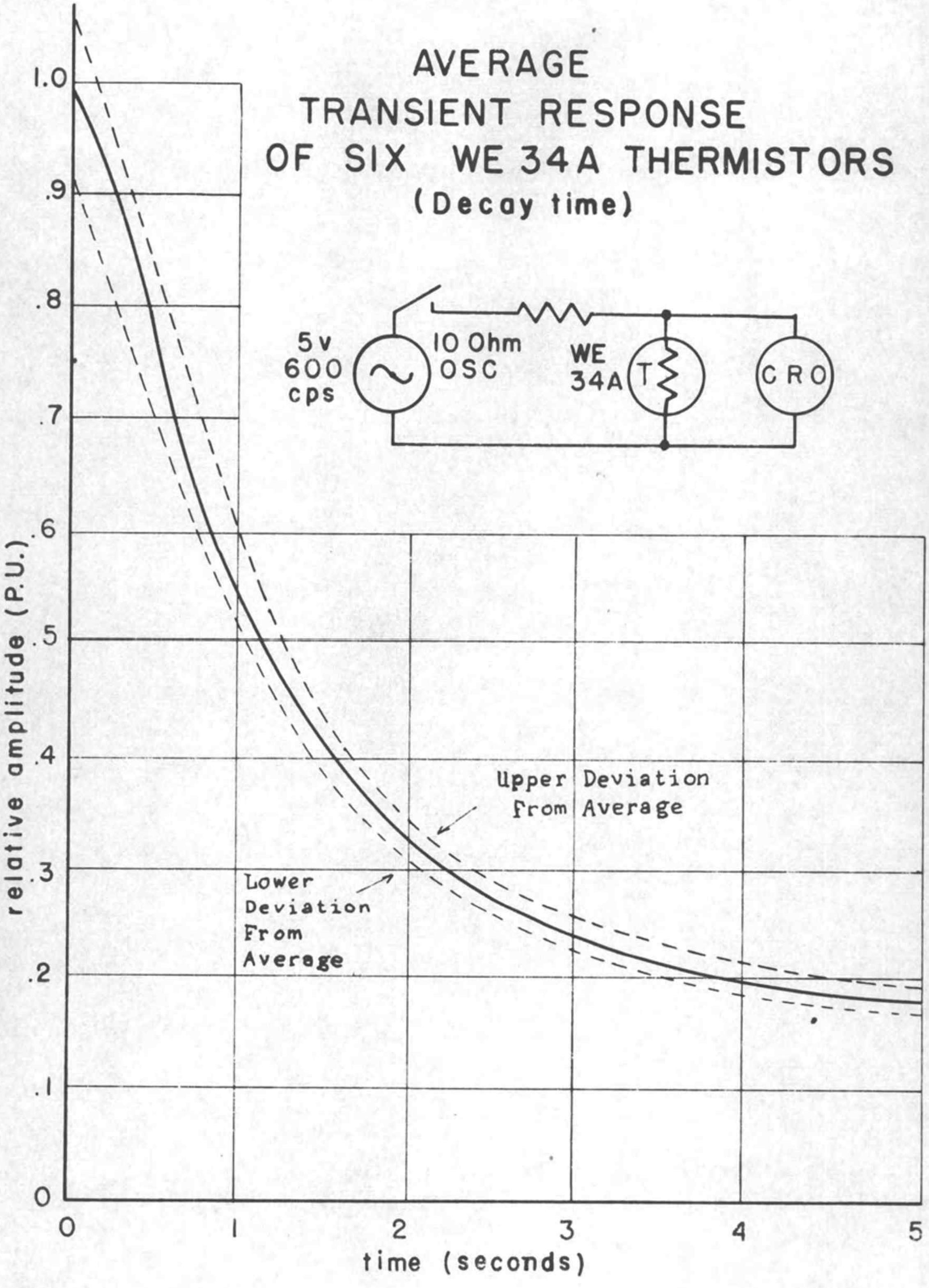

AVERAGE
TRANSIENT RESPONSE
OF SIX WE 34A THERMISTORS
(Decay time)
5 v
600
cps
10 Ohm
OSC
WE
34A
T
CRO
Upper Deviation
From Average
Lower
Deviation
From
Average
relative amplitude (P.U.)
time (seconds)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5

Fig. 17.

cooling and heating properties of the individual thermistors.

For the compandor circuit of Figure 8, resistor R_2 was selected large enough to result in a single-valued function of output voltage vs. input voltage of the compressor. R_1 was chosen to provide a relatively large control range. From these two values, the amplifier gain and the expandor resistances R_3 and R_4 were computed. Also, from the six available thermistors, the two which agreed most closely in their transient responses were chosen.

Figure 18 shows a photograph of the experimental arrangement for checking the thermistor compandor theory. An oscilloscope equipped with a polaroid camera was used to record the transient behavior of the circuit. Vacuum-tube voltmeters were used for steady-state measurements. In order to provide nearly ideal circuit conditions, voice-frequency amplifiers with low output impedances (about 15 ohms) and 10-watt output power capabilities were used for both the signal generator and the ideal amplifier. In order to make the amplifier outputs independent of the varying amplifier loads, the amplifier outputs were permanently loaded with thirty-ohm resistors. The complete circuit is shown in Figure 19a. The attack response is readily observed on the oscilloscope screen, because the oscilloscope sweep can be triggered to sweep at the

Fig. 18. Experimental Arrangement to Check the Thermistor Compandor Theory

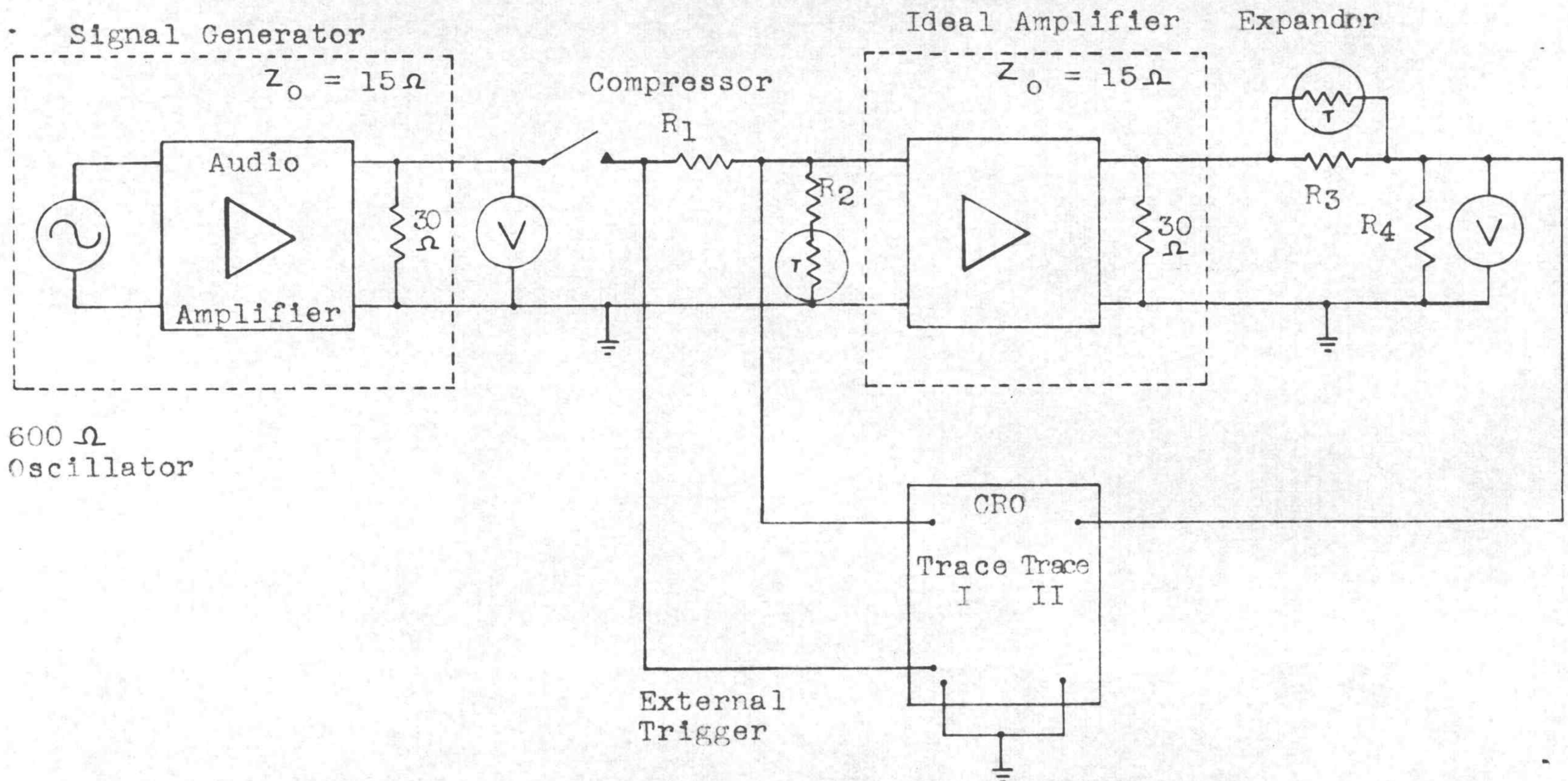


Fig. 19a. Circuit to Determine Steady state and Transient Response of the Thermistor Compandor. (Attack time only)

moment the signal is applied at the compressor (see Figure 19a).

Measuring the recovery time of the compandor presents a problem. Ideally, the signal should be removed, and the time it takes for the compressor and the expandor to reach their final gains should be measured. A simple, practical measurement technique was developed. The circuit which was used is shown in Figure 19b. A large resistor, bypassing the switch S, supplies a small constant current through the compressor thermistor at all times. The ideal amplifier supplies the same small current to the expandor thermistor. The current is made small enough not to heat the thermistors noticeably above room temperature. The changing voltages across the thermistors, or, for that matter, the voltages across the output of the compressor give an indication of the changing resistance of the thermistors. However, the expandor output voltage gives no indication of the state of gain the expandor is in, since ideally, after the large signal is removed, a constant small signal will appear across the expandor output. A constant output, however, will show that the circuit performance agrees with the theory developed earlier.

The oscilloscope is triggered by applying the full voltage of the signal generator to the external trigger immediately after the generator power is removed from the

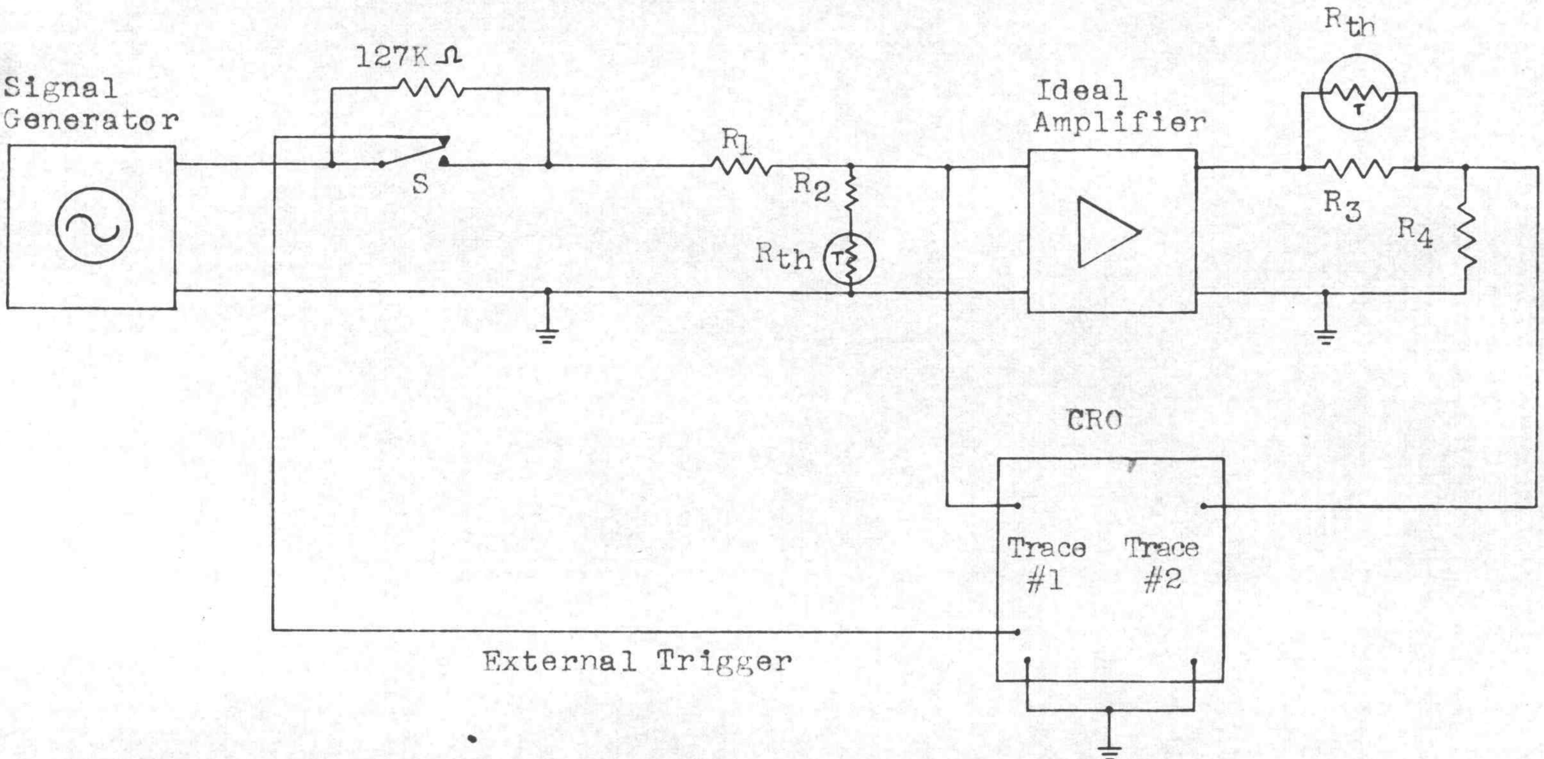


Fig. 19b. Circuit to Determine the Transient Response of the Thermistor Compandor (Recovery time only)

compressor circuit. This is accomplished with a separate contact of switch S in Figure 19b.

First, the overall steady-state voltage transfer ratio was measured over a range of 60 decibels. The ratio of output voltage, v_4, to input voltage E, was constant with deviations of less than 1 decibel. Secondly, the transient response was measured by keying a 1000 cps tone on and off. When a sufficiently large voltage was applied to the compressor to operate it in its control range, the output voltage of the compressor decayed exponentially as expected, and the output voltage of the expandor remained constant from application of the tone to its removal. The results were so close to ideal performance that there is no need to show them in the form of a graph. Instead, the performance of the thermistor compandor for somewhat less ideal conditions will be discussed in the following paragraphs.

The extremely slow cooling of the WE 34 A thermistors made transient response measurements somewhat impractical. Therefore, two thermistors with slightly different thermal time constants were selected from the group, and the glass envelopes were carefully opened to expose the thermistor elements to the air. This decreased the thermal time constants of the thermistors, but it also made them less power sensitive, as shown in Figure 20. To further decrease the thermal time constant, the thermistor elements were

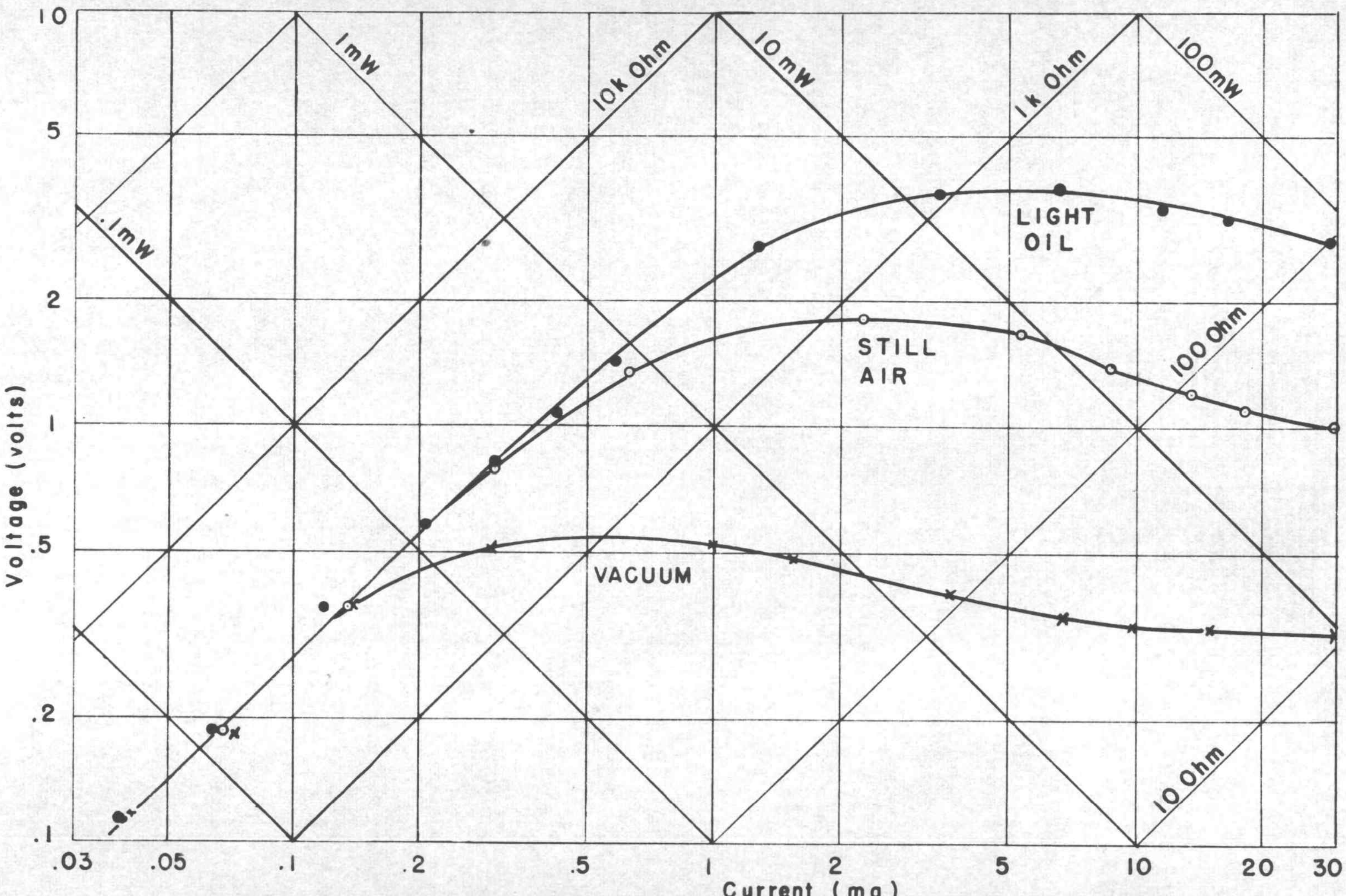


FIG. 20. E-I CURVES OF A WE 34A THERMISTOR FOR DIFFERENT SURROUNDING MEDIA

suspended in light oil. However, this type of cooling decreased the sensitivity of the thermistors so much that the amplifiers could not deliver enough output power to achieve satisfactory compression and expansion. Therefore, for further experiments, the unsealed thermistors used were cooled in still air.

In Figure 21, compressor and expandor output envelopes are shown. For the set labeled "I", the slower thermistor was used in the compressor. For the set labeled "II", the faster thermistor was used in the compressor. Figure 21 shows clearly that the ideal transient response is more nearly obtained by using the faster thermistor in the compressor. This fact can be explained in the following manner. When the slower thermistor is used in the compressor, the expandor thermistor will be momentarily overheated, and the output will show an overshoot from the ideal step response. The expandor output will return to normal only after the thermistor has cooled off to its final steady-state temperature. For a directly heated thermistor, cooling is a much slower process than heating. Heating time depends upon the applied signal, which can be made arbitrarily large, while cooling depends on thermal convection only. Therefore, it takes a relatively long time for the equilibrium to be re-established. However, as Figure 22 shows, the steady-state

COMPANDOR RESPONSE TO A 20 VOLT 600 cps STEP INPUT

To get the two sets of curves, the two thermistors with their slightly different thermal time constants were interchanged.

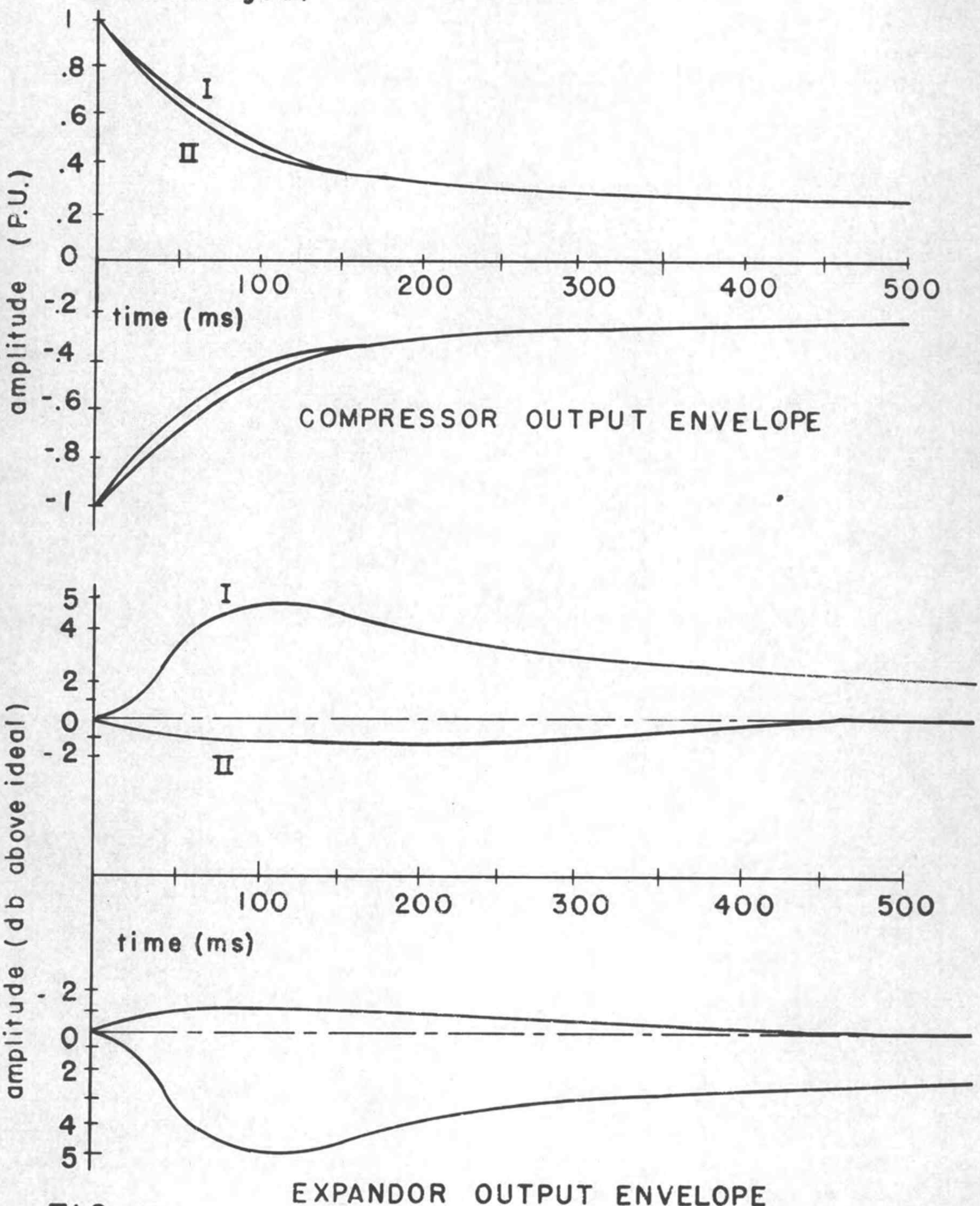


FIG. 21.

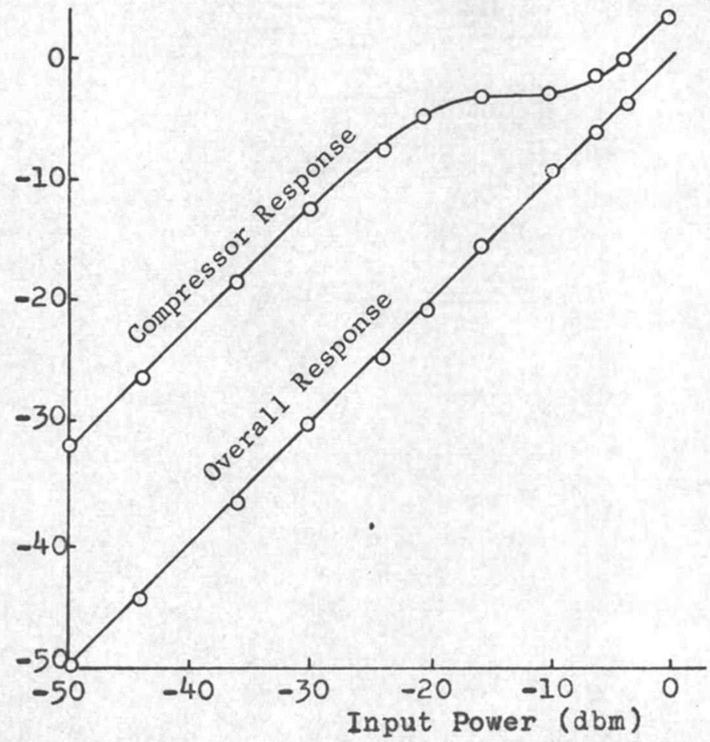


Fig. 22. Steady-state Response of the Thermistor Compandor

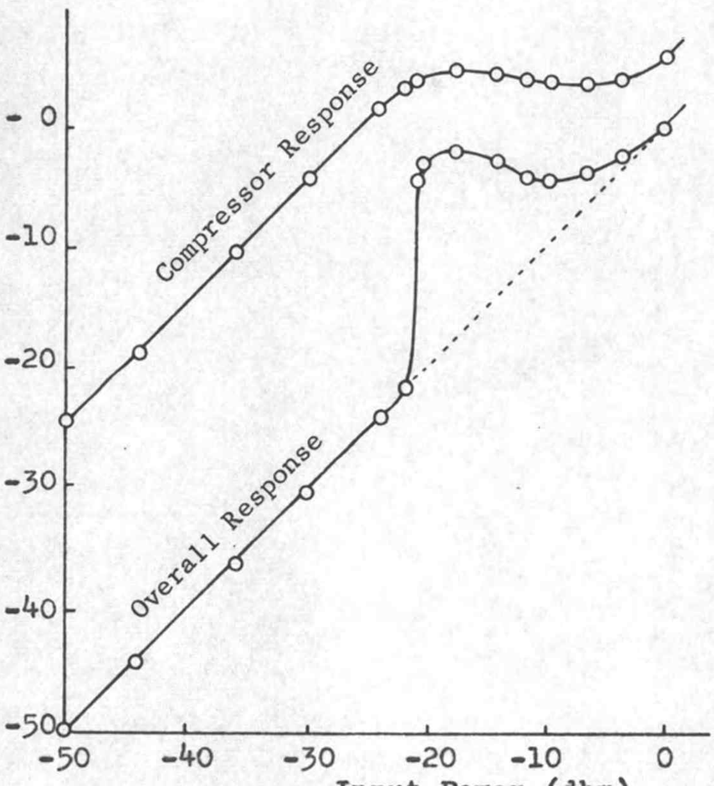


Fig. 23. Compressor Response and Overall Response of a Thermistor Compandor Using a Resistor R_2, Which is too Small

performance of the compandor is nearly perfect, even for thermistors with slightly different characteristics.

As there will always be slight differences in individual mass-produced thermistors, it may be well to divide thermistors into two groups and use the slightly faster ones in the compressors, and the slightly slower ones in the expandor.

As was mentioned before, the choice of the resistor R_2 of Figure 8 is limited to a minimum value which will still result in a single-valued function of $V_2 = f(E)$. Even though the circuits were designed by the writer with this limitation in mind, it is not obvious what effect a resistor smaller than the above value would have on the circuit performance. To find the effect, a circuit with a small R_2 was tested.

Figure 23 shows the compressor and the overall steady-state responses of a compandor using too small a design value for R_2 of Figure 8. The expandor is in a "runaway" condition during its complete control range, as indicated by Figure 23.

From the previous discussion, it is clear that the WE 34 A thermistor cannot be used for the actual design of a syllabic compandor. First, the WE 34 A thermistor has too long a time constant. Second, if the time constant is reduced by increased cooling, the thermistor will become power insensitive, and the circuit would require amplifiers with large power-handling capacity. Consequently, it becomes advisable to examine thermistor properties in detail.

Thermistor Properties Required for a Thermistor Compandor

For the purpose of this investigation, equations describing the behavior of thermistors as electric circuit elements are needed. It would also be desirable to find an equivalent circuit, involving only linear elements, for the thermistor. Investigations with the above aim in mind have been made in Sweden (3, 8, 9). In America, relatively few articles have been written on use and properties of thermistors. Some of these articles are cited in the bibliography (1, 10, 11).

Even when approximations are used, thermistor circuit analysis involves the solution of nonlinear differential equations. Fortunately, no extremely accurate knowledge of thermistor steady-state and transient responses is needed for the design of a thermistor compandor. Three characteristics are of interest, however. First, the thermistors used in actual compandors must have identical or nearly identical parameters. This is a manufacturing problem and will not be treated further here. Secondly, the thermistor should be power sensitive in order to reduce the amount of amplification that is needed. Amplifiers with large gains and high power output capabilities are too expensive to make a thermistor compandor economical. Thirdly, the thermistor should return nearly to room temperature in 50 to 100 milliseconds after heating power has been removed from it.

For examining the above requirements, John N. Shive's presentation of thermistor properties is most useful (17). The following explanations and Equations 1 to 7 are taken from Shive's book.

> "A thermistor is characterized by a number of important physical, thermal, and electrical parameters. Among these are the following:
>
> (1) Its mechanical dimensions, including those of the supports and capsulation, if any.
> (2) The material from which it is made and the properties of this material. Important material properties are resistivity, temperature coefficient of resistivity, specific heat, density, and thermal expansion coefficient.
> (3) Its d-c resistance R_o at some reference temperature T_o. A convenient reference temperature is 300° absolute, which is a good approximation to "room temperature".
> (4) Its power sensitivity, defined as the input in watts required to reduce the resistance of the element by 1 per cent, or from R_o to $0.99R_o$.
> (5) Its thermal dissipation constant G, defined as the ratio of the watts dissipated in the thermistor element to the degrees of temperature rise of the element above its surroundings in steady state. The dissipation constant is thus a measure of the effectiveness with which heat is conveyed away from the thermistor element. The dissipation constant is an important parameter because, along with the heat capacity to be described below, it helps to determine how fast a new steady state can be established when the input power is changed.

(6) Its heat capacity C, which is the number of joules of heat resident in the element when its temperature is one degree above that of its surroundings. The heat capacity is determined by the dimensions of the element and the specific heat of its material.

(7) Its thermal time constant τ , which is the time required for the temperature of the element to go $(1 - 1/e)$ of the way to a new steady-state value when the input power is suddenly changed.

....

(8) The maximum power which can be dissipated within the element consistent with stability and long life.

The temperature corresponding to the peak of the thermistor characteristics is:

$$(1)\quad T_m = \frac{B}{2}\left[1 - \left(1 - \frac{4T_o}{B}\right)^{\frac{1}{2}}\right] \text{ (degrees absolute).}$$

The thermistor characteristic is expressed in parametric form:

$$(2)\quad W_T = G(T - T_o)$$

$$(3a)\quad R_T = R_o e^{B\left(\frac{1}{T} - \frac{1}{T_o}\right)}$$

or

$$(3b)\quad T = \frac{1}{\frac{1}{T_o} + \frac{1}{B}\ln\frac{R_T}{R_o}}$$

$$(4)\quad V_T = \left[GR_o(T - T_o)e^{B\left(\frac{1}{T} - \frac{1}{T_o}\right)}\right]^{\frac{1}{2}}$$

$$(5)\quad I_T = \left[\frac{G}{R_o}(T - T_o)e^{-B\left(\frac{1}{T} - \frac{1}{T_o}\right)}\right]^{\frac{1}{2}}$$

Equation 6 shows the temperature decay after cutting off the input heating current

$$(6) \quad T - T_o = \frac{W_T}{G} e^{-\frac{t}{\tau}} \quad \text{(degrees absolute)}$$

where the time constant is

$$(7) \quad \tau = \frac{C}{G} \quad \text{(seconds)} \quad .$$

From Equation 2 it can be seen that the thermal dissipation constant, G, must be small to reach the nonlinear part of the thermistor characteristics when the power input is small. According to Equation 7, for a short time constant, G should be large. Then the obvious answer of decreasing the time constant of the thermistor without large power requirements is to decrease C, the heat capacity. If the same material is to be used, the heat capacity is determined by the dimensions of the thermistor element.

It is interesting to estimate the size of a thermistor having a time constant and a thermal dissipation constant which makes it useful in a thermistor compandor. An attempt was made to use the WE 34 A thermistor was a starting point for the calculations. This called for measuring the parameters of the thermistor. Equations 1 to 7 were rearranged to allow determination of all thermistor parameters by measuring the resistances at three bias points of the thermistor while it is cooling. The procedure is shown in the appendix.

The attempt was abandoned for the following reason. Close examination of the equations shows that it is extremely hard to measure the parameters accurately. The temperature at the maximum of the thermistor characteristics is only about thirty degrees above the reference temperature of 300^o absolute. Therefore, in Equation 1 in the appendix, $\ln\frac{R_o}{R_m}$ is close to unity. Equations 2 and 3 depend on the difference between temperature T_m and T_o. Hence, a small error in resistance measurement will cause a large error in calculated parameters.

As the next best estimate of the thermistor size that would be required for use in a practical thermistor compandor, the following published data of a fast-response bead thermistor made by the Fenwal Company were used.

R_o = 2000 ohms $B = 3495 \pm 175^o$ abs

$G = 10^{-4} \frac{\text{watts}}{1^oK}$ in still air at 25^o C

τ = 1 second

Bead diameter = 0.007 inches (Approximately spherical bead)

From that the heat capacity can be calculated.

$$C = \tau G = 10^{-4} \frac{\text{joules}}{1^o} \text{ temperature rise}$$

The time constant should at least be reduced by a factor of ten, from 1 second to 100 milliseconds. If G was kept constant, the heat capacity of the fast thermistor would have to be one-tenth of 10^{-4} or 10^{-5}. This means that the volume of the required bead would have to be one-tenth of the original volume. The diameter would have to be $1/\sqrt[3]{10}$ of the original diameter, or about 0.00325 inches, and the resistivity of the semiconductor material would have to be changed also, to have the same resistance R_o.

In the time available only a limited survey of different thermistor types could be made. In the catalogues searched, no thermistor of the speed required was listed. However, this does not mean that such a thermistor does not exist since thermistors today are often designed and produced according to the consumer's specifications, and such special types are not advertised in general catalogues. Even if such a thermistor does not exist today, no doubt, the required type of thermistor can and will be designed in the future, if a large enough demand should arise.

It is now time to investigate briefly how such a thermistor may be used in a telephone carrier system.

THE THERMISTOR COMPANDOR IN A TELEPHONE CARRIER TERMINAL

Figure 25 shows a simplified circuit diagram of one carrier channel terminal equipped with a thermistor compandor. The figure has been simplified by omitting filters and amplifiers which are required for signaling purposes. The compressor is in the transmit branch of the hybrid coil. Since the compressor feeds the modulator, which has a finite input impedance, the equivalent circuit in Figure 24b must be used. This circuit provides across its terminals A'-B' at all times the same voltage to the modulator resistance $2R_1$ which would be provided across A-B by the circuit of Figure 24a. This circuit is identical with the compressor circuit of Figure 25, assuming that the transistor output impedance of Q1 is large compared to 2R.

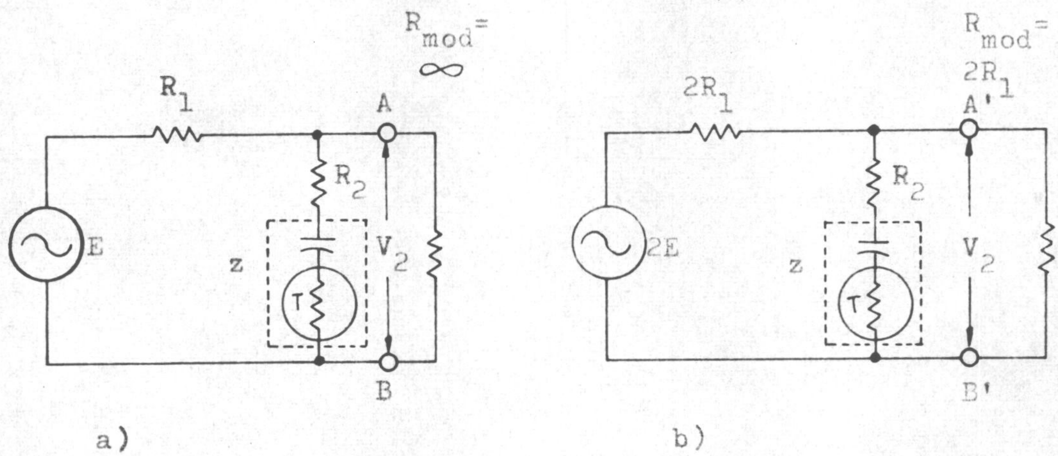


Fig. 24. a) Compressor Circuit for Infinite Load Resistance.

b) Equivalent Compressor Circuit for Finite Modulator Resistance.

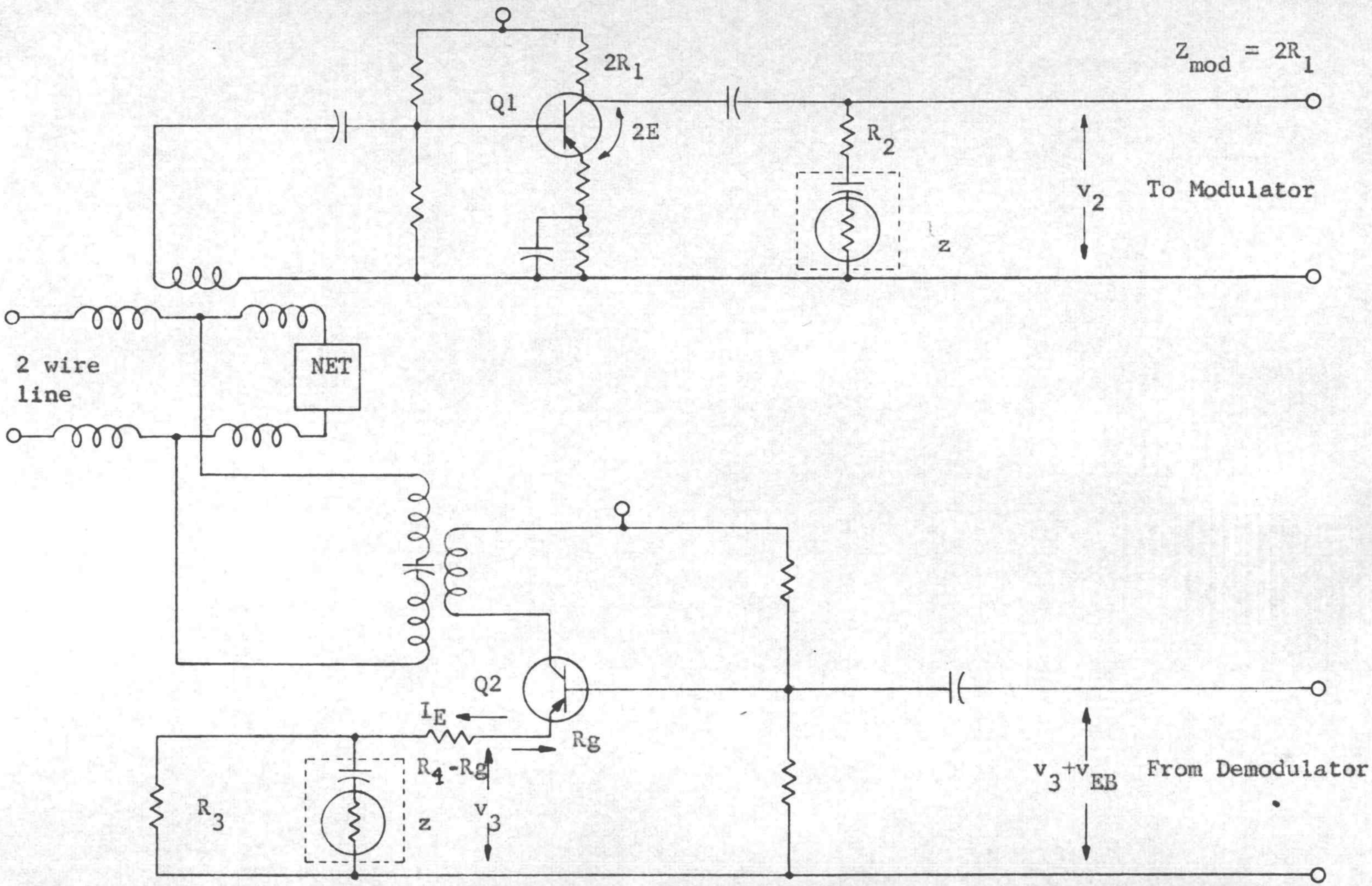


Fig. 25. Carrier Terminal of a Thermistor Compandor Circuit

The lower part of Figure 25 shows the expandor. At first glance it may not seem correct to put the complete expandor circuit into the emitter of transistor Q2. However, a short explanation will show that the double purpose of the transistor is to provide a low-impedance generator for the compandor and to provide amplification.

The impedance R_g marked in Figure 25 is approximately

$$R_g = r_e + \frac{R_b}{\beta}$$

where

r_e = emitter resistance of the transistor

R_b = impedance seen from the base of the thermistor

β = current amplification factor.

Previously, the following equation was developed.

$$(1) \quad \frac{v_4}{E} = \frac{R_2}{R_1}$$

In Figure 25

$$(2) \quad I_E = \frac{v_4}{R_4}$$

and

$$(3) \quad I_c = \alpha \, I_E.$$

Hence, Equations 2 and 3 inserted into Equation 1 become

$$(4) \quad \frac{I_c}{E} = \frac{R_2 \alpha}{R_1 R_4}$$

which shows that the collector current is not a function of z, the thermistor element. In effect, the emitter resistance changes automatically, thereby changing the amplification of the transistor which then provides proper expansion.

No complete design of a thermistor compandor terminal has been presented in the preceding pages. A detailed design of a compandor would involve consideration of transistor biasing to get sufficient overload capability without exceeding the power rating, of providing and receiving the proper power levels, and of adjusting for optimum operating range. These factors can only be considered for an actual system. They are, therefore, not covered here.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Matched thermistors having the desired characteristics can be successfully used to build limited range syllabic compandors.

Recommendations for Future Investigations

The thermal time constant of a bead thermistor can be decreased within reason to any desired value by sacrificing power sensitivity. A compandor using insensitive thermistors would require amplifiers with high output power capabilities. Such a test model should be constructed in order to make listening tests for the effect on voice transmission in the presence of, and in the absence of, interfering noise.

When the experimental model has proved that thermistors of the proper characteristics can be used successfully in a compandor, then thermistors with a thermal time constant of 50 milliseconds and maximum power sensitivity must be developed commercially.

Finally, suitable amplifiers and attenuator pads must be designed to give the overall circuit gains to fit the actual system requirements.

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APPENDIX

DETERMINATION OF THE THERMISTOR PARAMETERS

The procedure to be used in the determination of the thermistor parameters is as follows:

Step 1) Measure V_o, I_o, V_m, I_m, V_p, I_p.

Step 2) Measure room temperature To

Step 3) Calculate the d.c resistances R_o, R_m, R_p.

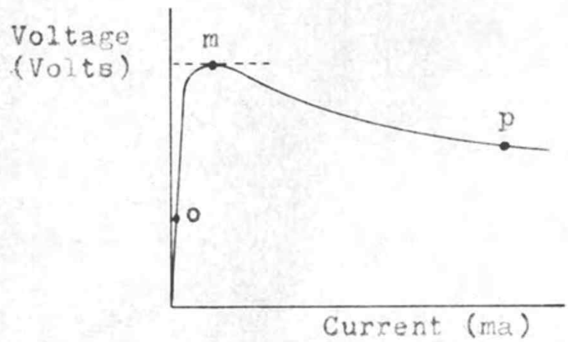


Fig. 26. Thermistor Bias Points

Step 4) Then calculate the values indicated.

(1) $T_m = T_o \ln\frac{R_o}{R_m}$ (°abs) Temperature at maximum of V-I curve

(2) $B = \frac{T_m^2}{T_m - T_o}$ (°abs) B-value of thermistor material

(3) $G = \frac{V_m I_m}{T_m - T_o}$ (watts/°abs) Thermal dissipation constant

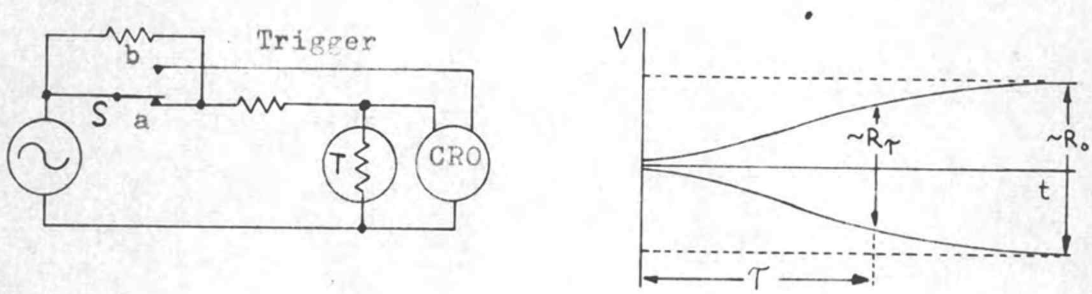
(4) $T_p = \frac{1}{\frac{1}{T_o} - \frac{1}{B}\ln\frac{R_o}{R_p}}$ (°abs) Temperature at point p

(5) $T_\tau = 0.37\ T_p - 0.63\ T_o$ (°abs) Temperature after one time constant

(6) $R_\tau = R_o e^{B(\frac{1}{T_\tau} - \frac{1}{T_o})}$ ohms   Resistance after one time constant

These equations have been derived by the writer from Equations 1 - 7 in the section entitled "Thermistor Properties Required for a Thermistor Compandor". The details of the derivation have not been included.

Step 5) Bias the following circuit to point p (Fig. 26). Switch S in Figure 27 to position b and photograph the rise of the voltage across the thermistor due to the constant small current through it. This current must be too small to heat the thermistor appreciably above the ambient temperature.



a)   b)

Fig. 27. a) Circuit for Determining the Thermistor Time Constant.

b) Oscilloscope Display for Determining the Thermistor Time Constant.

Step 6) Read the time constant τ off the oscilloscope face (See Figure 27b). Then

(7) $C = \tau G$ (joules/^{o}abs) Heat capacity of the thermistor element