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The Compandor—An Aid Against Static in Radio Telephony *

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One of the important conditions which must be met by any speech transmission system is that it should transmit properly a sufficient range of speech intensities. In long-wave radio telephony, even after the speech waves are raised to the maximum intensity before transmission, there remain energy variations such that weak syllables and important parts of strong syllables may be submerged under heavy static. The compandor is an automatic device which compresses the range of useful signal energy variations at the transmitting end and expands the range to normal at the receiving end, thus improving the speech-to-noise ratio.

This paper deals with some of the fundamental characteristics of speech waves and explains how the task of changing them for transmission over the circuit and restoring them at the receiving end is accomplished. It is also shown that raising the strength of the weaker parts of speech gives these results: 1, the successful transmission of messages for a large percentage of the time previously uncommercial; 2, a reduction of the noise impairment of transmission for moderate and heavy static during time classed commercial; and 3, the ability to deliver higher received volumes due to the improved operation of the voice controlled switching circuits. In addition to these advantages, the compandor makes it possible to economize on radio transmitter power in times of light static.

Introduction

When the original New York–London long-wave radiotelephone circuit was designed, it was recognized that radio noise would often limit transmission, especially for the weaker voice waves. Accordingly provision was made for manually adjusting the magnitude of the speech waves entering the radio transmitters to such a value as to load these transmitters to capacity.[1] While this treatment was very effective in improving the average speech-to-noise ratio and in preventing the strong peaks of speech from overloading the transmitter, it was, of course, unsuitable for following the rapidly varying amplitudes of the various speech sounds.

The total range of significant intensities applied to the circuit is in the order of 70 db, an energy ratio of 10 million to one. The manual adjustments referred to above were succesful in reducing this range to about 30 db. To further reduce this residual range an interesting

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device called the compandor has been developed. This device which works automatically makes a further reduction of one-half in the residual db range so that the range transmitted over the circuit is then only 15 db, an energy ratio of about 32 to one.

Speech Energy

Quantitative designation of speech intensity and hence of a range of intensities is rendered difficult by the rapidly varying amplitude characteristics of the various speech sounds. Devices called volume indicators are used fairly extensively to indicate the so-called "electrical volume" * of speech waves. A volume indicator is essentially a rectifier combined with a damped d-c. indicating meter on which are read in a specified manner the standard ballistic throws due to partly averaged syllables at a particular speech intensity. These devices are so designed and adjusted that they are insensitive to extremely high peak voltages of short duration, but their maximum deflection is approximately proportional to the mean power in the syllable. It has been found that, if commercial telephone instruments are used, the ear does not detect amplifier overloading of the extremely high peaks of short duration. Consequently, the volume indicator is a useful device for indicating the noticeable repeater overloading effect of a voice wave. These devices do not tell us much about the effect of the weaker voltages in overriding interference or operating voice-operated devices but they give a fairly satisfactory indication of loudness and possibilities of interference into other circuits.

The sound energy that the telephone transmits consists of complicated waves made up of tones of different pitch and amplitude. The local lines and trunks connecting the telephone to the subscribers' toll switchboard have little effect in changing the fundamental characteristics of these waves but, on account of various amounts of dissipation, the waves received at the toll switchboard are always weaker than those transmitted by the telephone. Furthermore, the strength of signals varies with the method of using the telephone, loudness of talking, battery supply, and transmitter efficiency. The subscriber may be talking over a long distance circuit from a distant city, in which case the loss of the toll line further attenuates the received waves. Figure 1 † shows that the range of outgoing speech volumes as measured by a volume indicator at the transatlantic switchboard at New York is nearly 40 db for terminal calls. When via calls and variation in volume

* The term volume will be used through the rest of this paper to designate this quantity and not as synonymous with loudness.[2]

† This curve is plotted on so-called *probability paper*, in which the scale is such that data distributed in accordance with the *normal law* will produce a straight line.

of the individual talker are taken into account, it is even greater than 40 db.

Volume Range of a Telephone Circuit

There are two limits on the range of volumes which a system can transmit. The upper limit of volume is set by the point at which

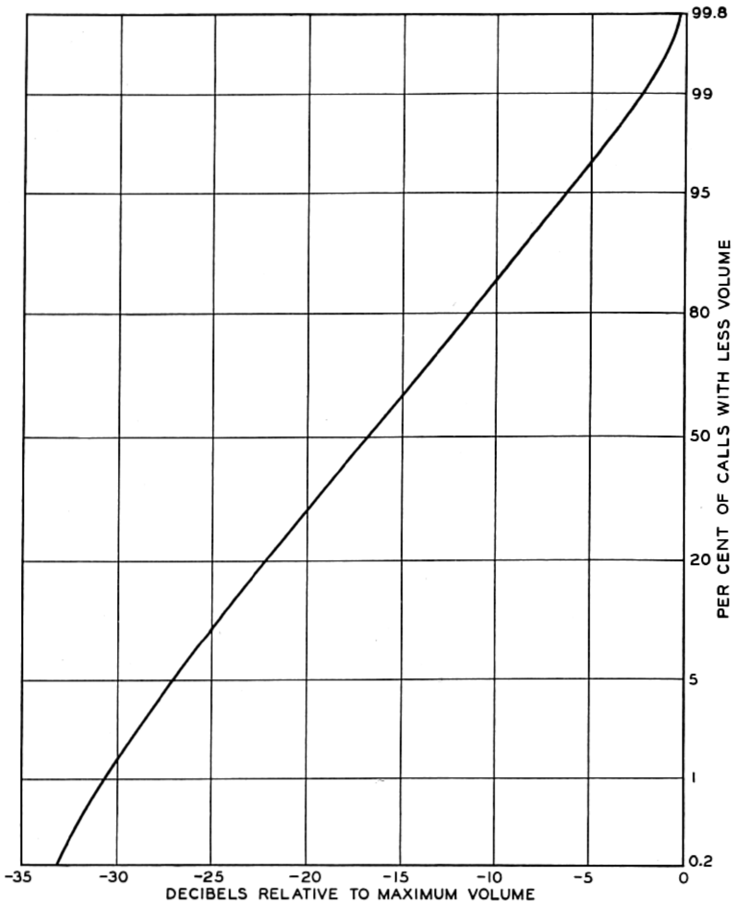

Fig. 1—Volumes of 950 local subscribers at New York transatlantic switchboard, January–April, 1931.

overloading appreciably impairs the signal quality or endangers the life of the equipment. It is an economic limit set by the cost of building equipment of greater load capacity. The lower limit of volume is set by the combination of the amount of attenuation and the amount of interference in the system such that the signal should not be appreciably masked by noise. This also is ordinarily an economic problem depending on the cost of lowering the attenuation or of guarding against external interference. In some cases, however, this limitation is a physical one. A striking case is that of radio transmission in which we have no means of controlling the attenuation of the electromagnetic waves in transit to the receiving station. They may arrive at levels below those of thermal [3, 4] noise in the antenna and other receiving apparatus. Thus, even in the absence of static there is a definite useful lower limit to the received and hence the transmitted volume. In such cases the problems raised by the spread in signal intensities become a matter of particular importance. Radio telephony was therefore one of the fields of use particularly in view for the development of the device to be described.

Effect of Volume Control

Until recently the only method in use for reducing the range of signal intensities on radio circuits was a special operating method for constant volume transmission. At each terminal the technical operator, with the aid of a volume indicator, adjusted the speech volume going to the radio transmitter to that maximum value consistent with the transmitter load capacity.

Referring to Fig. 2, we have a diagram showing the normal relation of input to output intensities of a zero loss transducer as given by the diagonal line. Points $A_{max.}$ and $A_{min.}$ on this line indicate the extreme values of signal intensities for sustained loud vowels covering a volume range of 40 db. The effect of the volume adjustments made by the technical operator is to bring all the applied volumes to a single value indicated by point B in Fig. 2. The value of B could be any convenient intensity. Here it is set at a value determined by transmission conditions in the line between the technical operator's position and the radio transmitter.

As the technical operator has reduced the strongest volumes 5 db and increased the weakest volumes 35 db, the result of this volume control is to increase the volume range which the circuit can handle by 40 db. It is possible to make this adjustment for two-way transmission in the case of radio circuits without danger of singing because of the use of voice-controlled switching arrangements [5] which permit transmission in only one direction at a time. By this method of operation volumes initially strong or weak are delivered to the distant receiving point with equal margins relative to interference and the transmission capacity of the whole system is thereby improved.

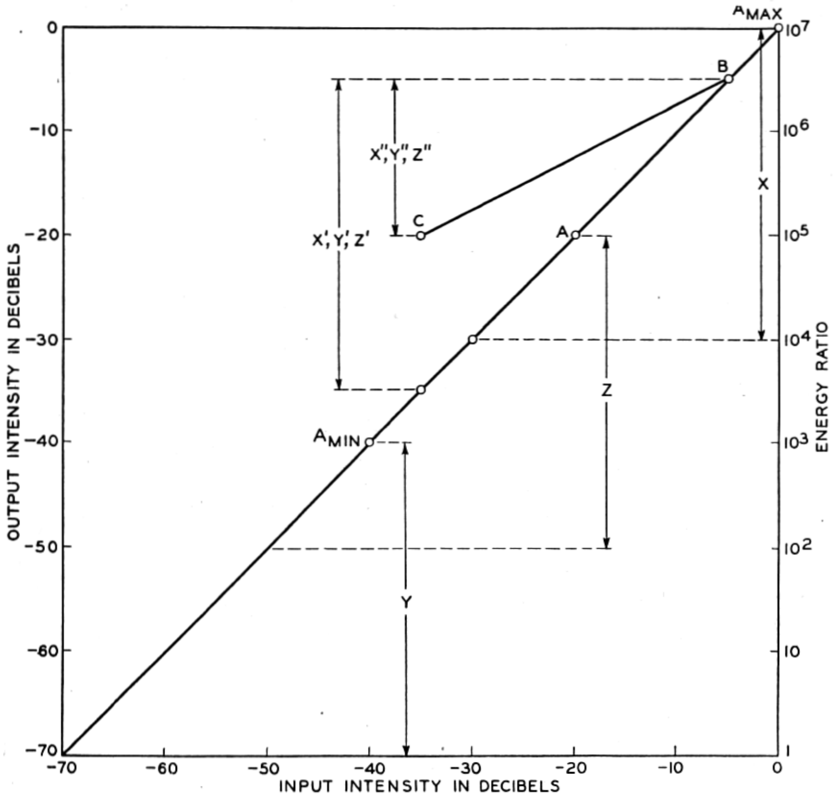

Fig. 2—Range control.

Intensity Range at Constant Volume

However, even with speech adjusted to constant volume at the transmitting point there are large variations in signal intensity from syllable to syllable and within each syllable. For example, the energy of some consonants as compared with the stronger vowels is down about 30 db. The importance of the weaker sounds is brought out by the fact that in the case of commercial telephone sets a steady noise 30 db below the energy in the strongest parts of the speech syllables produces an appreciable impairment in transmission efficiency. It is accordingly desirable to maintain transmission conditions such that generally more than this range is kept free from the masking effect of noise. This range of intensities within the syllable is also of importance in the operation of the voice-controlled switches used in the radio system. The sensitivity spread between a voice operated relay which just operates on the crests of loud syllables and one which operates sufficiently well not to clip speech is also about 30 db.

Considering on Fig. 2 that the coordinates are in terms of the average r.m.s. value over a period of time small compared with the time of a syllable, there is a spread of at least 30 db in signal intensity extending down from the maximum for each talker. Thus for the weakest talker this spread is indicated by the bracket Y and for the strongest, by X. Any other talker, as Z, falls somewhere in between. After manual control of volume this spread of intensities is represented by the bracket X', Y', Z' for all talkers. This residual spread makes desirable a means for further compressing the range of intensities in the speech signals so that the weaker parts of sound are transmitted at a higher level without at the same time raising the peak values of speech and so overloading the transmitter.

Types of Compression Systems

This problem can be approached in several ways. One, for instance, is from the frequency distortion standpoint. As many of the weaker consonants have their chief energy contribution in the upper part of the speech band, a simple equalizer which relatively increased the energy of the higher frequency consonants before transmission and another which restored the frequency energy relations after transmission should be found of value. Tests have confirmed this expectation to some degree. Unfortunately, the best type of equalizer depends upon the type of subscriber station transmitter, so that in general only a compromise improvement can be obtained.

Another general method of approach is that of amplitude distortion in which the weaker portions of the syllable are automatically increased in intensity in some inverse proportion to their original strength. The manual control of volume described above may be considered the genesis of this method. Early suggestions [6] included the use of an auxiliary channel such as a telegraph channel for duplicating the control operations in the reverse sense at the receiving end, thus restoring the original energy distribution. Another early suggestion along this line was made by George Crisson of the American Telephone and Telegraph Company.[7] If a voltage be applied to a circuit consisting of a two-element vacuum tube (with a parabolic characteristic) in series with a large resistance, the instantaneous voltages across the tube are approximately the square root of corresponding voltages applied. Thus a voltage originally 1/100 of the peak voltage can be transmitted at an intensity of 1/10 of the peak or ten times its original intensity. If the instantaneous energy is expressed on the logarithmic or db scale, the energy range is then cut in half. Such a device may be called an instantaneous compressor. At the distant end a circuit which is simply the inverse of that at the transmitting end is used. The output voltage is taken off of a low resistance in series with a parabolic element, thus restoring the signal substantially to its original form. This circuit may be called an instantaneous expandor. This scheme was successfully tested in the laboratory but unfortunately possesses a very serious limitation for practical application in the telephone plant. This is due to the fact that, to properly maintain the characteristics of the compressed signals, a transmission band width without appreciable amplitude or phase distortion of about twice the normal proved necessary.

THE COMPANDOR

The principle of the present device is the use of a rate of amplitude control for the compressing and expanding devices intermediate between manual and instantaneous control which may be considered approximately as a control varying as a function of the signal envelope.[8, 9] Such a modulation of the original signal in terms of itself does not appreciably widen the frequency band width of the modified signal as compared with the original signal. The transmitting device is called the compressor; the receiving device, the expandor; and the complete system, the compandor.

The functional behavior of a typical compressor may be considered with reference to the simplified schematic circuit No. 1 of Fig. 3.

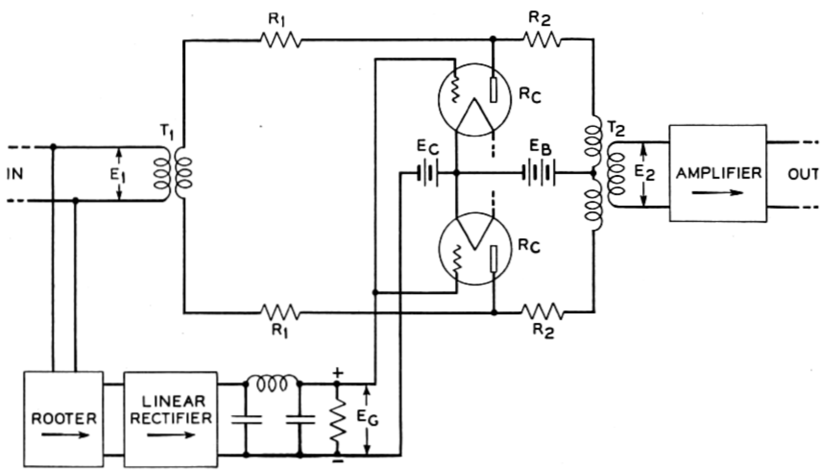

Fig. 3—Compressor circuit No. 1.

This circuit is of the forward-acting type; that is, the control energy is taken from the line ahead of the point of variable loss. The variable loss consists of a high impedance pad connected in the circuit through two high ratio transformers T_1 and T_2. The high resistances R_1 and R_2 are shunted by a pair of control tubes connected in push-pull. The push-pull arrangement is desirable for two reasons. It reduces the even order non-linear distortion effects caused by the shunt path on the transmitted speech and it balances out the control impulse and unfiltered rectified speech energy from the control path which might otherwise add distortion to the speech. The impedances of these tubes are controlled by the control voltage E_G, which is roughly proportional to the envelope of speech energy and which is derived from the line through a non-linear or "rooter" * circuit, a linear rectifier and a low-pass filter which may have a cutoff frequency in the range 20 cycles to 100 cycles. In the following analysis it is assumed that the delay due to this filtering is negligible:

Let E_1 = r.m.s. speech voltage at input

and E_2 = r.m.s. speech voltage at output in same impedance

R_C = a-c. impedance of control tubes.

Now if R_C is kept small compared to the pad impedance, we have approximately

$$E_2 = k_1 E_1 R_C. \tag{1}$$

Let E_G be the control voltage applied to the grids of the control tubes. With the plate voltage E_B just neutralized by the steady biasing grid voltage E_C, then only E_G may be considered as determining the space current and we may assume ideally that the space current

$$I_B = k_2 E_G{}^s.$$

Then

$$R_C = \frac{dE_B}{dI_B} = \mu \frac{dE_G}{dI_B} = \frac{1}{k_3 E_G{}^{s-1}}, \tag{2}$$

wheres s is determined by tube design and the ks are constants for constant μ tubes. For variable μ tubes equation (2) can be used to set requirements on the tube design.

From (1) and (2)

$$E_2 = \frac{k_1 E_1}{K_3 E_G{}^{s-1}}. \tag{3}$$

Now let the rooter be a non-linear circuit such that the instantaneous voltage is the tth root of E_1. After rectification and filtering we

* So called because the output is a root of the input; see equation (4).

shall have approximately

$$E_G = k_4 E_1^{1/t}. \tag{4}$$

From (4) and (3) we have

$$E_2 = \frac{KE_1}{E_1^{(s-1)/t}} = KE_1^{(t-s+1)/t}. \tag{5}$$

If $t = s = n$

$$E_2 = KE_1^{1/n}. \tag{6}$$

Now if the input voltage be increased by a factor x, the input increment in db will be 20 log x. The new output will be

$$E_2' = K(xE_1)^{1/n}.$$

The increment in output in db will be

$$20 \log \frac{E_2'}{E_2} = 20 \log x^{1/n} = \frac{20}{n} \log x.$$

The ratio of the output increment to the input increment in db is $1/n$ and the device is said to have a compression ratio of $1/n$. In other words, the per cent change in relative speech voltages in passing through the compressor is the same at all points in the intensity range. In the general form of this circuit, t and s need not be equal to secure a particular value of $1/n$.

In Fig. 4, Compressor Circuit No. 2 is shown, a backward-acting type of circuit. In this circuit the control tubes can be used to per-

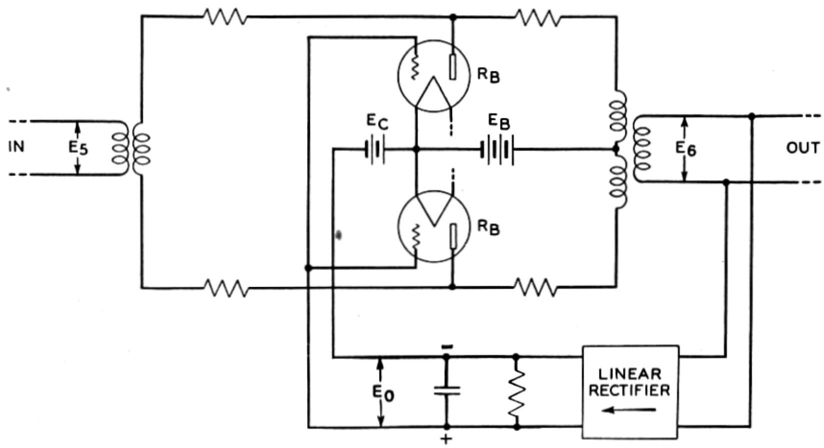

Fig. 4—Compressor circuit No. 2.

form the function of the rooter in circuit No. 1 when $s = t = n$. We may write for this circuit

$$E_6 = k_1 E_5 R_B,$$
$$E_0 = k_2 E_6,$$
$$R_B = \frac{1}{k_3 E_0^{n-1}} = \frac{1}{k_4 E_6^{n-1}},$$
$$E_6 = \frac{k_1 E_5}{k_4 E_6^{n-1}} = K E_5^{1/n}, \tag{7}$$

which is the same as equation (6) for circuit No. 1.

In Fig. 5 is shown the Expandor Circuit. If the resistances r are

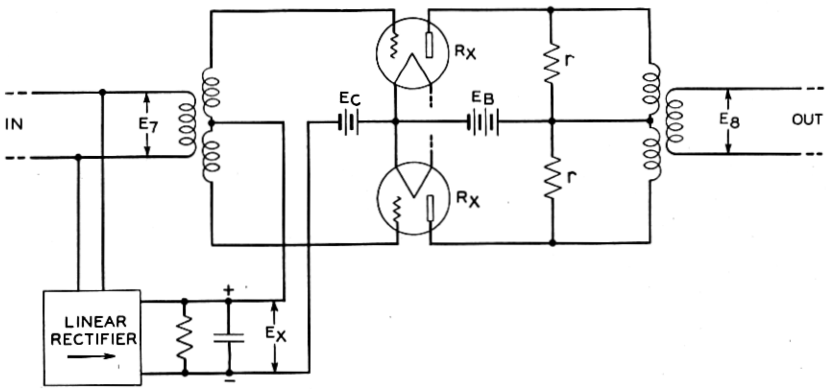

Fig. 5—Expandor circuit.

kept small compared with those of the control tubes, we may write

$$E_8 = \frac{k_1 E_7}{R_x},$$
$$E_x = k_2 E_7,$$
$$R_x = \frac{1}{k_3 E_x^{n-1}} = \frac{1}{k_4 E_7^{n-1}},$$
$$E_8 = K E_7 E_7^{n-1} = K E_7^{n}. \tag{8}$$

This relation is just the inverse of that given in equations (6) and (7). The increment ratio in db of output to input is n and the expansion ratio may be said to be n. When a compressor and expandor having the same value of n in their indices are put in tandem, the final output and input intensity ranges are the same. However, between the compressor and expandor the range of signal intensities, whose rate of change is not faster than the usual syllabic envelope, is $1/n$ in terms of db. In terms of voltage ratios the intermediate signal intensities are proportional to the square root of their original values if n equals 2, the cube root if n equals 3, etc.

The ideal relations postulated above cannot all be met in the physical design of the circuits. The indices s and t must be the dynamic characteristics of the tube and circuit and can be held to constant value only over limited ranges of operation. Equation 2 is only approximately true as some space current is permitted to flow when no speech is passing; otherwise, impractical values of control impedances would be involved. However, they do serve to illustrate the functional operation and can be approximated sufficiently well in commercial equipment for useful amounts of compression and expansion. Figure 6 shows experimental steady-state input versus output characteristics for devices built to have a compression ratio of 1/2 and an expansion ratio of 2.

The compressor is seen to operate substantially linearly over a 45 db range of inputs and the expandor over a 22.5 db range. This is about as much range as can be secured conveniently from a single stage of vacuum tubes. As such ranges would be entirely insufficient to handle the seventy odd db range at speech intensities, it is necessary to control volumes to a given point before sending through these devices, rather than compress or expand first and then control. The range is adequate, however, to take care of the range of signal intensities for commercial speech at constant volume.

Effect of Compandor

The compressor curve of Fig. 6 indicates that, when the input is 15 db above 1 milliwatt, the compressor gives no gain or loss. If the levels are adjusted so that this point corresponds to the intensity at point B on Fig. 2, then the line BC indicates the controlled intensities corresponding to the assumed 30 db spread of speech controlled to constant volume. The new range of intensities as indicated by the bracket X'' Y'' Z'' is now finally reduced to about 15 db. Tests show that a volume indicator on the output of the compressor reads from 1 to 2 db higher than on uncompressed speech at its input. Compressed speech sounds slightly unnatural but the effects of compression upon articulation in the absence of noise are negligible.

In considering the action of the expandor it is important to note that all of the improvement in signal-to-noise ratio is put in by the compressor. Considering any narrow interval of speech the insertion of the expandor does not change the signal-to-noise ratio. The desirability of using it depends on other reasons. First, it restores the naturalness of the speech sounds. Second, the apparent magnitude of the noise is greatly reduced since noise comes in at full strength only when speech is loudest and is reduced by the loss introduced by the expandor at times when the energy is low between syllables. When no speech is being transmitted, noises up to a certain limit, which

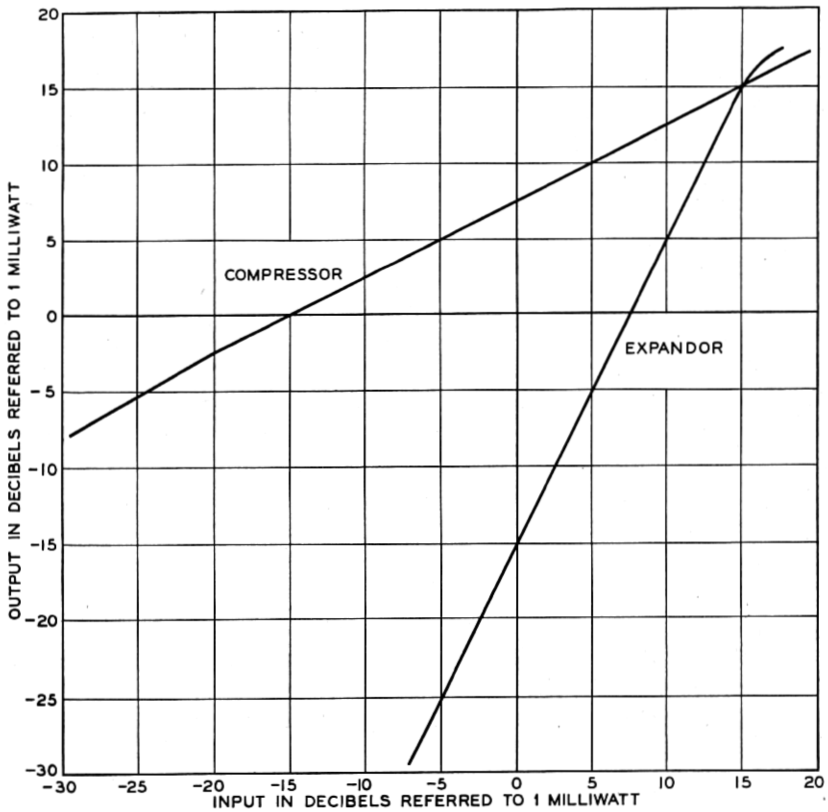

Fig. 6—Experimental input *vs.* output characteristics (1000 cycles steady state).

corresponds to the maximum energy in received speech, are reduced in varying amounts from about 20 db to zero depending on their value.

When speech is present the effect of the expandor is determined by the sum of the instantaneous speech and noise voltages, so that the effect on the noise, whether it is large or small, is determined largely by the existing speech intensity. For a circuit having somewhere near the limit of static, the use of the compandor allows on the average 5 db more noise than when it is not used. When the noise is less than this limit, somewhat greater improvements are obtained from the compandor, ranging up to at least 10 db.

The particular values of compression and expansion ratio were chosen initially for the relative ease in the design of the system with commercially available vacuum tubes whose characteristics closely approximated a parabola. Tests of the equipment have shown that this degree is sufficient for present telephone circuit intensity range requirements. Increasing the amount of compression is limited by increase in quality distortion and by increased variation in the intensity of radio noise as heard by the listener. A noise which is constant at the input to the expandor varies on the output as the speech intensity changes. Also variations in attenuation equivalent between the compandor terminals are multiplied by the expandor. Herein lies a reason for having a constant compression and expansion ratio over the working range. If it were different at different intensities, attenuation changes would distort the reproduced speech as well as appearing as a somewhat increased change in intensity. This change in intensity is n times the attenuation change in front of the expandor in db.

The degree of compression may obviously be controlled in a variety of ways: such as, using different values for the indices s and t, applying control voltages upon more than one variable stage in tandem, the use of variable μ vacuum tubes, etc. The circuits as shown use variable shunt control for the compressor and variable series control for the expandor. Either or both may be changed to the other by inverting the polarity of the control potential and properly designing the rectifier characteristics of the control circuits.

There are two major sources of possible speech distortion which must be considered in the design and use of these devices in addition to those ordinarily present. The first is due to the non-linear characteristics of the vacuum tubes used for controlling. The even order distortion terms are largely balanced out by using two tubes in a push-pull arrangement. The remaining distortion is minimized by having speech pass through the control tubes at a sufficiently low level. In the operating ranges for the device shown on Fig. 6, the harmonics of a single-frequency tone are 30 db or more below the fundamental.

The second major source of distortion is the time lag in the control circuits due to the presence of the filters after the linear rectifier. However, with a complete compandor circuit using the compressor circuit No. 1, it was found on careful laboratory tests with expert listeners that it was almost impossible to distinguish whether the device was in or out of circuit. Furthermore, distortion of this type is largely eliminated when compressor circuit No. 2 is used. In that case it will be noted that, if the two terminals are connected by a substantially distortionless transmission system, the identical control circuits of the two devices receive identical operating voltages. As the gain changes put in are reciprocal and occur now with equal time lag, the deviations from ideal compression are virtually counterbalanced by the inverse deviations from ideal expandor action. In Fig. 7 are shown

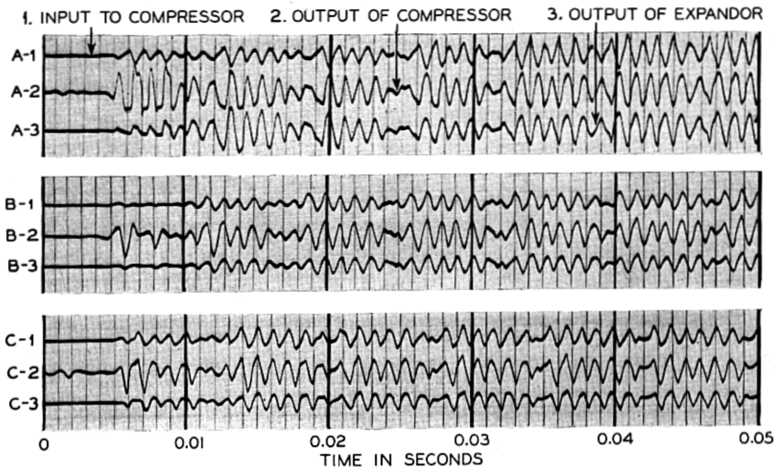

Fig. 7—Operation of compandor on beginning of word "bark." *A*. Compressor circuit No. 1. *B*. Compressor circuit No. 2 with low-pass filter in control circuit. *C*. Compressor circuit No. 2 without filter.

oscillograms taken of the first part of the word "bark." Each record shows the intensity changes before the compressor, between the compressor and expandor and on the output of the expandor.

Application to Transatlantic Circuit

A compandor system has been in service on the New York–London long-wave radiotelephone circuit since about July 1, 1932. At first compressor circuit No. 1 was used, and later a change was made to compressor circuit No. 2. Figure 8 is a photograph of the experimental installation at New York. It occupies about five feet of standard relay rack space. The blank panel shown in the photograph indicates the saving of apparatus resulting from the change to compressor circuit No. 2. Figure 9 is a schematic diagram showing the method of inserting the compressor and expandor in the radio telephone terminals at each end of the circuit. Since the two ends are similar, only one end is shown. The compandor circuits are indicated in their relation to the subscriber, the toll switchboard, the vodas and privacy apparatus, and the radio transmitter and receiver.[5] A meter located at the point designated *A* would indicate the full range of applied volumes, at *B*, the controlled volumes and at *C*, the compressed speech signals.

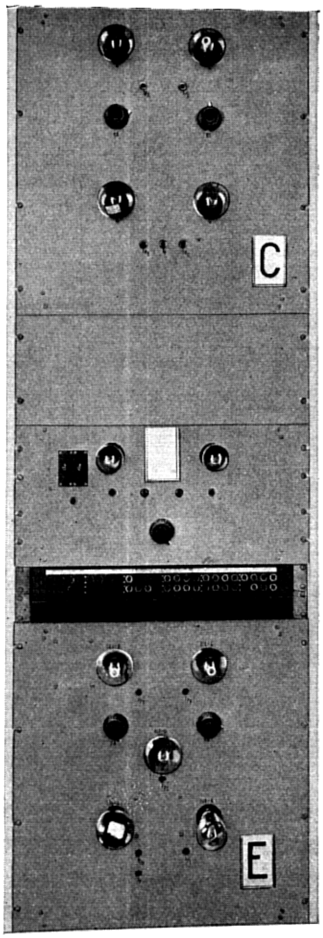

Fig. 8—Experimental installation of compandor at New York.

When the United States subscriber talks, electrical waves set up by his voice pass over a wire line to the toll switchboard. They then divide in a hybrid set; part of the energy is dissipated in the output of a receiving repeater and part is amplified by a transmitting repeater whose gain is controlled by noting the reading of a volume indicator at

B and adjusting a potentiometer ahead of the transmitting repeater. The waves then act on the vodas which consists of amplifier-detector, delay circuit and relays for switching the transmission paths in such a manner as to prevent echoes, singing and other effects. When in the transmitting condition, the vodas is arranged to have zero loss so that the waves impressed on the compressor are practically the same as at *B*. The waves put out from the compressor are then sent through the privacy apparatus, the output of which is then sent over a wire line to the radio transmitter. The radiated waves are picked up by the distant radio receiver, amplified and transformed into voice-frequency energy which passes over a wire line to the terminal at the distant end.

The path of received waves in either terminal may be traced in the lower branch of the circuit shown on Fig. 9. After being made intel-

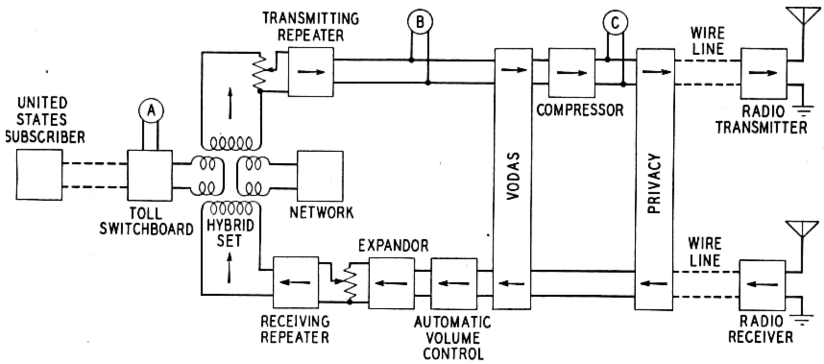

Fig. 9—Compandor applied to one end of a radio telephone circuit.

ligible by passing through the receiving privacy device, the compressed incoming waves are sent through the vodas into an automatic volume control and then into the expandor. The expanded waves are sent through a receiving repeater from whose output the amplified waves pass into the hybrid set, part being dissipated in the network and the other part going through the toll switchboard to the subscriber. Due to imperfect balance between the subscriber's line and the network, a portion of the received energy is transmitted across the hybrid set and amplified by the transmitting repeater. This echo might operate the transmitting vodas under certain conditions. For this reason a potentiometer is inserted in the receiving branch of the circuit so as to reduce the echo, and consequently the received volume, so that false operation of the transmitting vodas is prevented.

Results of Compandor Operation

The effectiveness of the compandor in service depends not only on its ability to reduce noise but also on its relation to the other characteristics of the circuit. Tests in the laboratory and on the long-wave transatlantic circuit have indicated that the presence of the compandor does not affect the quality appreciably, provided compressor circuit No. 2 is employed and provided the compression in the circuit itself is not serious. Delay distortion can be tolerated up to about the same amount as when no compandor is used. Frequency changing for privacy purposes is not materially affected by the compandor.

The expandor increases the transmission variations in the circuit exactly as it increases the voltage range of the waves applied to it. It is therefore necessary to guard against excessive variations in the overall circuit including the wire line extensions as well as the radio links. At the New York terminal there has been installed an automatic volume control operated from received speech signals which performs this function.

The received volume is limited by incoming waves which do not operate the receiving side of the vodas but which return as echoes from the land line to cause false operation of the transmitting side. The compressor increases these weak waves so that they are better able to operate the receiving side of the vodas, and the expandor effectively increases the stronger waves relative to the weak. This results in more received volume being delivered to the two-wire terminal than when the compandor is not used. The overall improvement in volume delivered to the subscriber varies with the noise, being greatest when the noise is low.

Summary

The allowable increase of about 5 db in noise before reaching the commercial limit increases the time when the circuit can be used for service. The increased circuit time is greatest in the seasons of the year when it is needed the most.

For conditions of moderate disturbances now classed as commercial, a reduction of the noise transmission impairment to very low values is accomplished by the compandor.

The improvement in the vodas operation results in delivering substantially higher volumes to the subscribers.

The beneficial effect of the compandor might alternately be applied to a reduction of transmitter power.

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