Devices for Controlling Amplitude Characteristics of Telephonic Signals *

By A. C. NORWINE

This paper describes a family of devices which automatically respond to signals and control the circuit amplification in such a way as to improve transmission. Their general characteristics are outlined, their differences explained, and some of their applications are listed.

Introduction

THE transmission of speech energy over electrical circuits is attended by the interesting and sometimes difficult problem of preserving the original signal in spite of limitations in the transmission medium. These limitations include load carrying capacity, interference with other service, noise, change in attenuation with time and many others. Because of special limitations it is sometimes desirable to alter the amplitude characteristics of the speech or other signal energy without, of course, materially lowering its intelligibility. In high quality systems the peak voltage from some speech sounds of a given talker may be over 30 db (some 30 times) higher than from his weakest sounds when there is very little inflection in the speech. Loudness changes for emphasis will increase this range of intensities. Ordinary message systems do not have to contend with quite so wide a range of instantaneous voltages from a single talker, but different talkers under extreme terminal conditions produce about a 45 db range of average voltage, which is additive to that for a single talker. Consequently, a voltage range of about 70 db (over 3000 to 1) must be considered for message circuits.

In order to accommodate such ranges of intensity to certain transmission media such as radio links a new family of automatic devices has been developed. In general all of these contain amplifiers or attenuating networks whose loss or gain is changed according to some function of the applied input and which may have a variety of time sequences in their control circuits. It is hoped that by the classification and description of some of these devices their distinguishing characteristics and fields of usefulness will be made somewhat clearer.

* Presented at the Pacific Coast Convention of A. I. E. E. and I. R. E. in Portland, Oregon, August 9–12, 1938.

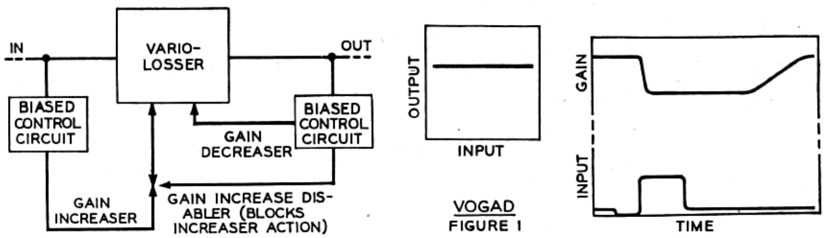
We are to be concerned here principally with those elements allied to the telephonic art, although some applications are to be found in other fields. It is not intended to include those voice operated functions which are essentially switching operations although the distinction in some cases becomes exceedingly fine.

Names of volume controlled devices * which have been used in published papers include vogad,†, [2, 3, 4] compandor,‡, [5, 6] and volume limiter.[7] Without direct comparison it may not be obvious how these and similar devices differ. First the apparent similarity of several of these devices will be shown in simple diagrams. Next the more important characteristics of a number of devices will be presented in tabular form, followed by descriptions of the different types. These will then be discussed with particular emphasis on their distinctive qualities, with notes on their variants which have some apparent value.

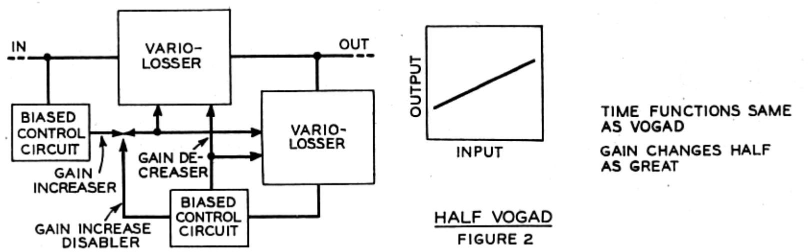
General Characteristics of Volume Controlled Devices

In Figs. 1 to 10 are shown simplified diagrams of some of these devices. While detailed descriptions of them will be deferred till later it may be pointed out that all those shown contain vario-lossers, and all have paths from the main transmission path to control circuits which affect the vario-lossers. A vario-losser usually consists of a balanced pair of vacuum tubes whose gain is changed by varying the grid bias, or of a network of non-linear elements such as copper oxide or silicon carbide whose loss is changed by varying a current through them. In some special cases it may be a mechanically adjusted variable network. The word vario-losser is thus a generic term relating to a circuit whose loss or gain is controllable. A control circuit ordinarily consists of an amplifier and rectifier whose direct current or alternating current output bears a chosen relation to its input. Thus some control circuits are marginal; they produce no control voltage till the input exceeds some critical value, then produce large control voltages for small additional increments of input. These are used, for example, when it is desired to limit the output of a vario-losser to a definite amount. Another type of control circuit produces a current or voltage which is linear with input expressed in decibels. In combination with a vario-losser whose gain is a linear function of control current or voltage one can produce a device whose gain is a linear function in decibels of the input to the control circuit.

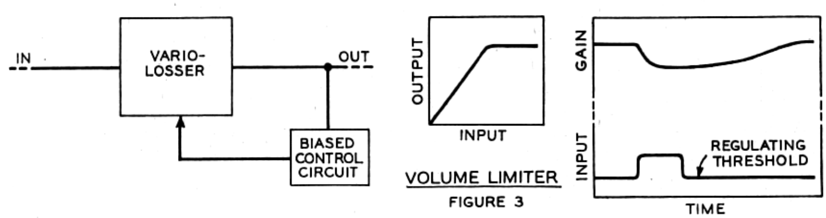
* See the footnote on page 543.
† "*V*olume *O*perated *G*ain *A*djusting *D*evice."
‡ A combination of the names "*Com*pressor" and "Ex*pandor*."



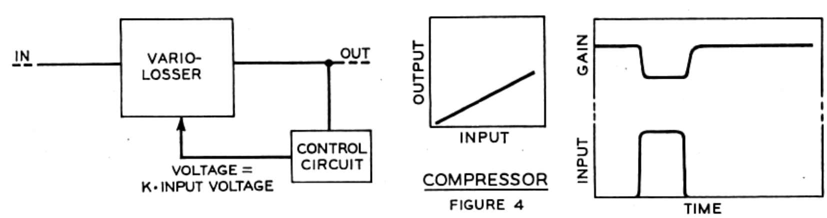
VOGAD
FIGURE 1



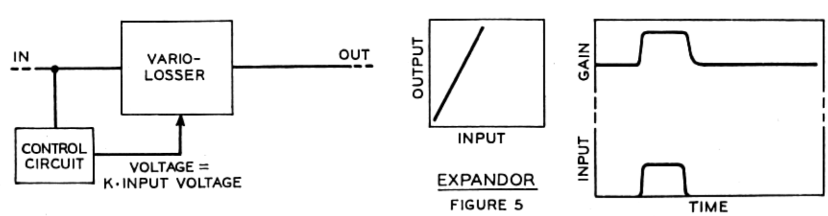
HALF VOGAD
FIGURE 2



VOLUME LIMITER
FIGURE 3



COMPRESSOR
FIGURE 4



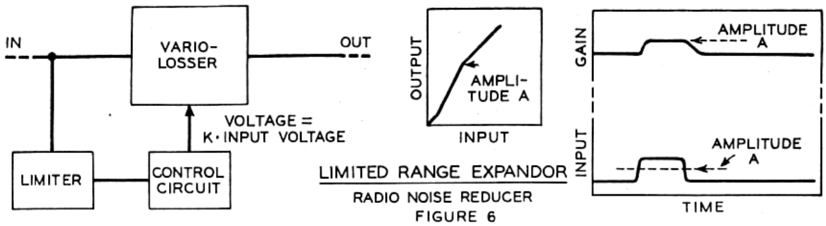
EXPANDOR
FIGURE 5

It will be recognized that if the application or removal of the control energy is retarded, the action of the control circuit may be made quite different on transient inputs than on steady state inputs. It will appear later that this is the important distinction between some of the devices to be discussed and that fundamental differences in their functioning are thus brought about.

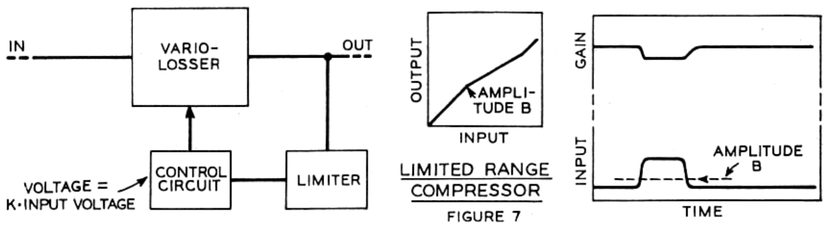
Referring to the figures once more it will be noted that some control devices are connected to the transmission path at the input to the vario-losser. These are known as "forward acting" control circuits. Other controls, connected at the vario-losser outputs, are known as "backward acting" control circuits. This is simply convenient terminology to indicate whether the control energy is progressing in the same direction as the main transmission or is progressing in a backward direction after traversing the main path, usually through a vario-losser. Some backward acting controls function to measure the output of the devices containing them and to make whatever adjustments are required. Others are placed in that position to take advantage of the vario-lossers in the transmission paths, i.e., such controls could be replaced by combinations of forward acting controls and extra vario-lossers.

In Table I, nine of the volume controlled devices * which have been developed for various commercial and experimental uses are listed with the functions of voltage, time, and frequency which are employed to obtain their respective performances. There is, of course, some latitude in the choice of these functions for any one device. Pending more complete description of the different types in the following paragraphs this table should be viewed as illustrating the general character of the different circuits and also the range of the variables which already have been employed. For example, it will be seen that instantaneous voltage of the signal wave, its short time average value, peak power, syllabic variations, and long time average power have all been used as criteria of gain settings in different circuits. Some devices change their adjustments only when critical values or ranges are exceeded, while others vary somewhat with every syllable if speech, for example, is being transmitted. Some are linear transducers to all but low or high amplitudes while others reduce or increase the output range from that at the input. It will be seen that proper choices of times for gain increase and gain decrease in combination

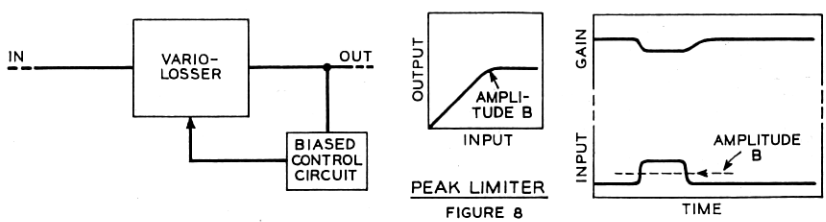
* The names employed do not follow an entirely logical classification, but they are given here because they have had considerable usage. For the same reason the term *volume controlled devices* is used, although to be strictly correct it might better be *sound energy controlled devices*, for example, for not all the devices operate in accordance with *volume* as measured by the well-known class of visual reading meters called *volume indicators*.



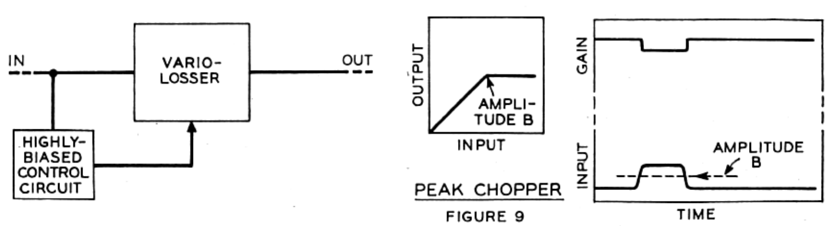
LIMITED RANGE EXPANDOR
RADIO NOISE REDUCER
FIGURE 6



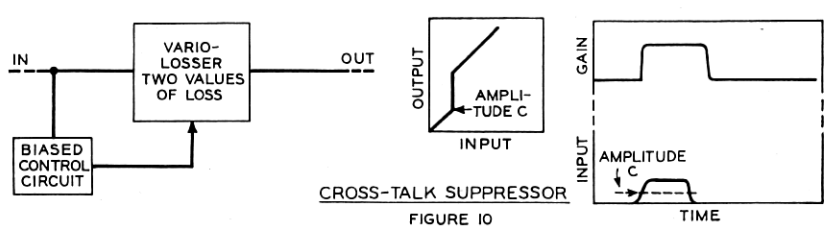
LIMITED RANGE COMPRESSOR
FIGURE 7



PEAK LIMITER
FIGURE 8



PEAK CHOPPER
FIGURE 9



CROSS-TALK SUPPRESSOR
FIGURE 10

TABLE I

CHARACTERISTICS OF VOLUME CONTROLLED DEVICES

Device	Gain Controlled by	Frequency of Adjustment	Time Required for Gain Changes		Ratio of Output Range to Input Range†	Position of Controls	Volume Range Controlled*	Frequency Range Controlled	Frequency Range Causing Control	Part of Input Range Causing Operation
			Gain Increase	Gain Reduction						
1. Vogad	Average volume	Infrequent. Gain fixed between trans-missions	After a few words—sometimes 8 to 10 words	After one or more words	Approx. 0	At input and output	Large	Full band trans-mitted	Full band	All
2. Volume Limiter	Average volume over part of input range	Relatively infrequent. Approaches max. gain in silent periods	Slow and continuous	After one or more words	1 up to operate point. 0 above	At output	Moderate	Full band	Full band	High amplitude only
3. Compandor *a.* Compressor *b.* Expandor	Syllabic variations	Continuous at syllabic rate	On each syllable	On each syllable	1/2 to 1/5 5 to 2	Compressor output expandor, input	Large	Full band	Full band	All
c. Special Compandor	do	do	do	do	do	ditto or expandor control over separate channel	do	High frequency only or multiband	High frequency only or multiband	All or high amplitude only
4. Radio Noise Reducer (Limited Range Expandor)	Syllabic variations over part of input range	Each syllable	On each syllable	On each syllable	2 for low ampli-tudes. 1 for high	At input	Moderate	Full band	Full band	Variable at low ampli-tudes only. Fixed gain to high amplitudes

TABLE I (*Continued*)

Device	Gain Controlled by	Frequency of Adjustment	Time Required for Gain Changes		Ratio of Output Range to Input Range†	Position of Controls	Volume Range Controlled*	Frequency Range Controlled	Frequency Range Causing Control	Part of Input Range Causing Operation
			Gain Increase	Gain Reduction						
5. Limited Range Compressor	Syllabic variations over part of input range	Each syllable within the operating range	Fast	Fast	1 up to operate point, then 0 to 1/2, then 1	At input or output	Small	Full band	Full band	High or intermediate amplitudes
6. Peak Limiter	Syllabic peaks	Infrequent	After about one word	On single syllable	1 up to operate point, then approaches 0	At output	Small	Full band	Full band	High amplitude only
7. Peak Chopper	Instantaneous peak voltage	Relatively infrequent	Instantaneous	Insta ntaneous	1 up to operate point, then 0	At input	Very small	Full band	Full band	High amplitude
8. Crosstalk Suppressor	Voltage exceeding a specified value low in input range	Relatively frequent	Fast	After one or two words	1 except at point of discontinuity	At input	Very small	Full band	Full band	All above specified low value
9. Rooter and Inverse Rooter	Instantaneous voltage	Continuous	Instantaneous	Instantaneous	Ordinarily 1/2 and 2	Integral with vario-losser	Moderate	Full band	Full band	All

* Outside these ranges most of the devices tend to be linear transducers except for higher volumes applied to "Limiters."

† It is important to note that these ranges are measured in the same units as the respective control circuits measure: viz., "volume," "syllabic power," "voltage," etc.

with certain gain control criteria make possible a wide variety of signal altering means to meet different requirements.

Description of Devices in Table I

With this introduction to the combinations of characteristics which are possible it should be less difficult to distinguish between the specific devices discussed in the following paragraphs, which, in addition to describing the devices, contain some comments which should assist in visualizing their forms and their operation.

1. The *vogad* (Fig. 1) is a device which will maintain at its output speech volume [1] which, over a certain range of input, is relatively independent of the speech volume applied to its input and which, in the ideal case, will not change its gain during periods of no speech input. It makes little or no alteration in the ratios of maximum and minimum instantaneous to average voltages of the speech.

2. The *volume limiter* (Fig. 3) is a device which is a linear transducer for all speech volumes up to a critical value, beyond which all input volumes produce essentially the same output volume. It is essentially different from the vogad in that its gain approaches the maximum value when input is removed.

3. The *compandor* (Figs. 4 and 5) is composed of a *compressor* and an *expandor*. A *compressor* is a device whose input-output characteristic on a decibel scale has a slope less than unity * and whose gain or loss is variable under control of the input energy at a time rate which will permit it to follow the syllabic rate of change of speech energy. Similarly, an *expandor* is a device whose input-output curve has a slope greater than unity and whose gain is variable at a syllabic rate under control of the input energy. Thus very shortly after all input is removed the gain of a compressor is maximum and the loss of an expandor is maximum. The reciprocal of the compressor characteristic slope is spoken of as the compression ratio, and the slope of the expandor characteristic is spoken of as the expansion ratio.

4. The *radio noise reducer* [8, 9] (Fig. 6) combines the functions of an expandor which operates in the range of amplitudes where noise and weaker speech sounds lie and a linear transducer which comes into play for all amplitudes exceeding a critical value, which can be set to best suit the atmospheric noise conditions. In other words, the radio noise reducer is a limited range expandor. Inputs which are below the expandor range are subject to transmission at the minimum gain.

5. The *limited range compressor* (Fig. 7) is a device whose operating

* That is, if the input increases by x db the output increases by less than x db.

range includes a region within which compression at a syllabic rate can take place; at other inputs the device is a linear transducer. Its connecting diagram and time functions are the same as those shown in Fig. 5 except that the control circuit contains a limiting device, so that compression takes place in only a portion of its input range, analogous to the action of the limited range expandor of Fig. 6. As a special case the *limited range compressor* may have no linear range above its compression range, thus becoming one type of peak limiter.

6. The *peak limiter* (Fig. 8) is a device whose gain will be quickly reduced and slowly restored when the instantaneous peak power of the input exceeds a predetermined value. The amount of gain reduction is a function of the peak amplitude, and in practice is usually intended to be small to prevent material reduction of the range of intensity of the signal.

7. The *peak chopper* (Fig. 9) is a device which prevents transmission of peak amplitudes exceeding a critical amount, an essential characteristic being that the loss it inserts is completely determined by the instantaneous voltage of the signal. That is, its operating and releasing times are substantially equal to zero.

8. The *crosstalk suppressor* (Fig. 10) is a device which normally presents a prescribed loss to transmission, which loss is removed rapidly when the input amplitude exceeds a certain threshold and is reinserted at a definite time after the input is removed. It reduces low amplitude unwanted currents such as crosstalk but does not affect amplitudes in the useful signal voltage range. This device differs from the limited range expandor in that the time during which the low loss condition is maintained is considerably greater, so the transition from one gain to the other occurs less frequently.

9. A *rooter* is an instantaneous compressor. Such a circuit can be made to produce an output whose instantaneous voltage is, for example, the square root or some similar function of the instantaneous voltage applied to the input. An *inverse rooter* is an instantaneous expandor whose characteristic is complementary to that of the rooter. A combination of *rooter* and *inverse rooter* will reduce the load requirements on a transmission system between the two units but requires that it transmit a wider band of frequencies than that for the original signal, and that it be essentially free from phase distortion. This does not seem to be an attractive arrangement from a commercial viewpoint and is included here simply as an illustration of one of the possible modifications of signal energy. It is not shown in the group of diagrams.

Variants to the Devices Described

In addition to these there are various devices which are essentially modifications of those described. For example, a half-vogad, Fig. 2, may have the same time functions as a vogad, Fig. 1, but the gain changes in the transmission circuit are half as great for the same range of input volumes. Thus in a vogad the range of gain changes in the transmission circuit is equal to the range of input volumes, so that the output volume is the same for all input volumes. In the case of the half vogad the range of gain changes in the transmission path is one-half the range of input volumes, so the output volume range is one-half that of the input. It is also possible to construct a vogad whose output volume range is any desired fraction of the input range. As another example of modification of the devices described, for special applications it may be desirable to incorporate a certain amount of syllabic compression in a vogad.

Communication circuits which have separate paths for oppositely directed transmission between the two terminals are usually operated at such an overall loss that with ordinary terminations there will be little tendency for circulating currents to build up to a "singing" condition. Sometimes there may not be a great deal of margin, however, so that volume controlled devices added to such circuits must add loss at some point to counterbalance whatever gain is put in at some other point. Thus a vogad inserted at the transmitting side of one terminal of such a circuit to amplify speech energy from weak talkers must be supplemented by a "reverse vogad" in the receiving side of the circuit. The reverse vogad is simply another vario-losser which is operated upon by the vogad control circuit in such a way that it always has a loss numerically equal to the gain of the vogad. Any vogad gain will be compensated by the reverse vogad loss, so no greater tendency to sing will be effected by the addition of the combination to the circuit. In like manner half vogads must be used with compensating reverse half vogads.

Combinations of some of the devices also have interesting characteristics. For example, a combined radio noise reducer and peak limiter at the receiving end of a circuit would suppress noise and would also reduce the amplitude of excessively high amplitude signals. Likewise, a vogad, compressor, and peak chopper in tandem in the order named could be made to reduce the range of input signals by a very large amount for transmission over a medium having only a small range between noise and maximum permissible signal. In this case it would be practically impossible to recover the original signal range at the receiving terminal of the medium, but the intelligibility of speech over such a system has been shown in the laboratory to be good.

Special compandors for high quality service may require compression and expansion which vary with frequency. The exact characteristics will depend upon band width, program material and transmission medium. For transmission media in which the noise reproduced at the receiving end is principally at the higher frequencies an unusual effect is obtained if the usual variety of compandor is used. Low frequencies unaccompanied by high frequencies will cause a gain change in compressor and expandor, thus changing the background of high-frequency noise which is not masked by the low-frequency signal energy. The resulting swishing noise has been given the onomatopœic name of "hush-hush effect." To avoid this, recourse may be had to split band compandors in which the compression and expansion is done only at high frequencies or separately for low and high frequencies. The successful application of the latter method is, however, more difficult than it appears from its simple description.

Distinguishing Characteristics

It is important to distinguish between the half vogad, Fig. 2, and the compressor, Fig. 4. As shown in Table I the latter operates on syllabic variations and the former on the average volume of the input. Thus the half vogad reduces the range of output volumes to one-half that at the input while the compressor reduces the range of syllabic power at its output to one-half that at the input. In other words, the compressor reduces the ratio of peak to average power on constant volume speech, while the half-vogad simply adjusts for that volume and does not alter the peak ratio. There is, of course, the additional important difference that the half-vogad retains its gain setting during silent periods while the compressor, by virtue of having followed the syllabic power, has its maximum gain during silent periods.

Volume limiters, Fig. 3, may be mistaken for vogads, Fig. 1, because during speech input above a certain value the two may produce the same output volume. They both employ something like a measurement of average power over periods longer than a syllable to determine their gain settings. The important difference is that a vogad retains its gain setting when speech currents are not present, while a volume limiter approaches its maximum gain during such periods. In terms of the output resulting from a range of input volumes there is another important difference if the volume limiter operates over only part of the input range: the vogad reduces the width of the distribution curve of volumes to a very small value, while the volume limiter moves all the area under the distribution curve above a certain point to the region near that point, which is its limiting volume. This is illustrated in Fig. 11, in which the calculated modifications of a volume distribution by a vogad and by a volume limiter are shown. In the cases "without volume control" and "with a vogad" the distributions are normal, and the standard deviation, σ, has its usual statistical significance. With a volume limiter, only volumes above the limiting volume are affected,

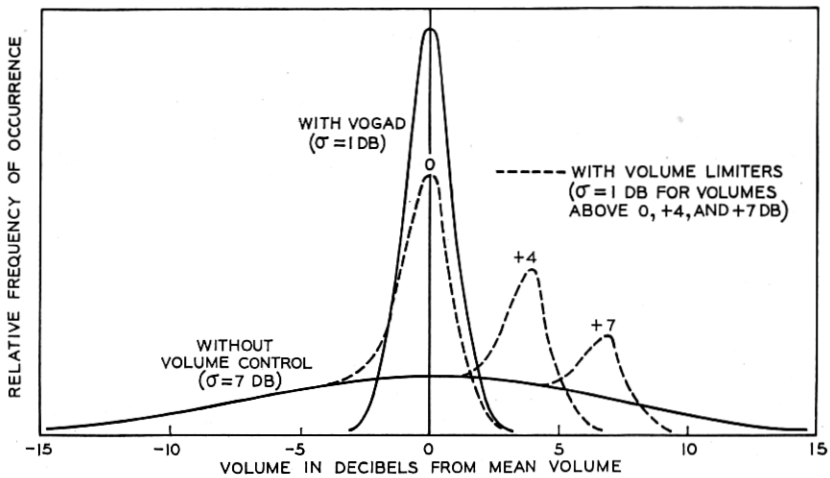


Fig. 11—Modification of volume distribution by use of a vogad or a volume limiter.

and these higher volumes are redistributed according to a normal law whose standard deviation is 1 decibel, as stated in the figure.

It is also important to distinguish between a peak limiter and a peak chopper, Figs. 8 and 9. Naturally they resemble one another since they are intended to permit transmission of signals at higher average amplitudes without excessive loading of transmission circuits. However, they are intended for different classes of service and hence are not interchangeable except in some borderline cases. For the highest grade of transmission harmonic production must be negligible and the reduction in amplitude range of signals small and infrequent. Gain changes must be smooth, though rapid enough to compensate for practically any input wave to be expected. These characteristics are found in the peak limiter now being furnished for use on program networks and radio transmitters.[10, 11] For services in which it is desirable to maintain the signal energy at a high value to over-ride noise and in which harmonic distortion must be kept low a peak limiter with somewhat smaller time constants may be used. A high ratio limited range compressor might be suitable in this instance. This device would lower its gain a little more quickly on excessive inputs, and it would also reinsert its gain much more quickly; it would affect the naturalness of the sound of the signal more than the slower peak limiter but it would also cause the signal to over-ride noise somewhat better. In a third variety of service the harmonic distortion introduced by a limiter is a secondary matter, the prime consideration being that the peak amplitude of the signal shall not exceed a specified value. This may be because higher amplitude signals would produce a tremendous increase in distortion or crosstalk into other channels or would damage expensive equipment farther along in the circuit. For these cases we may use the fastest possible type of limiter, the peak chopper, which simply cuts off any peak exceeding a certain value.

The crosstalk suppressor, Fig. 10, is a splendid example of the fine distinction between volume controlled and voice operated switching devices. This device has been described, but in the present state of the art its time functions have not been definitely fixed. If the characteristic of loss versus input is made steep enough and the speed of operation fast enough it will sound like a switching circuit and may in fact be replaced by a relay-switched attenuating network. If made somewhat slower and given a smaller slope of loss versus input it approaches the limited range expandor or noise reducer.

Applications and Expected Advantages

It may be of interest to give some approximate figures on the magnitudes of the advantages to be obtained by the use of some of these devices. It will be understood that the values to be given are simply illustrative, some having been obtained from field service on particular models and some from tests on laboratory equipment under special conditions.

Vogads appear to be most useful in such circuits as transoceanic radio connections, where it is important to properly operate the terminal switching equipment and to transmit over the radio circuit speech energy from loud and weak talkers equally well. It is essential in such cases that noise should not be increased in amplitude during speech pauses, hence the gain retaining feature of the vogad. On such a circuit a vogad will reduce a 45 db volume range to about 2 to 4 db. This is equivalent to expert manual volume control.

Volume limiters are in use at the present time to prevent peaks of speech energy in carrier circuits from "splashing" into telegraph channels.[7] Some 5 to 10 db limiting is allowed on loudest talkers, which causes little degradation of the speech channels but makes possible the use of telegraph on the same carrier system. There is no wide-spread use of volume limiters in point-to-point radio service so far, but in cases in which there is no disadvantage in raising noise in silent periods in speech, such as in push-to-talk installations, proper transmitter loading can be obtained with volume limiters fairly cheaply.

One commercial model peak limiter, used as part of a program amplifier [10, 11] is capable of introducing a considerable amount of compression without overloading on peaks, but for the preservation of adequate program volume range it is being recommended that only 3 db peak limiting be allowed. This, of course, reduces the range of intensity of the program, but from the standpoint of the listeners it is equivalent to doubling the transmitted power or obtaining the same signal-to-noise ratio with half the transmitted power.

Limited range compressors might be used either on land lines to insure full loading or on radio links whose fading is too severe to permit the use of normal compandors. There is no commercial application of either sort at the present time. Peak choppers are, however, used on some high power radio transmitters which might otherwise be temporarily disabled by high peaks in the signal being transmitted.

The chief usefulness of compandors is on radio links in which the transmission of a compressed signal with subsequent expansion permits operation through higher noise or with lower transmitter power. On a long-wave transatlantic radio telephone circuit a compandor with 40 db range has been shown to allow an increase in noise of some 5 db before reaching the commercial limit.[5] With smaller amounts of noise the noise advantage of the compandor approaches half its range in decibels. This benefit is sometimes applied to a reduction of transmitter power.

Radio noise reducers have been used to advantage in connection with short-wave ship-to-shore and transoceanic radio telephone service. In the former, routine transmission rating is given on a judgment basis using a merit scale from 1 to 5, 5 being practically perfect transmission and 1 so poor that intelligibility is very close to zero. It will then be seen that the observed improvement of ½ to 1 point in transmission rating due to the noise reducer is of considerable importance. Perhaps more graphic figures are those for transoceanic service, where the reduction of noise in the receiving path not only reduces the noise heard by the listener but also improves the voice operated switching with the indirect result that at times receiving volume increases of 5 to 15 db are realized.[9]

As has been noted, the radio noise reducer is a special use of an expandor alone. There are also two interesting applications for a compressor alone. The first, which uses a fairly high ratio of compression, has been mentioned as one type of peak limiting device. The second, using a moderate ratio of compression, is in connection with announcing systems for use in very noisy locations. Its effect is to amplify weak sounds more than strong sounds, which considerably improves the intelligibility through high noise. For quiet locations it is of less value, since the speech sounds lose some of their naturalness in this process.

Conclusion

In the course of developing various types of the volume controlled devices which have been described means have been worked out for providing almost any combination of time constants, range of control, and other characteristics which may be required. Some devices for which there were specific commercial applications or useful functional characteristics for experimental work have been constructed, with resulting advantages which have been briefly mentioned. There remain many possible ways to alter the characteristics of signal energy such as speech to which these methods are applicable and which await the special needs of new transmission problems.

Bibliography

1. C. C. I. F. White Book, 1 bis, pp. 77, 343.
2. C. C. I. F. White Book, 1 bis, pp. 251–3.
3. "A Vogad for Radio Telephone Control Terminals," S. Doba, Jr., *Bell Laboratories Record*, Oct. 1938, Vol. 17, No. 2, pp. 49–52.
4. "A Vogad for Radio Telephone Circuits," S. B. Wright, S. Doba, Jr., and A. C. Dickieson, Presented at *I. R. E.* Convention in New York, June 18, 1938; to be published in *Proc. I. R. E.*
5. "The 'Compandor'—An Aid Against Static in Radio Telephony," R. C. Mathes and S. B. Wright, *Elec. Engg.*, 1934, Vol. 53, No. 6, pp. 860–6; *Bell Sys. Tech. Jour.*, July 1934, Vol. 13, No. 3, pp. 315–32.
6. "The Voice Operated Compandor," N. C. Norman, *Com. and Br. Engg.*, Nov. 1934, Vol. 1, No. 1, pp. 7–9; *Bell Lab. Record*, Dec. 1934, Vol. 13, No. 4, pp. 98–103.
7. "Volume Limiter Circuits," G. W. Cowley, *Bell Lab. Record*, June 1937, Vol. 15, No. 10, pp. 311–15.
8. "A Noise Reducer for Radio Telephone Circuits," N. C. Norman, *Bell Lab. Record*, May 1937, Vol. 15, No. 9, pp. 702–7.
9. "Radio Telephone Noise Reduction by Voice Control at Receiver," C. C. Taylor, *Elec. Engg.*, Aug. 1937, Vol. 56, No. 8, pp. 971–4, 1011; *Bell Sys. Tech. Jour.*, Oct. 1937, Vol. 16, No. 4, pp. 475–86.
10. "Higher Volumes Without Overloading," S. Doba, Jr., *Bell Lab. Record*, Jan. 1938, Vol. 16, No. 5, pp. 174–8.
11. "A Volume Limiting Amplifier," O. M. Hovgaard, *Bell Lab. Record*, Jan. 1938, Vol. 16, No. 5, pp. 179–84.

For the sake of completeness the following references are included, although no allusion has been made to them under the specific device-names used in this paper.

12. "Über automatische Amplitudenbegrenzer," H. F. Mayer, *E. N. T.*, 1928, Vol. 5, No. 11, pp. 468–72.

13. "High Quality Radio Broadcast Transmission and Reception," Stuart Ballantine, *Proc. I. R. E.*, May 1934, Vol. 22, No. 5, pp. 564–629.
14. "Expanding the Music," A. L. M. Sowerby, *Wireless World*, Aug. 24, 1934, Vol. 35, No. 8, pp. 150–2.
15. "Extending Volume Range," *Radio Engg.*, Nov. 1934, Vol. 14, No. 11, pp. 7–9, 13.
16. "Amplitudenabhängige Verstärker," W. Nestel, *E. T. Z.*, 1934, Vol. 55, No. 36, pp. 882–4.
17. "An Automatic Volume Expandor," W. N. Weeden, *Electronics*, June 1935, Vol. 8, No. 6, pp. 184, 5.
18. "Die Arbeitsweise der selbsttätigen Regelapparaturen," H. Bartels and W. G. Ulbricht, *E. N. T.*, 1935, Vol. 12, No. 11, pp. 368–79.
19. "Practical Volume Expansion," C. M. Sinnett, *Electronics*, Nov. 1935, Vol. 8, No. 11, pp. 428–30, 446.
20. "Light-bulb Volume Expandor," *Electronics*, Mar. 1936, Vol. 9, No. 3, p. 9.
21. "Simplified Volume Expansion," W. N. Weeden, *Wireless World*, Apr. 24, 1936, Vol. 38, No. 17, pp. 407–8.
22. "Practical Volume Compression," L. B. Hallman, Jr., *Electronics*, June 1936, Vol. 9, No. 6, pp. 15–17, 42.
23. "Notes on Contrast Expansion," Gerald Sayers, *Wireless World*, Sept. 18, 1936, Vol. 39, No. 12, p. 313.
24. "Contrast Amplification: A New Development," W. N. Weeden, *Wireless World*, Dec. 18, 1936, Vol. 39, No. 25, pp. 636–38.
25. "Overmodulation Control and Volume Compression with Variable-mu Speech Amplifier," W. B. Plummer, *Q. S. T.*, Oct. 1937, Vol. 21, No. 10, pp. 31–33.
26. "Limiting Amplifiers," John P. Taylor, *Communications*, Dec. 1937, Vol. 17, No. 12, pp. 7–10, 39–40.
27. "Low Distortion Volume Expansion Using Negative Feedback," B. J. Stevens, *Wireless Engr.*, Mar. 1938, Vol. 15, No. 174, pp. 143–9.
28. "Distortion Limiter for Radio Receivers," M. L. Levy, *Electronics*, Mar. 1938, Vol. 11, No. 3, p. 26.
29. "Automatic Modulation Control," L. C. Waller, *Radio*, Mar. 1938, No. 227, pp. 21–6, 72, 74.
30. "An AVE Noise Silencer Unit," McMurdo Silver, *Radio News*, May 1938, Vol. 20, No. 11, pp. 46, 55.