The Lenkurt® Demodulator

VOL. 13, No. 10 OCTOBER, 1964

# *The Theory and Use of* COMPANDORS *in Voice Transmission Systems*

*Progress in the field of electrical communications records a relentless fight against interference caused by noise and crosstalk. Through the proper use of a specialized device, known as a* compandor, *toll quality voice transmission can often be achieved over telephone circuits otherwise unsuitable because of excessive noise or crosstalk. This article is a general introduction to compandors and includes a brief discussion of their application and of the characteristics of speech energy that required their development.*

Sound energy that is converted to electrical energy in ordinary telephones consists of a complicated wave made up of tones of different frequencies and intensities (or magnitudes). These speech frequencies and intensities are the fundamental signal characteristics which must be dealt with when designing a voice transmission system.

Most of the energy of speech signals is concentrated in a frequency band that ranges from about 200 cycles per second to about 3200 cycles per second. The intensity range is determined by two factors—the talker and the words or syllables spoken. The difference between the loudest syllable of a loud talker and the weakest syllable of a soft talker may be as much as 70 db (equivalent to a power ratio of *10 million to one*). The average talker produces an intensity range of about 30 to 40 db.

Such a wide range of speech powers presents a significant problem to the designer of transmission systems. Weak signals must be transmitted at a higher level than the noise and crosstalk encountered in the circuit, while strong signals must *not* overload the amplifiers. These factors essentially set an upper limit and a lower limit to the power range that a typical communications system can handle effectively. Building communications systems with greater load capacity and with greater noise and crosstalk protection is not always practical or economical. Coping with the noise performance of communications circuits, therefore, is usually an economic problem.

Reducing noise and crosstalk in communications systems is not an easy task. Some types of induced line noises are unavoidable because telephone lines are often necessarily placed near power transmission lines or other sources of electrical noise.

The maximum amount of power that can be transmitted over wire lines or cable carrier systems is generally limited by established transmission standards. Increasing the power would, of course, provide some increase in the ratio of wanted signals to line noise. However, there would not be any crosstalk improvement since the amount of crosstalk is independent of the line levels (provided all parallel systems operate at the same relative levels).

Reducing crosstalk between carrier systems on different pairs of a pole line sometimes requires extensive line transposition. Most lines used for carrier systems are constructed so that both noise and crosstalk are as low as practicable.

When the first New York-to-London radiotelephone circuit was installed back in the late 1920's, it was recognized that noise would be a major problem on such a long-distance radio circuit. Noise in radio systems consists mostly of stray electrical energy commonly known as static which usually causes more interference than the noise encountered in physical circuits.

To help overcome this noise problem, a volume indicator and a manual volume control were placed in the wire circuit between the overseas toll office and the radio. The volume indicator displayed the intensity of the speech signals transmitted over the circuit. A *technical operator* monitored the volume indicator and adjusted all signals to a level that fully loaded the transmitter. Manually adjusting the speech signals was effective in reducing the range of signal intensities applied to the circuit to about 30 db. However, it was rather difficult for the operator to follow the rapidly varying signal amplitudes, and static or noise was still annoying to the listener, especially during speech pauses and other silent periods.

Efforts to improve the signal-to-noise performance on the transatlantic radio-

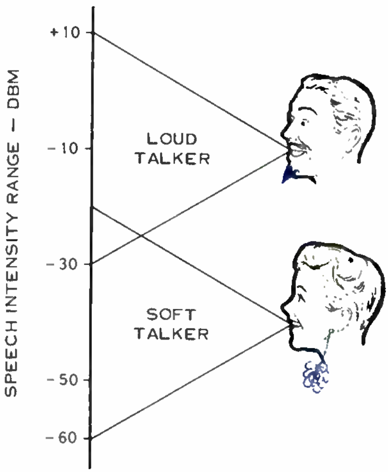


*Figure 1. The dynamic speech range of an individual is about 40 db; however, the difference between the strongest sounds of a loud talker and the weakest sounds of a soft talker may be as much as 70 db.*

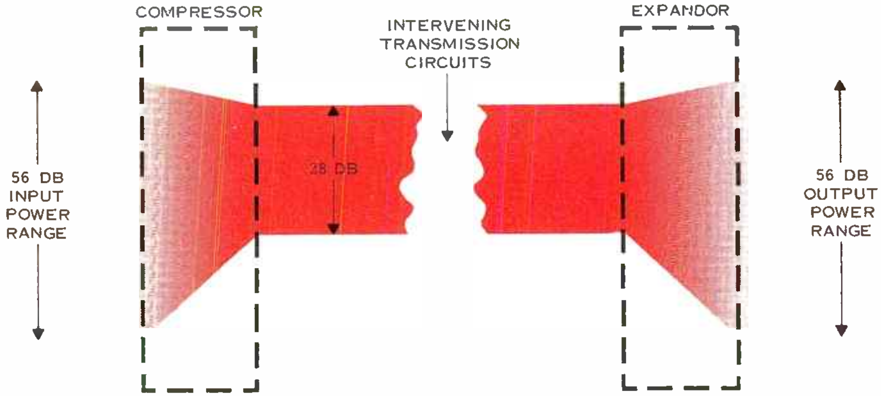


*Figure 2. The wide power range of speech signals is reduced by the compressor and restored to its natural power range by the expandor.*

telephone circuit led to the development of a voice-operated device called a *compandor*. The compandor, first used in the New York-to-London radiotelephone circuit in 1932, provided a great improvement in overcoming the problems of static, thus making the radio circuit usable for a greater portion of the time.

Cost and space requirements of the early compandors prevented their general use on wire circuits until the late 1930's. The Bell System first employed compandors on a wire line in 1941 on the Charlotte, North Carolina-Miami, Florida and the Charlotte, North Carolina-West Palm Beach, Florida routes.

Technically, the type of compandor described in this article is a *syllabic* compandor. There is another type of compandor, known as an *instantaneous* compandor, that is used to reduce quantum noise in pulse-code modulation (PCM) transmission systems. Since the instantaneous compandor has such a distinct function, it has not been included in this general discussion of the voice-operated compandor.

## What Is A Compandor?

A compandor is a combination of an intensity range COMpressor and an intensity range exPANDOR, from which it derives its name. The compressor is employed in the voice *input* circuit of a communications channel to compress the intensity range of speech signals by imparting more gain to weak signals than to strong signals. At the receiving end, or voice *output* circuit, of the same channel the expandor performs the opposite function of restoring the intensity back to its original range.

The compressor automatically raises the level of weak speech signals so that they can be transmitted above the noise and crosstalk encountered in the circuit *between* the compressor and the expandor. Thus, the signal-to-noise improvement for weak signals is produced by the compressor. In addition, the compressor attenuates strong signals, thereby preventing them from overloading the transmission equipment.

The expandor, at the receiving end of the circuit, presents more attenuation to weak signals than to strong signals and adjusts to a condition of maximum loss between speech syllables. The ordinarily weak crosstalk and noise signals that are very disturbing to the listener during silent periods or between syllables are greatly attenuated, thus quieting the circuit.

## How A Typical Compandor Works

As stated previously, the compandor consists of two devices: the compressor at the transmitting end of the circuit, and the expandor at the receiving end of the same circuit. The compressor and expandor each contain a variable loss device (variolosser), an amplifier, and a rectifier control circuit, as shown in Figure 3.

Speech signals entering the compressor first pass through the variolosser and then the amplifier. A portion of the speech energy leaving the amplifier is routed into the control circuit where it is rectified. The resulting direct current is fed into the variolosser circuit where it is used to control the amount of signal attenuation. The level of this direct-current signal is *directly proportional* to the strength of the speech energy, which is constantly varying. As the level of the direct current increases, the attenuation of the variolosser also increases. If a weak speech signal is present in the compressor, the control current is small and the attenuation of the variolosser is low. When the input speech energy increases, the attenuation of the variolosser increases in direct proportion. Thus, strong signals are attenuated more than weak signals, resulting in a compression of the speech energy range. The amplifier sets the proper level of the speech energy leaving the compressor.

At the receiving end of the circuit, the expandor restores the energy of the compressed speech signal to its original intensity range. This is done by introducing a loss that is inversely proportional to the level of the input speech energy and equal to the gain introduced by the compressor. Operation of the expandor is complementary to that of the compressor. A portion of the input speech energy (rather than the output energy as in the compressor) is routed to the rectifier control circuit to form the direct-current control signal. The attenuation of the expandor variolosser is *inversely proportional* to the level of the direct-current control signal. Thus, weak signals are attenuated more than strong signals, thereby restoring the speech sounds to their natural power range.

The performance of a compandor is controlled by three characteristics: 1) the compression-expansion ratio; 2) the companding range; and 3) the attack and recovery times. Each of these characteristics is discussed separately in the following paragraphs.

## Compression-Expansion Ratio

The degree to which speech energy is compressed and expanded is expressed by the ratio of *input* to *output* power (in db) in the compressor and the expandor, respectively. The compression ratio is always greater than 1. The expansion ratio is the inverse of the compression ratio and, therefore, is

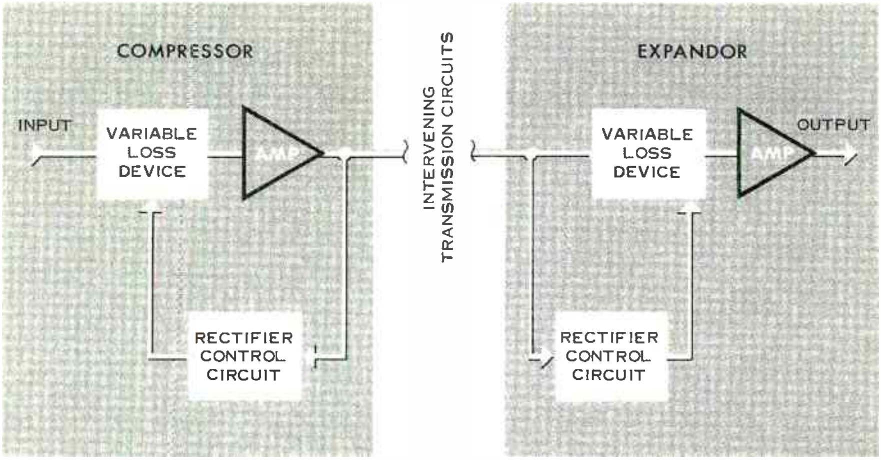


*Figure 3. Block diagram of a typical compandor. Both the compressor and the expandor contain a variable loss device, an amplifier, and a control rectifier.*

always less than 1. (The degree of expansion is sometimes expressed as the ratio of *output* to *input* power so that the compression and expansion ratios are equal.) If the compression (or expansion) ratio were 1, companding action would not occur and the compandor would behave like an ordinary linear amplifier.

Selection of the proper compression-expansion ratio usually involves a compromise. If the compression ratio is too high, minor irregularities in performance are likely to be magnified by the companding action, thus causing excessive distortion. On the other hand, if the compression ratio is too small, (approaching 1), the range of speech energy will not be compressed enough to realize a sufficient improvement in the signal-to-noise ratio.

A compression ratio of 2 (or 2 to 1) with a corresponding expansion ratio of ½ (or 1 to 2) provides satisfactory performance for compandors used in most telephone circuits. This means that the speech energy traveling in the circuit between the compressor and the expandor will have an intensity range of one-half its original value.

## Companding Range

To be effective, companding action must occur over the wide intensity range of speech energy. Distortion may occur if the companding range is less than the usual range of speech signals. A companding range of 50 db to 60 db is usually sufficient to avoid distortion and to provide the optimum signal-to-noise improvement. The few high or low intensity signals that appear outside of this range can be attenuated or limited without seriously affecting intelligibility.

Compression and expansion of speech energy in the compandor occurs around a focal point known as the un-

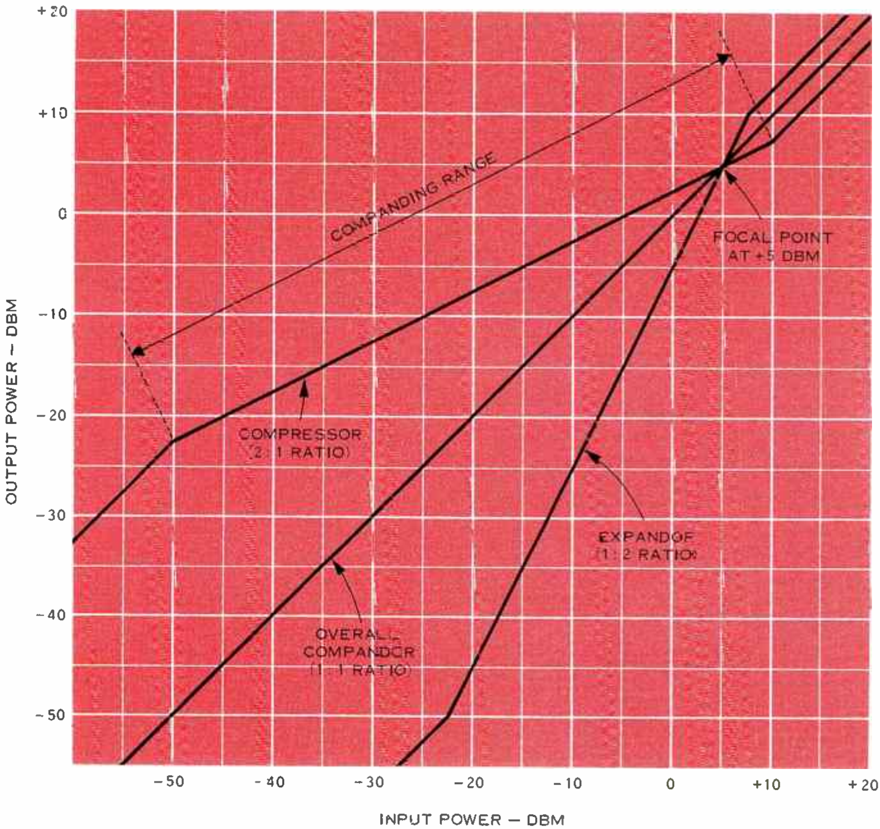


*Figure 4. Ideal load characteristics of a typical compandor with a 2:1 compression ratio, a 60 db companding range, and a +5 dbm focal point. Note that the 2:1 compression ratio applies to an intensity range of —50 dbm to +10 dbm and that the expansion ratio of 1:2 applies to the compressed intensity range of —22.5 dbm to +7.5 dbm.*

affected level. The focal point refers to that energy level, within the companding range, that is not affected by compandor action. Energy at the focal point level passes through the compressor and the expandor with zero loss or gain. As an example, the focal point of the companding action shown in Figure 5, occurs at +5 dbm.

Maximum noise advantage is achieved when the focal point coincides with the highest level of the companding range. In such an arrangement, all speech powers, except those at the focal point, are amplified in the compressor and attenuated in the expandor. However, to make allowances for the increase in mean power introduced by the compressor, and to avoid the risk of increasing the intermodulation noise and the overloading that might result, the focal point is sometimes reduced by as much as 10 db to 15 db below the top of the companding range. Selection of the actual focal point depends on the desired noise advantage and the power level capability of the particular system in which the compandor is used.

## *Attack and Recovery Times*

If the gain or loss of a compandor changed instantaneously with a change of input signal, the output signals would be badly distorted. Consequently, the operating time constants of the compandor are set so that the gain or loss varies as a function of the speech signal *envelope* and not the instantaneous amplitudes. Gain or loss, therefore, is controlled by syllabic variations of the input signal, rather than by individual speech peaks.

The time constants, which are designed into the compandor control circuits, are referred to as the attack and recovery times. Both the attack and recovery times are established in respect to a voice-frequency test signal. In accordance with CCITT Recommendations, the attack time is that interval

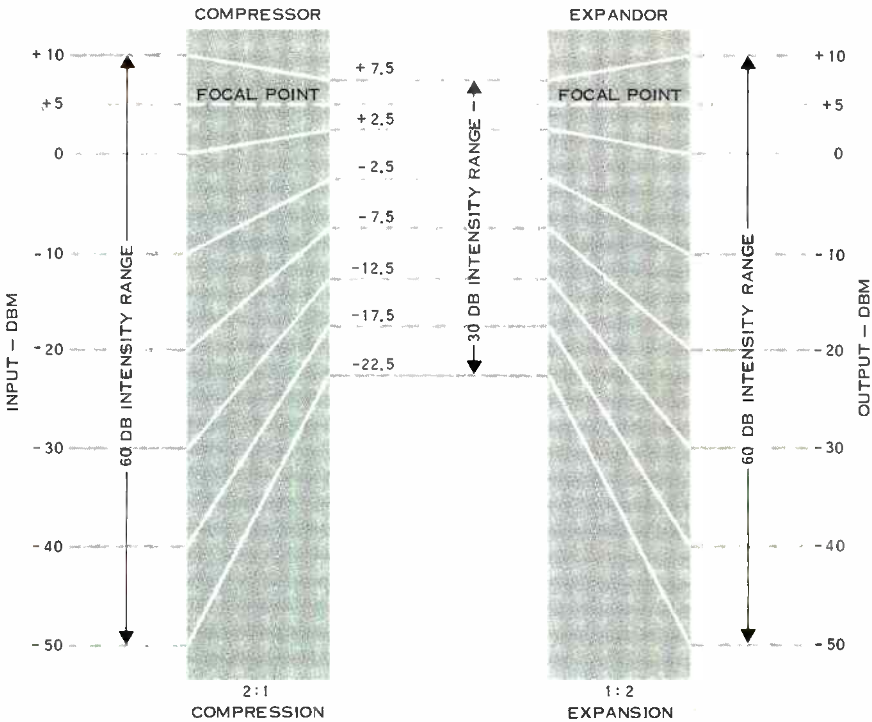


*Figure 5. The effect of a compandor with a 2:1 compression ratio on various power levels. In this particular example, compression and expansion occur around a +5 dbm focal point known as the* unaffected level.

between the instant when the power of a test signal, applied to the compressor input, is increased from —16 dbm0 to —4 dbm0, and the instant when the output voltage envelope of the compressor reaches 1.5 times its final steady-state value. The recovery time is that interval between the instant when the power of the test signal is reduced from —4 dbm0 to —16 dbm0, and the instant when the compressor output voltage envelope reaches 0.75 times its final steady-state value. The attack and recovery times for the expandor are determined in an equivalent manner. Normal values for these time constants are about 3 milliseconds for the attack time and about 13.5 milliseconds for the recovery time.

If the attack and recovery times are too abrupt, modulation products may cause distortion and noise. If the attack time is too slow, the initial parts of syllables may be mutilated. If the recovery time is too slow, the full loss of the expandor will not be inserted between syllables. In addition to establishing proper time constants, it is essential that the attack and recovery times of the compressor and the expandor exactly coincide to avoid overshoots.

## Noise Advantage

The effect of a compandor in a typical carrier channel is shown graphically in Figure 6. This illustration compares the operation of two carrier channels, one with a compandor and the other without. A line noise intensity of —51 dbm was assumed to exist at the input to the receiving carrier terminal. Gains and losses are shown for a high intensity signal of 0 dbm and a low intensity signal of —31 dbm, both at the zero reference level.

In Figure 6A, where compandors are not used, the low intensity signal reaches the input of the receiving carrier terminal at —54 dbm. This is 3 db below the assumed noise power. Since the noise will also be amplified in the carrier terminal, it will reach the listener at a level 3 db higher than the low intensity speech signal. For intelligible transmission, noise power should be more than 20 db *below* the weakest speech signal.

Now consider how the same range of signals would be transmitted over the carrier channel now equipped with a compandor, as shown in Figure 6B. The —31 dbm signal is fed into a compressor where it is amplified. The amount of amplification depends upon the signal power, and in this case, is 18 db. Therefore, the signal enters the carrier terminal with an intensity of —13 dbm and reaches the receiving carrier terminal at an intensity of —36 dbm instead of —54 dbm, as occurred in the example without a compandor. The line noise power is, of course, still —51 dbm. Both the signal and the line noise are amplified 23 db in the carrier terminal, but in this case they both enter the expandor instead of going directly to the toll switchboard. The weak speech signal enters the expandor with an intensity of —13 dbm, and the noise enters the expandor with an intensity of —28 dbm. Since the expandor signal is attenuated by an amount inversely proportional to its power (in this case, 18 db for the speech signal and 28 db for the noise), the margin between the signal and the noise has been increased. For the same signal which was 3 db

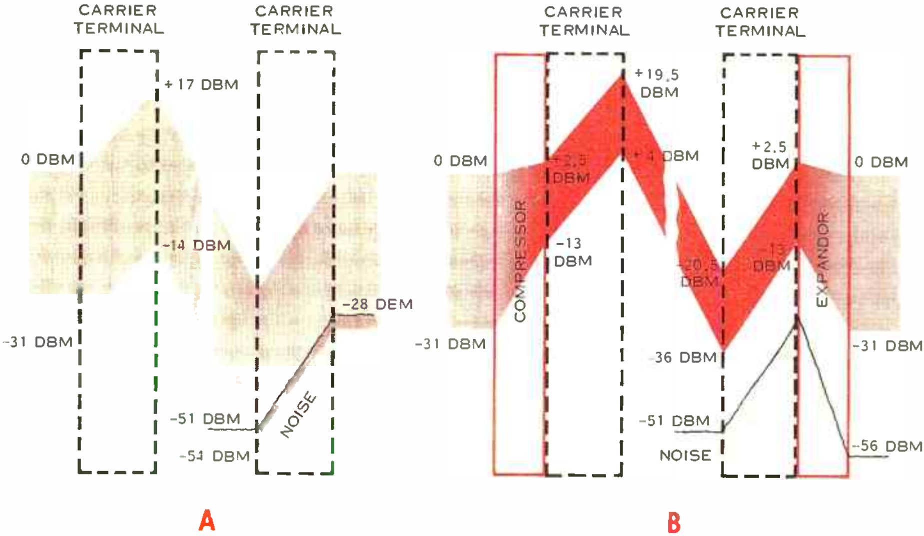


*Figure 6. Using compandors, toll quality transmission can often be achieved over a circuit otherwise unsuitable because of noise. Diagram A shows a typical circuit, without a compandor, where the weakest speech signal at the receiving end is 3 db below the noise level. Diagram B shows the same circuit with a compandor added. The weakest speech signal at the receiving end is now 25 db above the noise level, resulting in a 28 db noise improvement.*

*below* the noise when compandors were not used, the circuit now achieves a signal-to-noise ratio of 25 db. Compandor action is not apparent to the telephone listener. except for the desirable reduction in interference.

## Crosstalk Advantage

Compandors are especially helpful in reducing the crosstalk problems encountered in multi-channel carrier systems. High speech signal peaks constitute the greatest source of crosstalk. At the compressor, the amplitude of such loud signal peaks is reduced, thus preventing crosstalk to adjacent channels due to circuit overloading.

A crosstalk advantage is also realized through the action of the expandor at the receiving end of a circuit. The expandor takes advantage of the fact that crosstalk, like noise, is not too noticeable during speech but becomes objectionable during silent periods.

The expandor, as explained previously, adjusts to a condition of maximum loss when speech signals are not present. As a result, the relatively weak crosstalk signals that enter the receive circuit are greatly attenuated during such silent periods and thus do not disturb the telephone listener.

## Applications

Compandors are used in telephone voice channels to make noisy circuits satisfactory for toll transmission service. On physical and phantom voice-

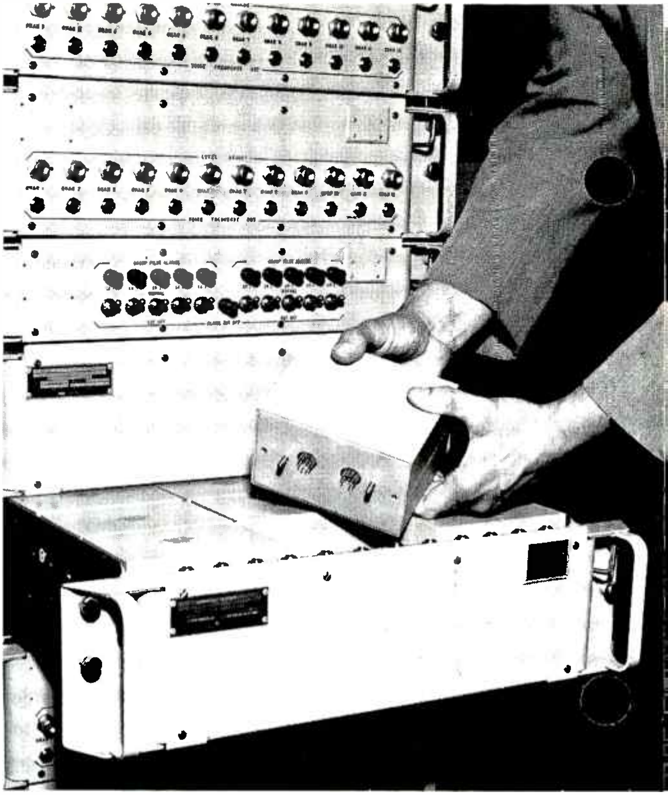

*Figure 7. The transistorized compandor developed by Lenkurt for the AN/FCC-17 multiplexer is designed to process AM and FM data signals with little distortion. Compressors and expandors are packaged separately in hermetically-sealed containers to withstand rugged military use. Photograph shows a plug-in compressor unit withdrawn to exhibit its sturdy mechanical construction. The compandor is especially useful in military networks to assure privacy in cable carrier systems where crosstalk may occur or to counteract the effects of enemy jamming in radio systems.*

frequency circuits the compandor is particularly valuable in compensating for the effects of power line induction and noise pickup from other random sources. Many older circuits which have fallen below transmission standards can be restored to toll quality by using compandors.

Compandors are employed effectively on amplitude-modulated carrier systems to reduce the effects of crosstalk as well as to improve the signal-to-noise ratio. Repeater spacing of carrier systems operating over wire lines or cable pairs is often limited by line noise conditions or excessive near-end crosstalk. With the noise advantage offered by compandors, repeater spacing may be limited only by the maximum system gain.

Multi-channel microwave radio carrier systems can achieve greater fading margins, longer transmission paths, and make use of more repeaters to extend the system because of the additional signal-to-noise advantage of the compandor. Such an advantage can also reduce the radio antenna gain requirements, thus permitting the use of smaller antenna systems. When compandors are employed on multi-channel radio-carrier systems, it is necessary to consider an average power increase of about 5 db for voice circuit loading. This additional power must either be attenuated or added to the nominal figures used to calculate the loading effect on radio equipment.

Substantial savings can often be realized in designing and manufacturing carrier systems with compandors built into the channel equipment. Because of the noise and crosstalk improvement, design requirements of line filters, in addition to other carrier terminal and repeater equipment, can be lowered— resulting in lower equipment costs.

## Data Transmission

In modern transmission systems, there is the ever present need to transmit data signals over already existing voice channels. However, it is not desirable to send data over voice circuits containing compandors since they offer little or no noise improvement for such signals. In addition, compandors tend to introduce intermodulation distortion, and can be especially detrimental to pulse-type data signals with changing power levels. When practical, therefore, compandors should be removed from voice circuits that are to be used for data. Nevertheless, it is possible to transmit data signals through compandors without too much signal degradation. It is currently being done over telephone networks that provide data transmission service on a dial-up basis, and for systems employing in-band signaling.

## Conclusions

When measured under idle circuit conditions, compandors provide a noise advantage equal to the maximum gain of the compressor. For the compandor characteristics shown in Figure 6B, the noise advantage would be 28 db. In actual practice, however, the effective noise advantage is always less than the value achieved during idle conditions, and typically ranges from about 20 db to 25 db. The actual noise advantage depends on such things as the speech power level, the noise level, the compandor focal point, and the companding range.

The compandor offers relief, but not a cure, in the fight to overcome the disturbing effects of noise and crosstalk— the principal enemies of communications. It is, therefore, a remedial device that offers a practical method of improving the quality of voice transmission over otherwise marginal or unsatisfactory telephone circuits. •

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