APPLICATION OF COMPANDORS TO FM RADIO SYSTEMS WITH FREQUENCY DIVISION MULTIPLEXING

M. C. Harp, M. H. Kebby and E. J. Rudisuhle
Lenkurt Electric Co.
San Carlos,
California

Compandors are used to improve the intelligibility of speech transmission circuits by increasing the signal-to-noise ratio. Originally developed in the early 1930's for use with transoceanic radio circuits, they have since been applied to some extent on long distance telephone circuits, usually of the carrier-derived type. Within the past few years new telephone carrier systems have been developed which include a compandor as an integral part of the equipment for each speech channel.

Compandors are now also available as general purpose units suitable for application to almost any carrier derived voice channel. Of particular interest here are the benefits which may be obtained in system planning and operation through the application of compandors to the frequency division multiplex equipment used with FM radio systems.

Because of the limited use of compandors for this purpose in the past, many questions about their application have been asked recently. But, because of the very nature of the device, a simple question cannot always be answered in a simple and direct fashion. In this paper, by discussing how compandors operate, we will show how they improve signal-to-noise ratio. We will then discuss how this improvement in signal-to-noise ratio can be utilized to advantage in the planning of radio systems.

The name 'Compandor' describes a combination of two devices--a volume COMpressor at the transmitting end of a circuit, and a volume exPANDOR at the receiving end. The compressor reduces the total dynamic range of transmitted signals by imparting more gain to those with low intensity than to those with high intensity. Signals are thus generally transmitted at higher levels with respect to outside noise interference than would otherwise be possible. The expandor at the receiving end of the circuit restores the original dynamic range by attenuating weak signals more than strong ones. Any noise entering the expandor is also attenuated of course.

In general, the maximum reduction of received noise intensity is obtained when no speech is present. Then expandor loss is maximum and the noise observed by a listener is minimum.

Thus, unlike squelch circuits commonly used with mobile or marine communications which effectively turn transmitters or receivers ON and OFF, compandors are dynamic devices which are always in operation while the equipment is in use. Addition of compandors to a circuit has no effect on the operation of the other transmission equipment concerned.

Although the average noise improvement from available compandors is 22 db, the actual improvement obtained is a function of how noisy the circuit is without a compandor, and of how loud the user is talking. With a very loud talker on a very noisy circuit, there may conceivably be no improvement.

The miniaturized compandor manufactured by Lenkurt is designed for general purpose use on both physical and carrier-derived speech channels. Since the compandor is an independent unit, it is particularly adaptable for optional use with FM radio systems where conditions are such that the compandor noise advantage is required. The complete unit as shown in Figure 1 is only 3-1/4 inches wide, 2 inches high, and less than 10 inches deep. Only two tubes are required. Test points on the front of each unit facilitate testing for routine maintenance and trouble shooting, and the entire unit can be quickly removed from its mounting and replaced by another. An interchangeable resistance hybrid or four-wire strapping arrangement plugs into each unit. This provides flexibility in connection to various types of voice frequency circuits. Four complete compandors plug into a rack-mounted shelf which occupies only 3-1/2 inches of vertical space on a standard 19 inch relay rack. The compandor mounting shelf also contains necessary fusing and alarm circuitry.

Both the compressor and expandor have time constants of syllabic length. Final gain or loss values are reached within 1 to 5 milliseconds after a speech burst, the exact time depending upon the strength of the signal. After the speech bursts compressor gain and expandor loss reach their original values within 20 to 100 milliseconds.

Circuits are arranged so either radio receiving type tubes with 6.3-volt filaments or industrial type tubes with 20-volt filaments can be used.

How a Compandor Works

The basic equipment of a compandor is illustrated in Figure 2. Both the compressor and the expandor consist of a variable loss (or gain) device, an amplifier, and a rectifier control circuit. Part of the expandor input signal or compressor output signal passes through the rectifier and controls the operating point (and therefore the gain or loss) of the variable loss device by application of a rectified bias voltage.

The effect of a compandor on a range of input signals is illustrated in Figure 3. An input intensity range of 56 db is compressed to one-half or 28 db for transmission between terminals. At the receiving end of the circuit these signals pass through an expandor and the original intensity range of 56 db is restored.

Compandor operation is illustrated more completely in Figure 4 where the compression and expansion of signals in a compandor is indicated for two different speech powers.

Noise Advantage

The two examples of carrier channel operation, one with and one without a compandor, shown in Figure 4, indicate how the compandor permits operation over circuits otherwise too noisy for use. A noise intensity of -51 dbm has been assumed at the input to the carrier terminal. This noise can be either crosstalk or white noise. Gains and losses are shown for a high intensity signal of 0 dbm at 0 level and a low intensity signal of -31 dbm at 0 level.

In Figure 4A, where compandors are not used, the low intensity signal reaches the input of the receiving carrier terminal 3 db below the assumed noise power. Since received noise is amplified in the carrier terminal by the same amount as the received signals, the noise would reach the listener 3 db higher than the signal.

In Figure 4B, signals of the same intensities are shown transmitted over the same carrier channel equipped with a compandor. Instead of going directly into the carrier terminal, the signals first go through a compressor where they are amplified. The amount of amplification depends on the signal power. The low intensity signal now reaches the receiving carrier terminal at an intensity 18 db higher than previously. The noise power is still -51 dbm. Both the signal and the noise are amplified equally in the carrier terminal, but in this case they both enter the expandor instead of going directly to the toll switchboard. The desired signal enters the expandor with an intensity of -6 dbm and the noise enters the expandor with an intensity of -21 dbm. Since signals are attenuated by an amount proportional to their power (in this case 18 db attenuation for the desired signal, 28 db for the noise), the expandor serves to increase the margin between signal and noise. For the same signal which was 3 db below the noise in the circuit without a compandor, the circuit with a compandor provides a signal-to-noise ratio of 25 db. Except for increasing the signal-to-noise ratio, the action of the compressor and expandor is not apparent to the listener.

In the example described here, it has been assumed that the action of the compandor is determined by a single tone. In operation, of course, the action is dynamic--compressor gains and expandor losses change constantly as the intensity of the transmitted intelligence changes. Compressor gain and expandor loss are determined by the total power being transmitted. If both the high and low intensity signals described above were sent simultaneously, the action would be determined by their combined power or, since the weaker signal is so low, effectively by only the strongest signal. In this case the instantaneous noise improvement would be 2-1/2 db when both signals are being transmitted; however, the noise would be attenuated immediately when speech transmission is stopped, so the circuit would still sound quiet in the absence of speech.

It is apparent, therefore, that the actual improvement in signal-to-noise ratio must depend on the volume of the speech being transmitted and on the amount of noise encountered.

An interesting point to note here is that the overall noise improvement observed by a listener will generally be greater than the calculated improvement when speech is present. This is caused by the fact that during quiet periods (between words) the expandor returns to the condition of maximum loss. Therefore, the noise improvement is maximum. Then, when the circuit is in use, the noise level may rise, but it is masked by the speech. Because the listener observes a quiet circuit when no speech is present, his ear tends to strike a balance between idle and talking periods. Determination of compandor noise improvement must therefore be made by listening tests with various volume talkers and various noise intensities rather than by direct meter readings.

Compandor advantage in noise reduction during speech has been very loosely quoted as 22 db, and this figure is generally used for planning purposes. Actually, the noise advantage varies considerably with the strength of the speech and the magnitude of the noise.

To help determine the practical noise advantage to be expected, extensive tests have been made under controlled conditions using both 1000-cycle tone and a 3-kc band of thermal noise as interference. Three typical expected talker volumes were used to approximate maximum, average, and minimum speech intensities. The compandor advantage for various 1000 cycle interference levels for the various speech intensities is shown in Table 1.

These test results are the average of impressions by careful listeners whose judgement generally differed by less than 1 db. Although tests with a 3-kc band of thermal noise were less conclusive than were those with the 1000-cycle interference, the average of individual observer's reactions agreed essentially with the tabulated results shown.

Use of a compandor will reduce the intensity only of interference arising in the compandored portion of the circuit. Any noise entering the compressor will be amplified and attenuated in the same manner as the desired intelligence. For these reasons the principle benefits arising from compandor usage are reduction of thermal noise and reduction of crosstalk (babble) due to distortion in the radio equipment.

Compandor Application

Generally speaking, compandors can be used to advantage on any telephone-type channel used for speech transmission. The method of application, and the advantages derived when radio is the transmission medium will vary depending on the type of radio facility and communication plant concerned.

Proper operation of compandors requires that the compressor and expandor sections be installed at specific level points in a four-wire v-f circuit. For example, internal strapping options on the Lenkurt compandor permit installation of the compressor at the -16, -13, or -4 db level points and of the expandor at the +4 or +7 db level points. Such levels are normally available on the drop sides of carrier channels terminating in telephone switchboards. Providing standard carrier equipment is used, the addition of compandors to the individual channels should present no problems from the level standpoint. A typical application of a compandor to a carrier telephone channel is shown in Figure 5.

Another important factor to be considered when adding compandors to a radio system are the effects of compandors on the radio system loading. Experience has indicated that the increased average transmitted power level due to compressor action is from about 3 to 5 db. While this results in heavier loading of the radio equipment with proportional rise in distortion products, the compandor compensates for the adverse effects.

Utilizing Compandor Noise Advantage

One of the principal limiting factors in the engineering and installation of multichannel radio systems is the signal-to-noise ratio which must be maintained. This is of particular importance when the radio system forms part of a telephone system where established standards for wire line and cable transmission facilities must be met.

The channel signal-to-noise ratio in a radio system is determined by two types of noise. These are (1) thermal noise of the radio equipment, and (2) interchannel crosstalk or babble due to cross modulation of the carrier frequencies in the radio equipment.

Since both of these noise sources are within the compandored portion (between compressor and expandor) of the speech circuit, the full noise improvement of a compandor can be applied to radio system planning.

The ultimate object of this planning is to provide sufficient fade margin so the noise on each channel does not rise above a maximum level for more than a pre-established percentage of the time.

Obviously, if some means can be used to decrease the noise intensity observed by the users of the circuit, the signal at the input to the radio receiver can be lower without degradation of transmission quality of the circuit. Therefore, by utilizing the average 22 db improvement offered by a compandor, the total losses permissible between a given radio transmitter and receiver can be from 17 to 22 db greater, depending on the loading allowance.

This 22 db extra margin can be used in a number of ways. Part can be used to increase fade margins--or the link length can be increased--or smaller antennas with less gain can be used--or longer cable runs can be tolerated between equipment and antennas--or distortion requirements of the radio equipment can be relaxed--or a given type of radio equipment can be extended through several more repeater sections than would otherwise be possible.

Limitations To Compandor Application

It is important to remember that the improvement threshold in an FM radio system limits the minimum level to which a signal can fall without being completely obscured by noise. Therefore, the full noise advantage of compandors cannot be used unless the minimum signal for a non-compandored system is at least 22 db or more above the FM improvement threshold. The reasons for this can be seen in Figure 6 which shows signal-to-noise ratio vs. received signal level for two different channels on a typical wide-band FM radio system. When the received signal falls below the FM improvement threshold, the signal-to-noise ratio decreases much faster than the received signal decreases. Deterioration in the vicinity of the FM improvement threshold would be less for a system with narrower bandwidth.

Compandors are normally meant for application to speech circuits rather than to circuits used for telegraph transmission since compandor advantage is dependent on the dynamic range of transmitted intelligence. In the case of FM telegraph signals, the addition of a compandor to a circuit would merely increase the radio system loading. For AM telegraph signals the compandor would cause increased distortion. There is as yet no reliable data on the effects of operating telegraph or teleprinter circuits through compandors. Where multichannel systems transmit both telegraph and speech, only the speech channels would normally be equipped with compandors.

Compandors can be applied to party line circuits with the same advantages as obtained on single channels, providing a compandor is installed at each of the stations on the party line. It would also be necessary, of course, to adjust the circuits so the compandors at each station are installed at the proper level points, and so that these level points would remain constant regard less of the number of stations in use.

Sample Calculation

Because of the many variable factors concerned in a radio installation, it is difficult to make all-inclusive statements concerning compandor advantage. Such variables as type of terrain (determining fade margin requirements), types of antennas, cable connections, and radio and carrier equipment specifications will vary for each radio system.

The results to be expected from compandor application can, however, be seen from the following calculations. Equipment considered is a typical wide-band 900 mc radio system multiplexed with 72 channels of Lenkurt 45-class single sideband suppressed carrier equipment. Characteristics and specifications for this equipment are available from the manufacturers.

Without compandors, this equipment is normally recommended for no more than three tandem links if standard toll quality telephone channels are to be obtained. Beyond this limit radio distortion products accumulate to exceed the noise limit of +38 dba at the 0 level on the worst channel for a greater percentage of time than telephone standards permit.*§ (This corresponds to an unweighted signal-to-noise ratio of 44 db for a normal test tone of 0 dbm at 0 level.) This limitation, of course, assumes that fade margins of from 1/2 to 1 db per mile are included in system planning.

When compandors are used on this same equipment, they reduce the effect of the accumulated distortion products to permit systems of much longer length.

In the following calculation the total noise in the worst channel from all sources is determined in micromicrowatts and converted to dba (F1A weighted) for easier comparison with telephone standards.

Conditions

900 mc radio equipment. Modulation bandwidth 300 kc.

72 channels of 45-class carrier equipment. Compandors on all channels. Constant signaling tones transmitted.

---

* Dba is a unit of noise measurement widely used in the telephone industry. It is a weighted measurement adjusted to compensate for the frequency-attenuation characteristics of standard telephone transmitters and receivers. F1A weighting refers to a network which attenuates various frequencies in the same manner as an F1A subset with an HA1 receiver. A 1000 cycle tone of -85 dbm is equivalent to 0 dba and is the reference point for F1A weighted measurements. A weighting correction of 3 db is then made to convert dbm of random noise to dba, F1A weighted. Thus, a random noise of -82 dbm, unweighted, corresponds to 0 dba.

§ Level in a telephone circuit defines the amount of attenuation or gain between any point and a zero reference level point. The zero level point is generally the 2-wire side of the carrier hybrid.

15 tandem radio links using back to back repeaters.

40 mile average link span.

40 db fade on one link.

Second order distortion products in the average channel are 48 db below test tone level.

Third order distortion products in the average channel are 60 db below test tone level.

3 db level unloading to compensate for the increase in transmitted power caused by the compandors.

Calculations

Noise Source	Noise Contribution in uuW
Radio modulator noise as stated in equipment specifications -- -60 dbm or 1000 uuW per link.	15,000
Crosstalk from 2nd order distortion products of -48 dbm or 16,000 uuW average per link adds on rms basis.	240,000
Crosstalk from third order distortion products of -60 dbm or 1000 uuW average per link adds in phase in worst condition.	225,000
Thermal noise from receivers on unfaded links. Taken from equipment specifications and assuming free space propagation between 10 foot parabolic reflectors over 40 mile average links. -73 dbm or 50 uuW per link.	700
Thermal noise from receiver on one link which is 40 miles long and in a 40 db fade is -30 dbm or	1,000,000
Total Noise Power	1,480,700

This places the thermal noise at a level of approximately -28 dbm. Since the signal level is 0 dbm, a resulting per channel signal-to-noise ratio without compandors of 28 db results. With compandors in the circuit, the signal-to-noise ratio would be 28 + 22 or 50 db. As measured on a 2B Noise Measuring Set with F1A weighting, the compandored circuits would show a noise power of +32 dba at 0 level. Due to the increased average loading effect of the compandor, the radio system should be unloaded approximately 3 db. Under such conditions, the per channel signal-to-noise ratio would be 47 db. Noise would be +35 dba at 0 level.

Table 1. Compandor Noise Advantage

Magnitude of 1000-cycle Interference (dbm at 0 level)	Compandor Noise Advantage Speech volume at 0 level -26 vu	 -16 vu	 0vu
-30	27	25	24
-25	24	22	20
-20	22	19	18
-15	18	16.5	15
-10		14	11

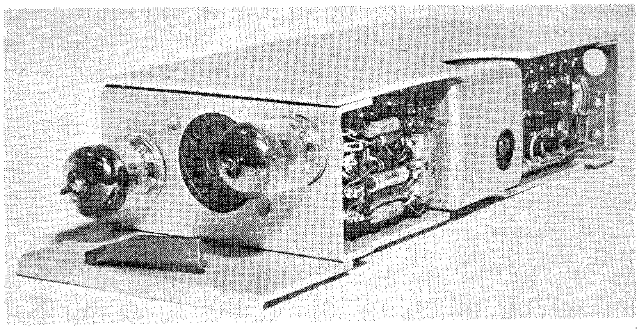

Fig. 1 - The Lenkurt Type 5090A Compandor for General Purpose Use