An Improved Circuit for the Telephone Set

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A telephone set known as the 500 type has been in production for Bell System use for some time.[1] *The successful outcome of an intensive study has made it possible to simplify the circuit and some of the components of this set, and thereby to increase dependability and life and significantly to reduce the manufacturing cost. This change now has been completed and telephone sets embodying the necessary modifications are in production. This paper discusses some of the problems involved in this work and outlines the improvements which have been effected. Presented also is information concerning the superior performance of the 500 set over the preceding telephone set when used in noisy locations.*

INTRODUCTION

One of the outstanding characteristics of the 500 type set is a 10 db increase in combined transmitting and receiving performance on long loops. This gain is equally divided between receiving and transmitting. This improvement has resulted largely from the use of a transmitter and a receiver which are not only more efficient, but also have better frequency response characteristics. To take full advantage of these transmission gains, two new elements were introduced in the original 500 set design. One of these elements was a better sidetone balancing circuit to offset the more sensitive transmitter and receiver, and maintain sidetone at a level no greater than it was with the previous design of set (known as the 302 type). The other was a tungsten filament and thermistor element to control automatically the transmitting and receiving levels so that the desired gains occur on a graduated basis as the loop length increases. This combination of filament and thermistor bead was called the transmission equalizer. While the transmission objectives were met with telphone sets having these elements, this additional component increased the manufacturing cost of the set appreciably, and therefore more economical means of attaining the desired results were sought. Such means have been found in the form of an arrangement in which a pair of silicon carbide varistors serves for both the sidetone balancing and equalizing functions, and with certain novel modifications in the circuit of the set, yields essentially the same overall transmission performance as the original design at lower cost. The advantage is retained of a telephone set which from a transmission standpoint is universal in its application in the telephone plant. This universality avoids additional codes of set which require effort and expense to administer. Telephone sets having these features are designated as 500C (manual) and 500D (dial) types. The original design is known as the 500A (manual) and 500B (dial types).

GENERAL

When the sidetone, which is the sound level in the receiver caused by voltage developed in the local transmitter, becomes too high, the subscriber subconsciously lowers his talking level thereby reducing the level of outgoing transmission.[2, 4] To avoid this loss and make the higher efficiency provided by the new transmitter and receiver effective, a reduction in sidetone must be made. When the room noise level at the station is high, another undesirable effect of high sidetone occurs. This is the loss in effective receiving which results from the masking of incoming speech by the high level of sidetone noise in the receiver. This will be discussed in more detail later.

In developing the original design of 500-type set, several different equalizing means were considered, and the type involving a filament in series with the transmitter, and a thermistor bead in shunt with the receiver was selected as the most suitable with the means available at that time. Reduction in sidetone was realized by the use of a special balancing network which required an auto transformer. The set now being produced is based on a new circuit arrangement, utilizing a pair of semiconductors in the form of silicon carbide varistors, one of which has a resistance in a range which required development for this specific purpose.

CHARACTERISTICS OF SILICON CARBIDE VARISTORS

Fig. 1 shows the relation between the dc voltage and current for the two varistors used in the 500C and D sets. These varistors were coded 312D and 312E, but for brevity in this paper, they are referred to as V_1 and V_2 respectively. Also shown in Fig. 1 is the dc resistance of these varistors as determined by the ratio of applied voltage to current. It is

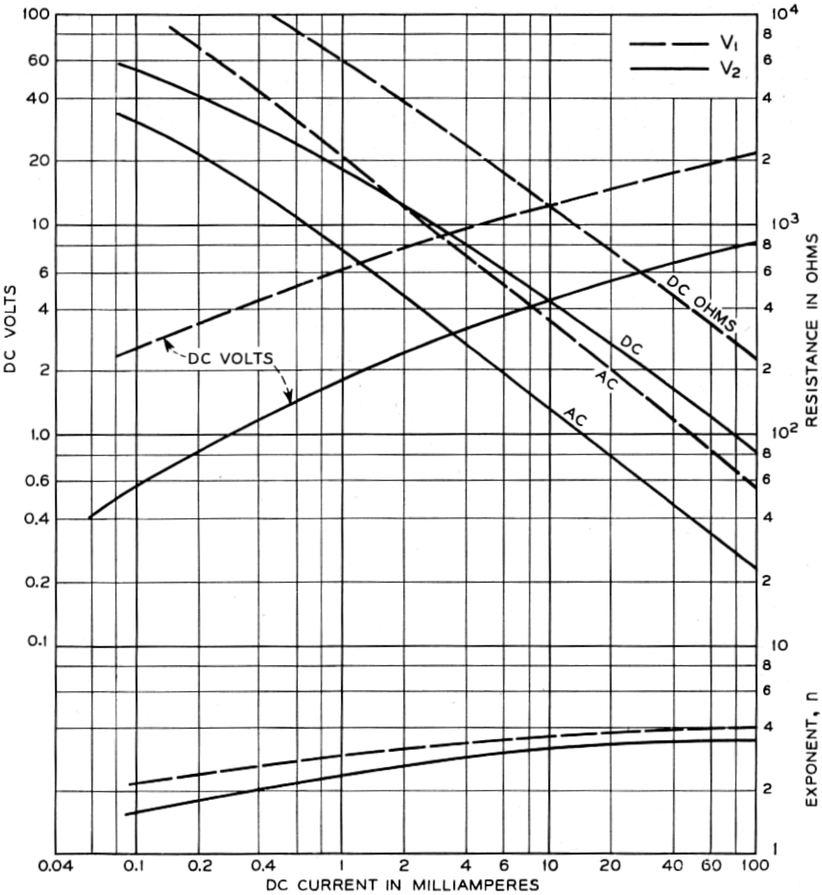

Fig. 1 — Characteristics of V_1 and V_2 varistors.

observed that the resistance decreases markedly with increasing voltage or current.

The direct current characteristics of a silicon carbide varistor may be expressed in a simple form by

$$I = AE^n, \tag{1}$$

where I is the direct current through the varistor and E is the applied dc voltage. When $n = 1$ the equation (1) reduces to an ohm's law relationship. A and n are generally regarded as constants when considered over a limited range in current. However, over the range shown in Fig. 1, it may be seen from the curvature of the voltage — current characteristic that this is only a rough approximation and can be considered as valid only over a limited range in current. The value of the exponent n, which on a logarithmic scale is the reciprocal of the slope of the voltage-current characteristic and which also is plotted on Fig. 1, is seen to increase appreciably with increasing current. For example, n for the V_1 varistor covers a range from about 2 to 4.

In a telephone set the alternating signal currents are small relative to the direct currents. Therefore, in explaining how the silicon carbide varistor controls the transmission equalization and sidetone, it is necessary to examine how its ac resistance to small signals varies with direct current.

Equation (1) can be put in the form

$$E = \left(\frac{I}{A}\right)^{1/n}. \tag{2}$$

Differentiating this with respect to I we get for the ac resistance to small signals

$$\frac{dE}{dI} = \left(\frac{1}{A}\right)^{1/n} \frac{1}{n} I^{(1/n-1)} = \frac{1}{n}\frac{E}{I}, \tag{3}$$

where E/I is the dc resistance at the particular current at which n also is evaluated.

Thus, we see that the ac resistance of the varistor is the dc resistance divided by the exponent n, and further, that the ac resistance is con-

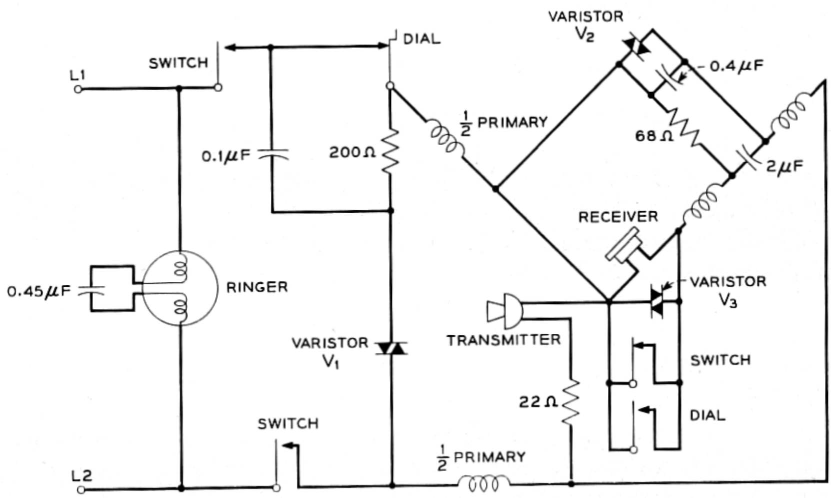

Fig. 2 — Circuit schematic of 500D telephone set.

trolled by the value of direct current. This is of great significance in the control of sidetone and transmission equalization, as will be apparent later.

Silicon carbide varistors have been used as circuit elements for various purposes for a number of years. In fact, the V_1 varistor was used in the original design of 500-type set to protect the tungsten filament against abnormal voltages. In this instance it was shunted directly across the filament, so that its inherent property of decreasing in resistance with applied voltage would serve to bypass current from the filament and thereby prevent damage when the applied voltage became too high. The requirements imposed by the transmission equalization and sidetone balance functions for the 500-type set are quite severe. A new varistor, the V_2, had to be developed which not only was much lower in resistance, but also maintained the n of the voltage-current characteristic at a high value. The successful outcome of this development and of the accompanying problems of design and manufacture, were of critical importance in making possible the simplification and economies offered by the 500D set.

TRANSMISSION EQUALIZATION

Fig. 2 is a circuit schematic of the 500D telephone set. This circuit is a modification of the circuit used in the 500B telephone set, which in turn is one of the Campbell anti-sidetone circuits[2] that has been standard in the Bell System for a number of years.

A simplified diagram of the transmission portion of the circuit is shown in Fig. 3, and it can be seen that there are three branches in the

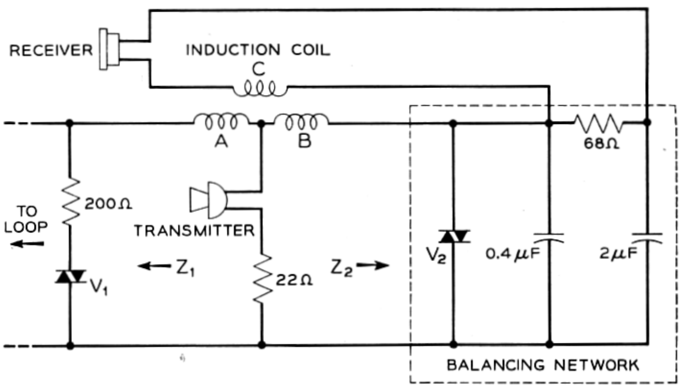

Fig. 3 — Diagram of transmission circuit of 500D telephone set illustrating side tone balance.

circuit which carry direct current. One is through the combination of the varistor V_1 and the 200-ohm resistance, which is bridged across the set. Another is through the winding A of the coil, the transmitter and 22-ohm resistance. The third is through winding B of the coil and the varistor V_2.

Fig. 4 shows the dc and ac resistance of the V_1 and V_2 varistors at various loop currents when connected in the telephone circuit in the normal way. The magnitude of the direct currents which flow through the varistors under these conditions differs from the currents shown in Fig. 1 and, therefore, the resistances are different. However, the inherent property of decreasing in resistance with increasing current is evident, as is also the fact that the ac resistance is much lower than the dc resistance. From this it is apparent that the varistors will introduce shunt losses and that these losses will be greater for ac than for direct currents because the resistance of the varistor is lower in the former case.

The variation in transmitting plus receiving loss with loop current is shown in Fig. 5. These curves are plotted in terms of the level of the 302-type set. If no equalization were provided in the circuit, the full transmitting and receiving gain offered by the new transmitter and receiver would be obtained at all loop currents. This condition is indicated by the broken line at the top of the diagram. With the equalization introduced by the varistors, the loss is graded from an insignificant

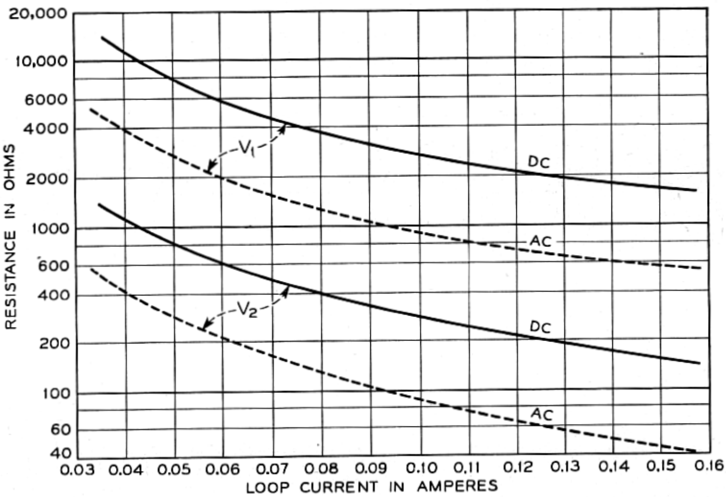

Fig. 4 — Characteristics of V_1 and V_2 varistors in circuit of 500D telephone set.

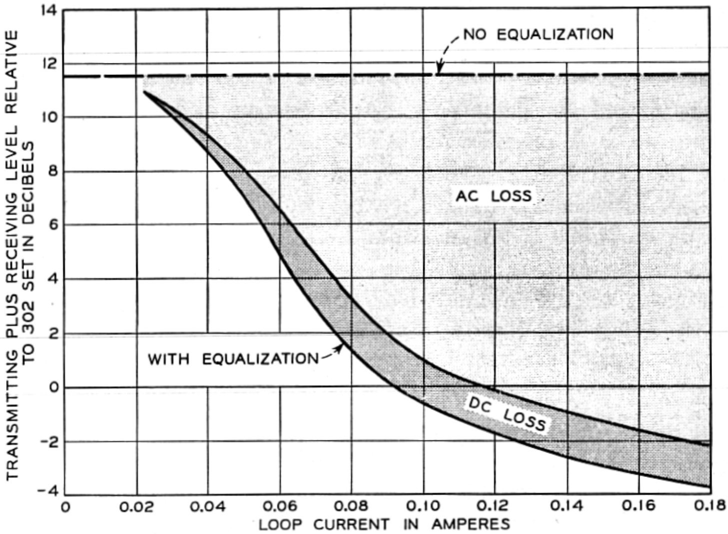

Fig. 5 — Level of 500D telephone set at various loop currents with and without equalization.

amount for long loops to a maximum for short loops. It is important to note that the greatest portion of this loss is the ac shunting loss introduced by the varistors.

SIDETONE BALANCE

Before considering the matter of sidetone balance, it will be helpful to examine some of the features of the telephone set circuit which are required for good receiving and transmitting performance. For simplicity, the induction coil is shown in a hybrid arrangement in Fig. 3. The speech currents received from the loop pass through the windings A and B of the induction coil which are so connected that they produce additive voltages in winding C which is connected to the receiver. These additive voltages would cause a resultant current to flow in the network resistance (68 ohms), were they not opposed by an approximately equal voltage 180° out of phase which results from the receiving current in winding B. Therefore, there is little or no voltage drop across the network resistance. Maximum receiving levels are thus obtained without appreciable power loss in the network resistance.

The transmitter of the set is made low in resistance because it is in series with the loop and influences the permissible loop range of the set from the standpoint of supervision. The impedance Z_1 looking toward the loop is relatively high. To obtain acceptable transmitting levels, the low impedance of the transmitter must be approximately matched to the high impedance loop by providing a proper ratio of turns between windings A and B. Therefore, the impedance Z_2 looking toward the balancing network must be made low and since an important element of this network is the V_2 varistor, this had to have an unusually low resistance. This is the reason why it was necessary to undertake a special development to make available a silicon carbide varistor having suitable characteristics.

Sidetone would be eliminated if the vectorial sum of the voltages in the mesh which includes the receiver, and which arise as a result of speech and noise picked up by the transmitter, were zero. The complete elimination of sidetone is not desirable, but the objective is to keep it at a low level by a balance of opposing voltages. To achieve this result any voltage developed in the local transmitter is divided in the windings A and B so that the voltages induced in winding C are opposing. Furthermore, the voltage across the network resistance arising from current flowing in winding B is arranged to oppose this resultant of voltages induced in winding C. The overall effect of this balance is that the current in the receiver as a result of voltages developed in the transmitter is small. Also, this result gives maximum transmitting levels because there is little power loss in the receiver. However, to maintain the balance which gives low receiver currents the impedances Z_1 and Z_2, as affected by the transformation ratio of the coil, must be comparable. This is the key to good sidetone balance — that the impedances Z_1 and Z_2 be effectively matched both in magnitude and phase.

Now in the telephone plant, the impedance looking from the station toward the loop varies widely from one installation to another, and even from one call to another. The loop may be long or short, of small gauge or large gauge, and composed of cable or open wire or combinations of the two. Furthermore, the loop may be loaded or non-loaded and it may be connected through central office circuits of different characteristics to a trunk or distant loop and telephone set which also may cover a range in impedance. It is quite obvious that under these conditions the impedance looking toward the loop will not only vary over a wide range in magnitude, but may be inductive, or capacitive or essentially resistive.

If we assume that the V_2 varistor were not present, the impedance Z_2 looking toward the balancing network is not influenced by loop current. This is the situation that has obtained in balancing sidetone in preceding designs of telephone set. One of the impedances to be matched was fixed and the other varied over a wide range. The sidetone balance under such conditions represented the best compromise that could be made among a large number of uncontrolled factors.

Let us examine next how the varistors affect this balancing problem and consider the influence of long and short loops. From what has already been shown, the varistor is a variable impedance element — that is, both its dc and ac resistance depend on the direct current. If the loop is long and composed of open wire the impedance looking toward it is high, perhaps 1200 ohms, and the direct current is low. The dc resistance of the V_1 varistor is then so high (approximately 10,000 ohms) that it has no appreciable effect on the impedance Z_1. Even the ac resistance of about 4,000 ohms does not have an appreciable shunting effect on Z_1. On short loops and local connections where the current is large and the impedance looking toward the loop may be of the order of 900 ohms, the dc resistance of 1,800 ohms has little effect. However, the ac resistance of 600 ohms does have an appreciable effect on Z_1, bringing about a better impedance match.

The impedance looking toward the balancing network and receiver without V_2 connected in the circuit is approximately 75 ohms, and is not affected by the loop current. If we go through the same process of examining the shunting effect of V_2 on the impedance Z_2, we see that at small loop currents both the dc and ac resistance of V_2 are too high to have any appreciable effect. At large loop currents the dc resistance of V_2 is under 150 ohms, but the ac resistance has dropped to well below 50 ohms and has a decided effect on the impedance.

Since the varistors are essentially pure resistances they tend to make the impedances Z_1 and Z_2 presented to the coil more resistive than they would be if the varistors were not present. This has the effect of reducing the difference between loop impedances which are capacitative, inductive, or resistive from the standpoint of phase angle and thereby improves the impedance match.

The overall effect of the automatic changing in resistance of the V_1 and V_2 varistors is to provide better matching and thereby reduced sidetone. This is shown in Fig. 6, where the loudness level of sidetone of the 500D set is plotted against loop current. It will be noted that with V_1 and V_2 open circuited, there is a continuing increase in sidetone loudness level with increasing loop current. When both V_1 and V_2 are connected in the circuit a decrease in sidetone level of 10 db or more is obtained at medium and large loop currents. The decrease is less at small loop currents. The close interrelation between the varistors and the circuit is well illustrated by the fact that if either the V_1 or V_2

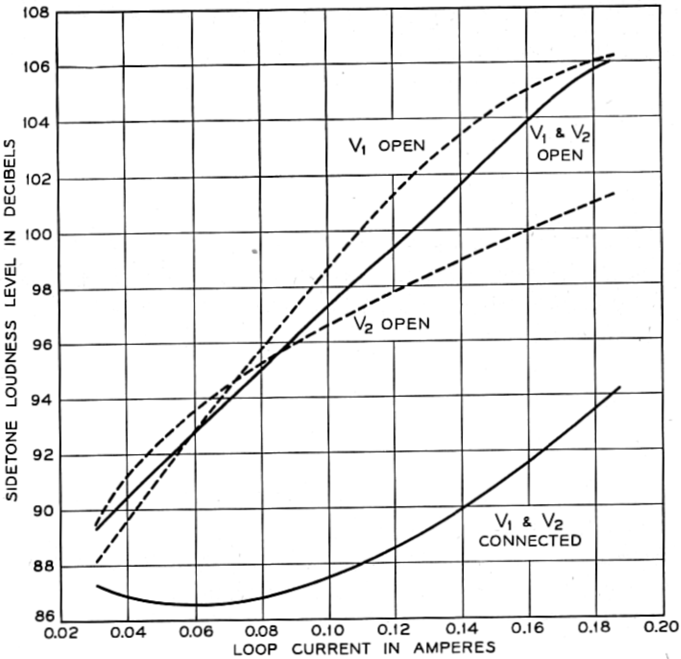

FIG. 6. — Effect of V_1 and V_2 varistors on sidetone loudness levels of 500D telephone set for average speech.

varistor is opened, almost all the effects of sidetone balancing are lost. It requires the presence of both V_1 and V_2 to obtain the impedance matching necessary for good balance.

From all that has been said, it should not be thought that the sidetone balance of the 500D set is perfect under all plant conditions. The impedance looking toward the loop varies so greatly in magnitude and phase that the best overall balance involves compromise. However, the balance provided is as good as with the original design of 500 set, which was considerably better than that attained by any previous design of commercial telephone set.

OTHER MODIFICATIONS

The introduction of the new equalization and sidetone controls in the telephone set has required a number of changes in other components of the set to realize all possible economies. Fig. 7 is a photograph of the transmission network (425A) which was employed in the earlier 500 A and B type sets. In the new arrangement shown in Figure 8

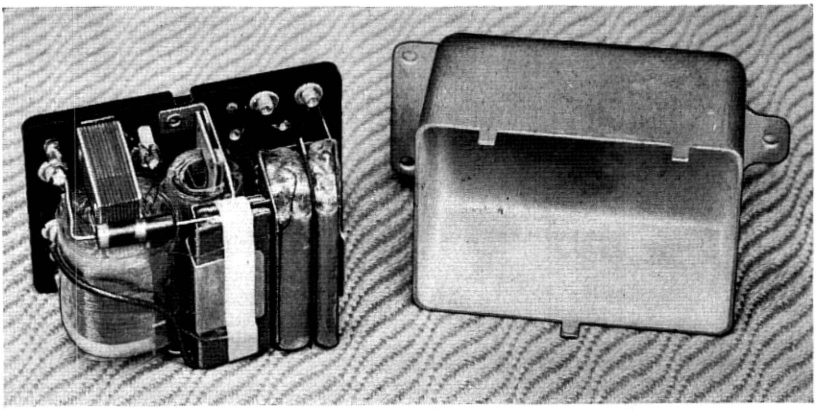

Fig. 7 — 425A Network used with early design of set — the 500A and B type.

the V_1 and V_2 varistors have been included in the network (425B), thereby providing mechanical protection for these elements. It has been necessary to design a new terminal block which is the plastic member to which the components of the network are mounted.

OVERALL RESULTS

By means of the V_1 and V_2 silicon carbide varistors and the rearrangements made in the circuit, the overall transmission performance of the modified set has been made substantially the same as that provided by the original design of set. The savings in manufacturing cost resulting from this modification are significant. Figure 9 shows on the left the

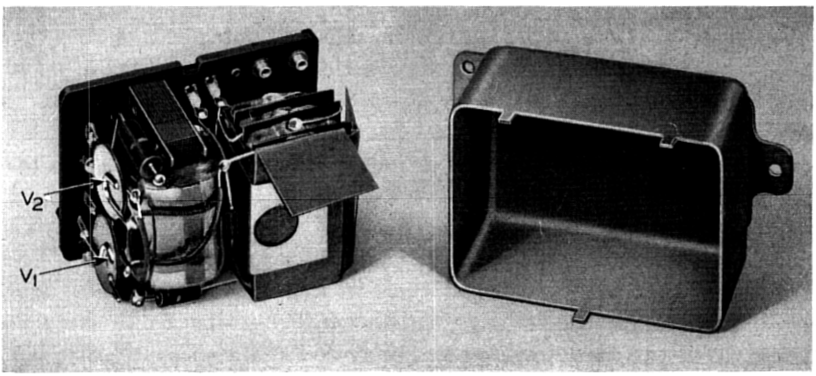

Fig. 8 — 425B Network used in present production set — the 500C and D type, showing the V_1 and V_2 varistors.

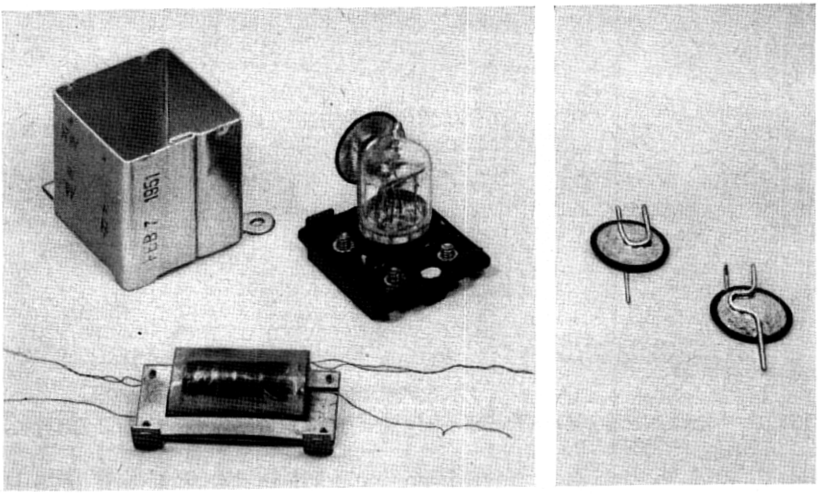

Fig. 9 — The 311A equalizer and autotransformer on the left are replaced in the 500C and D set by the V_1 and V_2 varistors on the right.

parts which have been eliminated — the 311A equalizer and auto-transformer. On the right are shown the V_1 and V_2 varistors which provide essentially the same performance as the replaced parts.

Another advantage of the change in design, though a difficult one to evaluate, is that of dependability. The silicon carbide element has an extremely long life and in this respect is inherently better than the type of equalizer which involves the use of a heated tungsten filament.

OPERATION IN NOISY LOCATIONS

Since the previous paper on the 500 set was published,[1] a study has been completed on the comparative performance of the 500-type set and its predecessor, the 302 type, in locations where room noise is severe. This is of particular interest, because the sidetone characteristics which have been discussed play an important part in transmission performance under such conditions.

For many years the securing of improved performance of the telephone set under noisy conditions has been a serious problem. It has been established that receiving impairment in a noisy location is far more limiting than the transmitting impairment resulting from the noise picked up at the noisy location and delivered to the distant party. This is due to the fact that the signal to noise ratio in the transmitting direction is improved by the natural tendency of the speaker to raise his voice when the ambient noise level is high. A major factor in the impairment of received speech in the noisy location is the masking of received speech by noise picked up by the transmitter and delivered via the sidetone path to the receiver. Therefore, a telephone set which minimizes the masking sidetone noise during the listening interval should operate more satisfactorily in noisy locations. In many previous instances where the noise conditions were extreme, a "push-to-listen" switch was provided to cut off the local transmitter while listening and thus prevent the introduction of noise to the receiver via the sidetone path. With its higher efficiency and better sidetone balance, the 500-type set approaches the good performance of such a "variable" set under noisy conditions and provides this adequate performance to the user more conveniently and with the expenditure of less effort.

Laboratory tests have been made which permit appraisal of the merits of various telephone sets or modifications of them under high noise level conditions. These include talking and listening tests between two telephone stations under typical loop and central office conditions with an adjustable amount of typical room noise at the listening end. During the tests the length of trunk between the two stations was increased until the received speech was just sufficiently intelligible to permit carrying on a conversation. This threshold of intelligibility expressed in db of trunk loss was taken as a criterion of the performance of a given set.

Fig. 10 shows the results of the tests made with the 500-type set compared with the 302-type set, and with variations of the 500 type set. 500C- and D-type sets having silicon carbide varistors were used in this comparison, but in this respect the performance is no different than for the earlier design (500A and B). The curves shown are for the average of eight observers.

The abscissae of the curves are the noise levels at the listening end expressed in db above 10^{-16} watts per sq. cm. For reference purposes it should be kept in mind that the average noise in a fairly large business office is, on this scale, approximately 65 db. For further orientation as to the significance of the noise levels shown, it should be noted that when a level of about 100 db or higher is reached, it is extremely difficult to carry on a face-to-face conversation where no telephone is involved. The ordinates show the relative trunk loss in db over which it is possible, under the stated conditions, to just carry on a telephone conversation. Therefore, the larger the trunk loss, the better the performance.

It is seen from Figure 10 that the 500-type set is from 6 to 8 db better than the 302 set over the indicated range of ambient noise conditions.

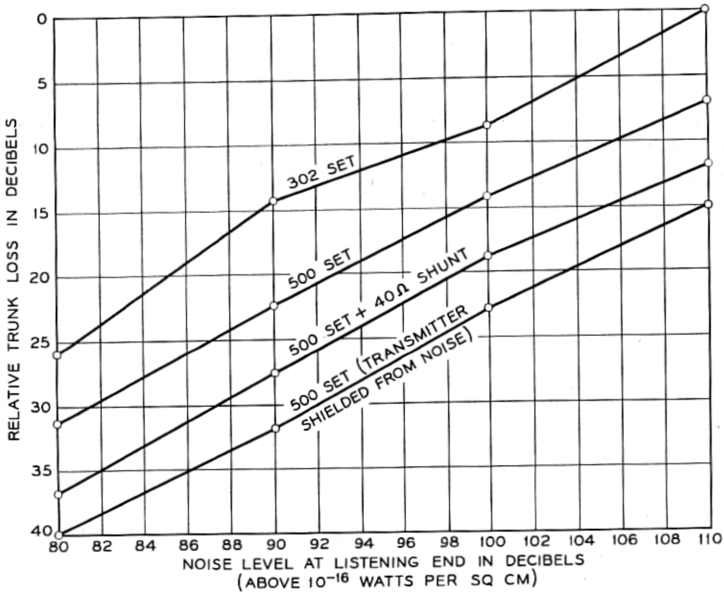

Fig. 10 — Effect of noise at listening end on trunk loss.

This improvement is attributed to the following:

1. The better sidetone balance of the 500-set circuit reduces the level of sidetone noise picked up by the transmitter and reproduced by the receiver, thereby providing a gain in signal to noise ratio.

2. The acoustic impedance looking from the ear canal into the U1 receiver[3] of the 500-type set is lower than the acoustic impedance of the HA1 receiver of the 302 set and, therefore, the acoustic noise pressure built up in the ear canal by leakage around the receiver cap is lower than when the HA1 receiver is used.

3. The output from the transmitter of the 500-type set under noise conditions contains less extraneous distortion products, giving it a character which is less disturbing than with the 302 set.

Included in the laboratory tests were experiments in which the output of the transmitter was intentionally lowered. It is known that a speaker in a noisy location instinctively raises his talking level. Since it is desirable to keep the sidetone level low to improve the signal to noise ratio, the output level of the transmitter at the listening end was reduced about 10 db by shunting a resistance of approximately 40 ohms across the transmitter. The sensitivity of the transmitter is reduced and sidetone noise is directly lowered. The level of the received speech is unaffected. Therefore, the signal to noise ratio in the receiving direction is improved. The transmitting level is not too adversely affected, because the tendency of the subscriber to increase his talking level when the room noise level is high largely offsets the lower efficiency of the transmitter to speech sounds. These effects are borne out in the applicable curve of Fig. 10 which shows that an improvement of approximately 5 db in trunk results from the shunting of the transmitter.

Carrying this experiment further and acoustically shielding the local transmitter completely from noise, the lower curve of Fig. 10 was obtained. This is equivalent to shorting the transmitter as is done in the earlier "push-to-listen" types of telephone set, except that it does not introduce any electrical effects in the circuit. This shielding provides about 4 db additional discrimination against noise. This, then, indicates the limit to which we can go in reducing the effects of room noise on received speech by operating on the transmitter element alone.

From the data presented in Fig. 10 it is evident that the 500-type telephone set provides a significant improvement when the subscriber is carrying on a telephone conversation under noisy room conditions. While it has been indicated above that the greatest gain of the 500-type set over the 302 type under high room noise conditions is with respect to received transmission, it is also better in transmitting from noisy locations. This is because of the less disturbing character of the transmitted noise and because the signal to noise ratio is improved by having the transmitter closer to the subscriber's lips, which is a feature of the new handset.

Where noise conditions in the field are severe, the 500-type set will provide material improvement. Typical of such conditions are noisy business locations, telephone stations which are located in power plants and near loading ramps at airports. Where the noise is particularly severe, the provision of a 40-ohm shunt resistance on the transmitter of the 500-type set offers still further improvement and is recommended for application by the local telephone people.

CONCLUSION

The simplification of the 500 set made possible by the use of silicon carbide varistors, with its attendant reduction in manufacturing and maintenance costs and increase in life represents a significant step forward in station set design. A valuable characteristic of the 500-type set is the substantial improvement in transmission performance under conditions of severe ambient noise.

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