Negative Impedance Telephone Repeaters

By J. L. MERRILL, JR., A. F. ROSE, and J. O. SMETHURST

(Manuscript received June 8, 1954)

In the exchange telephone plant, speech is transmitted largely at voice frequencies over a single pair of wires that carries conversation in both directions. Until recently, adequate transmission was assured through a suitable choice of coil loading and conductor size. The need for voice frequency amplifiers had long been recognized, but wide use of the conventional hybrid type of repeater with separate amplifiers for conversation in the two directions had not been economic. In 1948, however, a new type of repeater was introduced that used the same source of gain for transmission in both directions, and did not require costly filters. This repeater is known as the E1 repeater. It operates as a negative impedance in the line.

This paper describes the wide field of usefulness of two new types of negative impedance repeaters, the E2 and E3. Sufficient theory is given to show the advantages of using two types of negative impedance in a line, the series type and the shunt type, and how, by the addition of the shunt type to the series type, it is possible to insert gain without serious reactions on line impedance. The new equipment is described and maintenance features, together with methods of testing this relatively new type of repeater, are discussed.

APPLICATION IN THE BELL SYSTEM

INTRODUCTION

The application of the telephone repeater, the development of which made countrywide telephone service practicable, had been confined largely to toll plant from the year 1915 when the transcontinental line was first established, until a few years ago. About 1948 the negative impedance repeater[1] was developed and placed in production. This repeater operates on the principle of inserting negative resistance (and, if desired, negative inductance or capacitance) in series with the line, thus reducing the overall impedance and increasing the current in the line. This results in transmission gain in the same sense as that resulting from a repeater of the conventional type. This principle and the package nature of the assembly resulted in a telephone repeater so low in cost and so simple in application and installation that it has found extensive use primarily in the local telephone plant.

In the period from 1948 to the present time, over 50,000 series-type negative impedance repeaters were manufactured and incorporated in the Bell System telephone plant. These repeaters have been used largely on intraexchange trunks and on trunks extending from the exchange areas to near-by smaller towns. Such installations have been very effective in improving the transmission on short haul calls and in many cases have also reduced trunk costs by permitting the use of smaller and cheaper conductors. They are usually operated at gains that reduce the nonrepeatered trunk loss by more than half.

Negative impedance repeaters are especially suited to exchange trunk use, not only because of their simplicity and ease of maintenance, but also because unlike earlier types of repeaters, they preserve the dc continuity of the circuits on which they are installed. This latter feature means that they do not interfere appreciably with the signaling methods ordinarily used on such trunks. Also, they have the added advantage that, in the event of tube failure, the circuit still functions but with its loss substantially raised until the defective tube has been replaced.

APPLICATION OF SERIES-TYPE NEGATIVE IMPEDANCE REPEATERS

In a multioffice exchange area, trunks can generally be grouped in three classes. Largest in number are those known as interoffice trunks which extend directly from one local operating center to another local center in the same exchange operating area. In some cases direct trunks between two centers can not be justified and each office has trunks to a central location known as a tandem center where a through connection is made when required. This second class of trunks is known as "tandem" trunks. Frequently trunks of this type are provided to supplement the direct trunks and thus give the added advantage of alternate routing. A third type of trunk extends between the local office and the toll office and therefore always forms part of a toll connection to the local office. These are known as toll connecting trunks. In single office areas the toll connecting trunks to neighboring small towns are known as "tributary" trunks.

In some large multioffice exchange areas there are also trunks between the toll office and tandem centers which may be some distance from the toll office and through which local offices reach the toll office for long distance calls. These trunks are also called tandem trunks but are more in the nature of intertoll links and are required to operate at very low loss similar to an intertoll circuit.[2]

The most extensive use of negative impedance repeaters has been in connection with the interoffice trunks. In this role they have been extremely useful and have contributed greatly to transmission improvement in the last few years. It would also be desirable to utilize this new and effective tool in reducing the losses of toll connecting and tandem trunks. There have been many cases of this type where improvement has been effected, but a very wide use has been prevented by their effect on return loss.

The insertion of a series negative impedance in an otherwise uniform loaded circuit introduces an impedance discontinuity which means that a substantial amount of energy is returned to the sending end of the circuit as "echo." As the introduction of negative impedance is the method of obtaining gain from the series repeater it follows that the magnitude of the impedance discontinuity and therefore the "echo," is proportional to the gain of the repeater. The effect of echo on ease of conversation depends both on its magnitude and on the amount of delay[3] before the echo reaches the talker's ear. When the delay is small as in the case of an interoffice trunk a large amount can be tolerated, but in the case of a toll connecting trunk which becomes a part of a toll connection the delay may be large and only a small amount of echo can be permitted. This limits the amount of gain from a series repeater when it is used in toll connecting trunks.

As a result of this feature of the series negative impedance repeater, most cases requiring substantial gains in toll connecting or tributary trunks usually had to be handled by the older and more expensive hybrid-coil type repeater. With this latter repeater, it is practicable to introduce gain without serious reflection effects if proper attention is given to network design and to uniformity of construction of the line itself. However, the cost of the more complicated repeater was relatively high so that the new development described herein was undertaken to meet the indicated need, i.e., a repeater embodying the same desirable features of simplicity of design but still approaching in performance that of the hybrid-coil repeater in its effect on return loss.

The new repeater (E23) consists essentially of the earlier series repeater with the addition of a shunt negative impedance element. This combination has approximately as small an effect on return loss as the hybrid-coil repeater and will give about the same gain when used under similar line conditions. As a result, the field of use of the negative impedance type repeater will be greatly extended, especially in the toll connecting plant where, from a practical standpoint, certain features of the hybrid-coil repeater are not needed. For example, more than 10 db gain is rarely required, and unequal gains in opposite directions would not ordinarily be useful. Besides, methods of signaling requiring a 4-wire split of the repeater are not utilized on exchange area trunks.

In addition to its important new characteristics, the series-shunt combination retains the desirable features of the earlier series repeater, i.e., it preserves dc continuity, it is simple in design and it is easy to install and maintain. If properly engineered and installed on circuits of reasonably uniform impedance, the new repeaters can be operated in tandem, do not have serious reactions on return loss, and are capable of reducing the losses of the trunks to about the same values as hybrid-type repeaters.

SCOPE OF APPLICATION OF THE NEW REPEATER

With the reduction of the return loss reaction of the earlier form of negative impedance repeater, the extent of application of the new E23 repeater becomes largely a matter of economics. In the telephone trunk plant, there are generally three gauges of conductors available for trunk use, namely, 19, 22 and 24. The larger gauges, utilizing more copper and requiring more conduit space, naturally cost more than the smaller

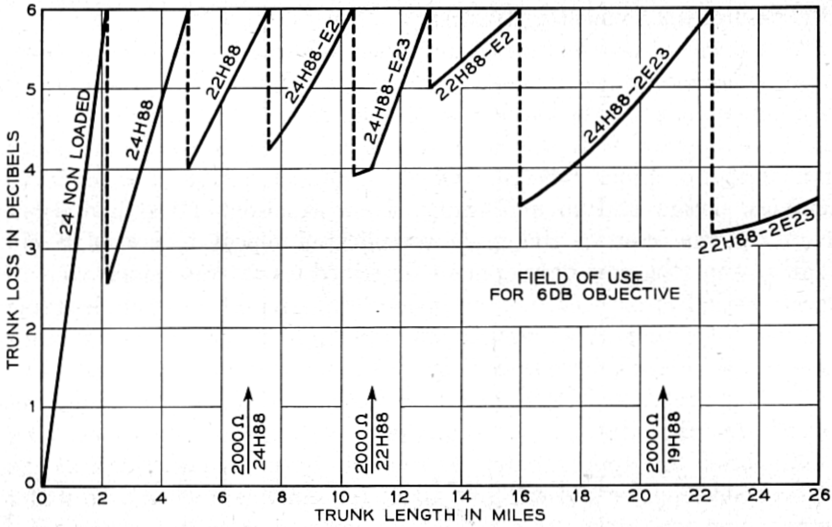

Fig. 1 — Illustrative field of use; interoffice trunks.

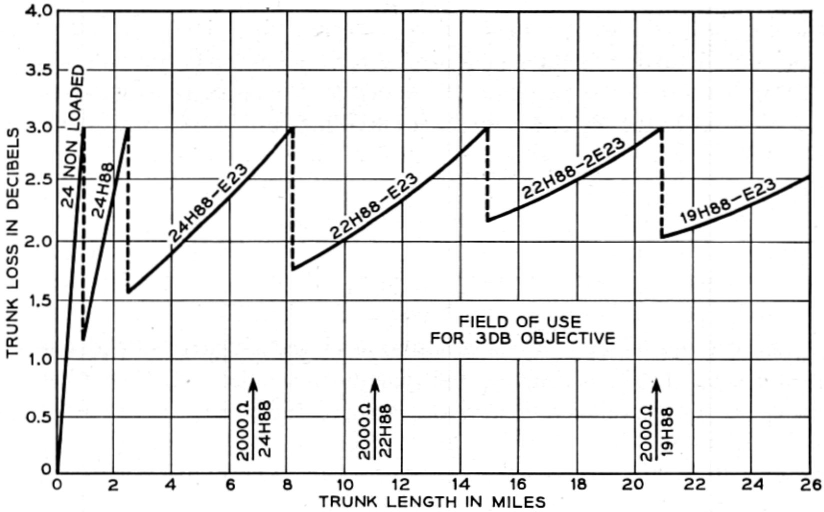

Fig. 2 — Illustrative field of use; toll connecting or tandem trunks.

gauge. In general, it is the practice to select the smallest gauge which will give the required transmission loss. For short distances, the differential in cost between trunks of different gauges is not large but as trunk length increases it will be found that a smaller gauge trunk with a repeater will cost less than one of larger gauge without a repeater. For example, at 10 miles a 22-gauge circuit with a repeater will cost substantially less than a 19-gauge circuit with no repeater. Also, as transmission objectives are improved, there may be cases where a smaller gauge trunk with two repeaters will be cheaper than a larger gauge with one repeater. Furthermore, in cases where the costs are about equal or even where the larger gauge is slightly cheaper, it will be found that lower losses can be obtained with repeatered circuits and the engineering choice would accordingly favor the smaller gauge.

Construction costs differ considerably depending on local conditions; hence the differential cost between the various gauges of conductors will differ correspondingly. However, for illustrative purposes Figs. 1 and 2 have been prepared which utilize average Bell System costs for both outside plant and telephone repeaters. In the case of the E23 repeaters, the experience so far has been somewhat limited so there is a greater degree of uncertainty as to the actual costs than for the older type repeater or the outside plant construction.

Fig. 1 shows the field of use for various conductor gauges when used in interoffice trunks where an over-all transmission objective of 6 db for the trunks has been assumed. In considering this chart it will be seen that non-loaded 24-gauge conductors can be utilized for the shorter distances up to about two miles. The next step is to apply loading, which is indicated in the chart by the symbol H88 meaning 88 millihenry coils at 6,000 foot spacing. After reaching the limit of about 7 miles without repeaters on 22-gauge, the differential between 22- and 24-gauge is more than enough to pay for a repeater, the simple series repeater (E2) being used for distances up to 10 miles and then the improved E23 repeater extending the use of 24-gauge to about 14 miles. Beyond this point the most economical combination is indicated.

The general effect of the introduction of the negative impedance repeater is to shift the average gauge distribution so that more small gauge cable can be economically utilized, accompanied in most cases by improved transmission. It will be noted from the figure that no 19-gauge cable will need to be added in the future to care for interoffice trunks up to distances as great as 25 miles between offices. Of course, in cases where 19-gauge is already available in plant it can be used to advantage despite the fact that for new construction a smaller gauge with the negative impedance repeaters would be cheaper.

It has also been assumed in making up Fig. 1 that supervision or pulsing requirements will not limit the use of the smaller gauges. In a specific case where some of the older type central offices are involved, signaling may have an important bearing and substantially distort the economic ranges indicated on the chart.

Fig. 2 illustrates the field of use of toll connecting or tandem trunks. As a toll connecting trunk forms part of a multilink connection, and since there are always at least two (and often more) trunks in series on connections involving these trunks, the Bell System companies find it economical to plan for a maximum loss of 3 db for this type of trunk. Likewise for the tandem trunks, where two in series may be used in place of an interoffice trunk, 3 db is considered a reasonable objective.

It will be noted again by referring to this chart that 19-gauge has very little future field of use and in all cases the new "series-shunt" repeater will be utilized rather than the earlier series type because of return loss considerations and also because of the greater gain required to reduce the trunk losses to the desired values. In the tandem and toll connecting case, signaling may again be a distorting factor though not to so great an extent as in the direct interoffice trunk case. To this extent, however, the curves are theoretical, as they have been made up without regard to this limitation which may apply in a few practical cases.

SPECIFIC APPLICATIONS

Many installations of the new repeaters have been engineered for completion in 1954. In all cases economic studies were made and results of these studies broadly confirmed the indications of the two charts discussed above. To bring out more clearly the effectiveness of the E23 repeater, it may be worth while to consider a few specific cases involving installations of the new repeaters being made this year.

The first case shown on Fig. 3 is in the area of the Pacific Telephone and Telegraph Company. The figure shows the two alternatives that were considered for providing additional tandem trunks between San Francisco proper and the East Bay Area, needed this year because of an extension of customer toll dialing arrangements.

The engineering study for this project was somewhat more complicated than would ordinarily be the case because two possible routes of unequal length and with slightly different amounts of submarine cable were involved. The present route which touches Yerba Buena Island is subject to some hazard from dragging ship anchors but the circuit relief would have been cheaper here than on the other route shown, were it not for the new repeaters. The second route is considerably less hazardous and, in addition, is sufficiently removed from the present one to provide increased reliability under disaster conditions. Without the repeaters, however, the second route would have been somewhat impracticable, since it does not allow easy installation and access to required loading points between the two shore lines. However, with two of the new repeaters on each pair of conductors, nonloaded 22-gauge cable gives substantially the same effective transmission loss as loaded 19-gauge conductors on the shorter route and over a future period will involve less annual cost per circuit. Furthermore, the use of 22-gauge cable permits more than twice as many pairs to be included in the same size sheath in the expensive submarine section.

The initial installation of the new type repeaters on this cable will total about 1,300, divided between the Main Office in San Francisco and the Main Office on the East Bay side. Individual repeater gains are 5 to 7 db at 1,000 cycles but the repeater gain characteristic is shaped to offset the increasing cable losses at the higher frequencies so that the over-all circuit has relatively uniform transmission in the voice range.

The second case is one where the need for the repeaters results from the complex toll switching system at Chicago, Illinois. Here it has been found desirable, because of the great volume of toll traffic, to have several toll offices scattered throughout the city and suburbs. In general, toll calls coming into these offices from other cities are completed over toll

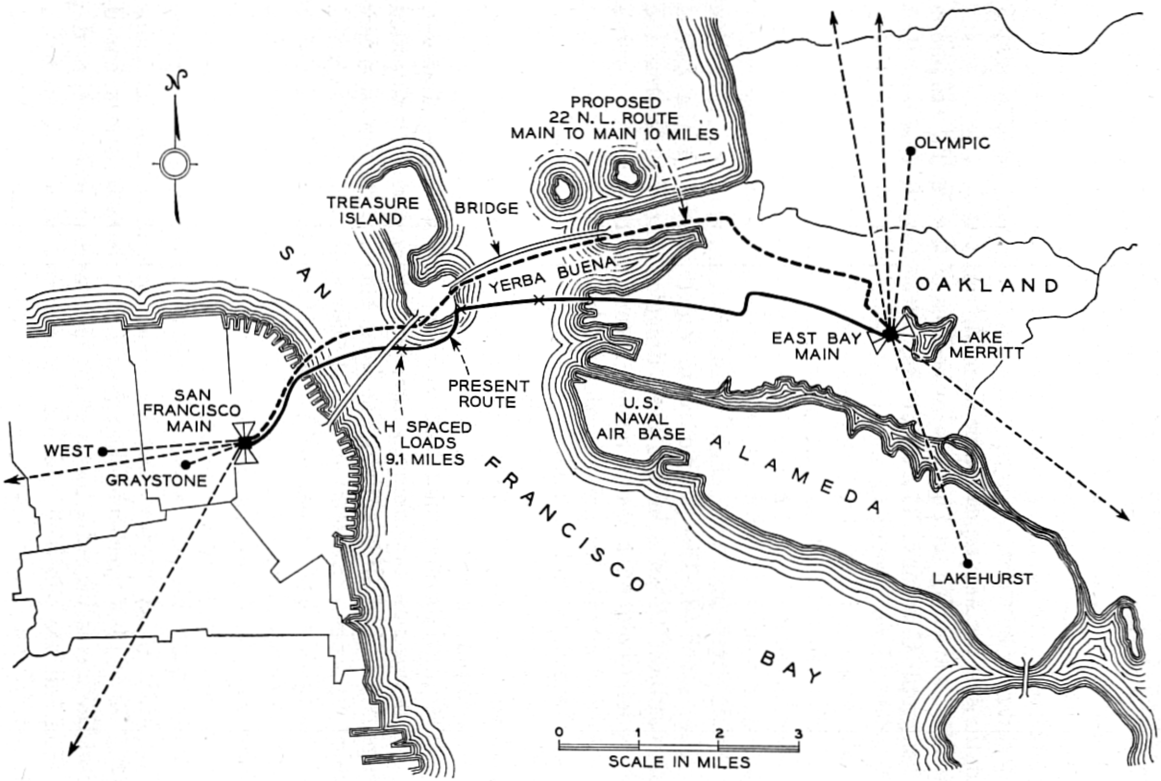

Fig. 3 — Typical E23 repeater application, San Franciso — East Bay tandem trunks.

connecting trunks direct to the called subscribers' central offices. It is not economical, however, to provide enough such trunks to handle peak loads. When all of these direct trunks are busy, an incoming toll call is switched to the subscriber's central office via a tandem office serving his general area. Since the losses of trunks between the tandem and local offices are of the same order as those of the direct trunks from toll to local offices, it would be desirable to operate the trunks between the toll and tandem offices at losses close to 0 db if this were practicable. In this way the same transmission objectives would be met on both routings and no contrast in transmission would be evident to the same subscribers on calls completed over the different routes at different times. Fig. 4 illustrates a specific case of 36 trunks between toll office No. 3

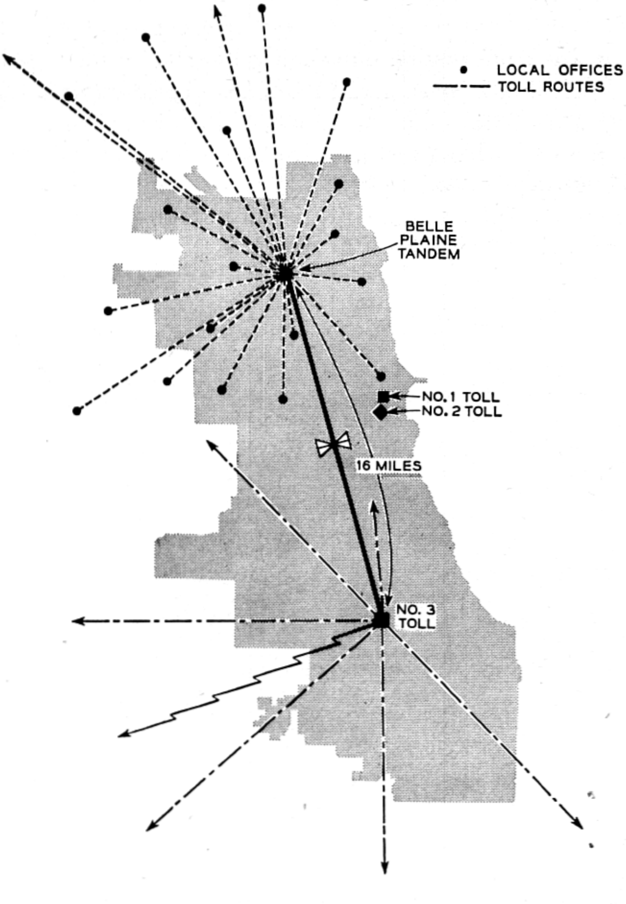

Fig. 4 — Typical E23 repeater application; Chicago toll tandem trunks.

and Belle Plaine tandem, a distance of about 16 miles. Without repeaters these trunks would have been operated at a loss of about 10 db but with the repeaters they are operated at about 2 db. The only alternative to using E repeaters in this specific case would have been to use the more expensive hybrid-type repeaters.

In some cases similar to this one, it was found practicable to temporize by installing the series repeater first and operating it at limited gain until the shunt element became available. Later, when the production of the shunt element was started, the additional units were added and full advantage of the new series-shunt design utilized in reducing the equivalent of the trunks to the lowest value permitted by echo return loss considerations.

The third example shown on Fig. 5 is in the city of Pittsburgh between Churchill tandem and the town of New Kensington, approximately 17 miles. Here the transmission on existing 19-gauge loaded cable without a repeater would have been about 8 db. The repeaters reduce this figure to between 2 and 3 db which should be satisfactory in this case. It should be noted, however, that 22-gauge with two repeaters would also provide a low enough equivalent, and should it become necessary to supplement the present cable at some future date, there will be an opportunity for further savings from the E23 repeaters.

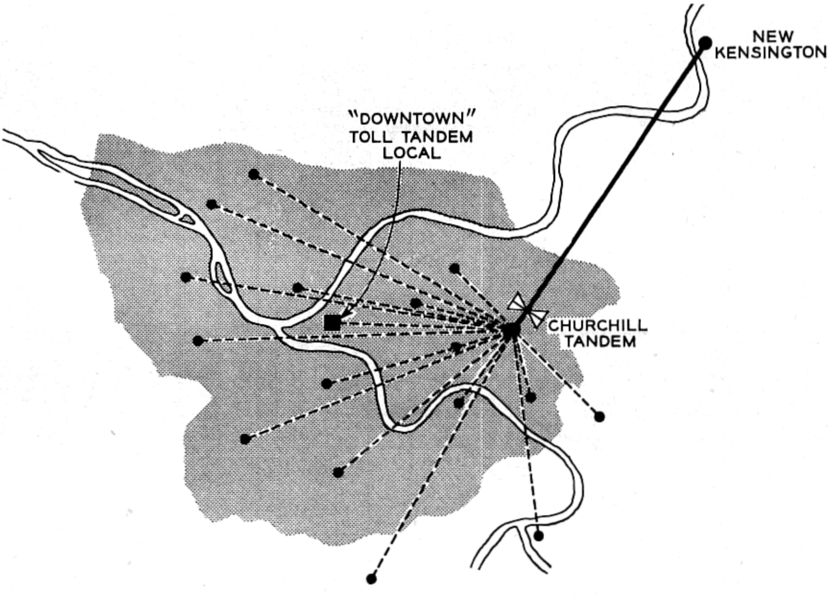

Fig. 5 — Typical E23 repeater application; Pittsburgh toll connecting trunks.

THEORY

NEGATIVE IMPEDANCE CONCEPT

Both the E2 and E3 repeater elements contain an amplifier having multiple feedback paths. The operation of an amplifier circuit of this type can be explained by classical feedback theory. However, experience with the E1 repeater over the past four years has shown the value of using a negative impedance concept in engineering such a device. Hence, in the explanation of operation given here, the repeater units will be treated simply as two-terminal networks which have negative impedance inputs over the frequency band of interest. The effect of introducing these impedances into telephone circuits can then be computed by the same simple network theory used to determine the effects of passive impedances.

THE E2 REPEATER UNIT

The E2 repeater is essentially a two-terminal network the impedance of which has a magnitude $| Z |$ and a negative phase angle that can vary with increasing frequency from minus 90 degrees, or less, through minus 180 degrees to at least minus 270 degrees. This type of negative impedance is shown in the diagram of Fig. 6(a). It has been known for many years as the series type because it could be produced by connecting the output of an amplifier back in series with its input. More recently it has come to be known as an open circuit stable, negative

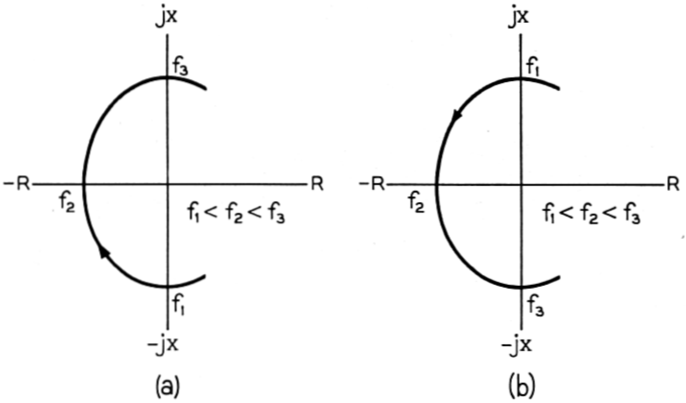

Fig. 6 — The two types of negative impedance: (a) Open Circuit Stable and (b) Short Circuit Stable.

impedance, because it will not oscillate when its two terminals are open circuited.

THE E3 REPEATER UNIT

The E3 repeater is essentially a two-terminal network the impedance of which has a magnitude $|Z|$ and a positive phase angle that can vary with increasing frequency from plus 90 degrees, or less, through plus 180 degrees to at least plus 270 degrees. This type of negative impedance is shown in Fig. 6(b). It has been known as the shunt type because it could be produced by connecting the output of an amplifier back in shunt with its input. In more recent years it has become known as the short circuit stable type because it will not oscillate when its two terminals are short circuited.

THE NEGATIVE IMPEDANCE CONVERTER

The amplifier circuits of both of these repeater units perform the same function: that of a negative impedance converter. The operation of such converters is illustrated in Fig. 7.

Fig. 7(a) shows the converter as a four-terminal network having a ratio of transformation k and a shift of phase through a negative angle of approximately 180 degrees over the operating band of frequencies. If, as shown, an impedance Z_N is connected to terminals 3 and 4 then the impedance seen at terminals 1 and 2 will be the impedance Z_N multiplied by the ratio k and shifted in phase through a negative angle of 180 degrees. This impedance will (over the frequency range of zero to infinity) fulfill the definition given for the impedance presented by the E2 repeater. Hence, Fig. 7(a) can represent the operation of the E2 repeater.

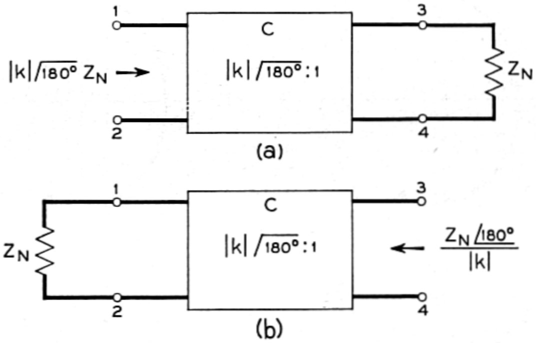

Fig. 7 — The Negative Impedance Converter: (a) E2, open circuit stable and (b) E3, short circuit stable.

Fig. 7(b) shows the same converter, but here the impedance Z_N is connected to terminals 1 and 2. The impedance seen at terminals 3 and 4 (at least over the frequency band of interest) will be Z_N divided by k and shifted in phase through a positive angle of approximately 180 degrees. This impedance will (if frequencies from zero to infinity are considered) fulfill the definition given above for the E3 repeater impedance. Thus Fig. 7(b) can represent the operation of the E3 repeater.

From Fig. 7, it is apparent that the same converter circuit could have been used for both the E2 and the E3 repeaters. For practical reasons it was not. However, the ratio k and the phase shift in both the converter of the E2 and that of the E3 were made approximately the same.

OPERATION IN TRANSMISSION LINES

Within limitations, the E2 repeater can be represented by a negative impedance, $-Z$, and the E3 repeater can be represented by a negative admittance, $-Y$. With a negative impedance and a negative admittance available, losses of transmission lines can be reduced in the manner illustrated in Fig. 8. The transmission line is represented by two networks as shown in Fig. 8(a). One of these (Network A) is in the form of a T network the series arms of which are represented by impedances Z; and the shunt arm, by an admittance Y. This network has a propagation constant $\alpha_1 + j\beta_1$. The attenuation α_1 represents the major portion of the line attenuation, and the phase shift β_1 is that just sufficient to make Network A realizable physically. This representation is necessary because Network A has image impedances each equal to the characteristic impedance (Z_0) of the line. If the characteristic impedance of the line were a pure resistance, then the phase shift through this network could be zero and β_1 could be zero. But the characteristic impedances of actual lines are not pure resistance; thus the phase shift β_1 must be included in Network A. The other network (Network B) is shown as a box. It has a propagation constant $\alpha_2 + j\beta_2$. Here β_2 represents the remaining phase shift in the transmission line and α_2 is an attenuation just sufficient to make Network B physically realizable in view of the image impedances which are both equal to Z_0, the characteristic impedance of the line. Fig. 8(b) shows the addition to this line of a repeater consisting of a T network made up of negative impedances $-Z$ in the series arms and a negative admittance $-Y$ in the shunt arm. The arm $-Z$ of the repeater adjacent to the line cancels Z of the line. The two admittances $-Y$ and Y cancel and the other series arms $-Z$ and Z also cancel. The result, as shown in Fig. 8(c), is that only the attenuation and phase shift of Network B remain.

In practice the amount of attenuation (α_1) which can be canceled by the repeater depends on the uniformity, the loss and the type of line. The permissible magnitude is computed by conventional methods which are beyond the scope of this paper.

Fig. 8 has shown how the combination of a series and a shunt repeater can annul a large part of the attenuation of a telephone line. Much may be accomplished also by a series negative impedance alone as illustrated in Fig. 9. In Fig. 9(a) a transmission line is again represented by two networks A and B. However, Network A now is shown as an *L* configuration having a series arm *Z* and a shunt admittance *Y* together with an ideal transformer of ratio 1:*K* where *K* exceeds unity. Network A of Fig. 9 is equivalent to Network A of Fig. 8, and Network B of Fig. 9 is the same as Network B of Fig. 8. In Fig. 9(b) the addition to this transmission line of a single $-Z$ such as the E2 repeater is shown. This negative impedance $-Z$ cancels the series impedance *Z* of Network A. The result is shown in Fig. 9(c).

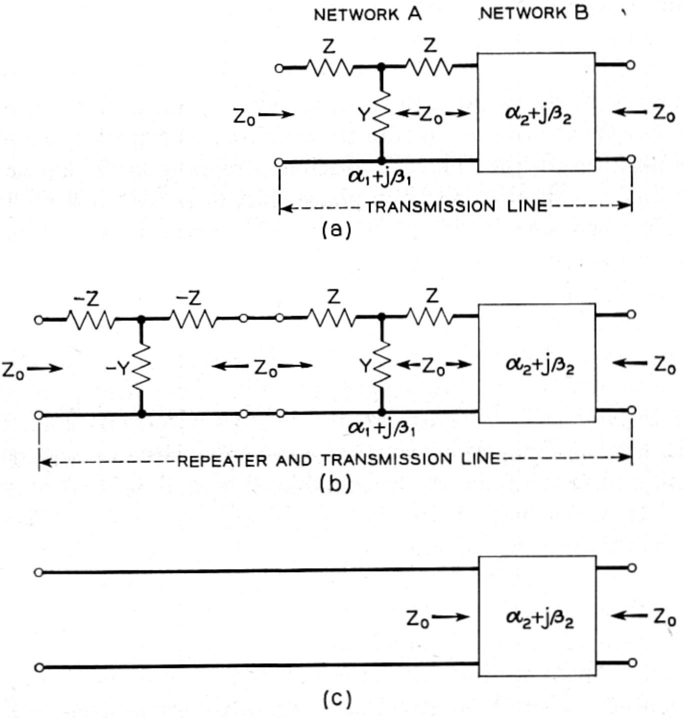

Fig. 8 — Operation of the "T" in a transmission line: (a) transmission line, (b) repeater and transmission line, and (c) result of addition of repeater.

Thus Fig. 9 shows that when a single $-Z$ is added in series with the conductors of a transmission line the attenuation is reduced, but the equivalent of a shunt conductance Y together with an impedance transformation is left. The impedance transformation $1:K$ could be corrected by means of a transformer if it were not for the shunt element Y. Thus an impedance irregularity is introduced, and this irregularity reflects power back toward the source. When the reflected power becomes a significant part of the total power passing through the line, transmission is unsatisfactory. Echo is excessive and therefore the use of the single series repeater is limited.

THE BRIDGED T STRUCTURE

The discussion of the T repeater, illustrated in Fig. 8, was based on the use of two series negative impedances and a shunt negative admittance. It is perfectly possible, and more economical, to obtain the same effect by using a single series impedance in a bridged T structure and this

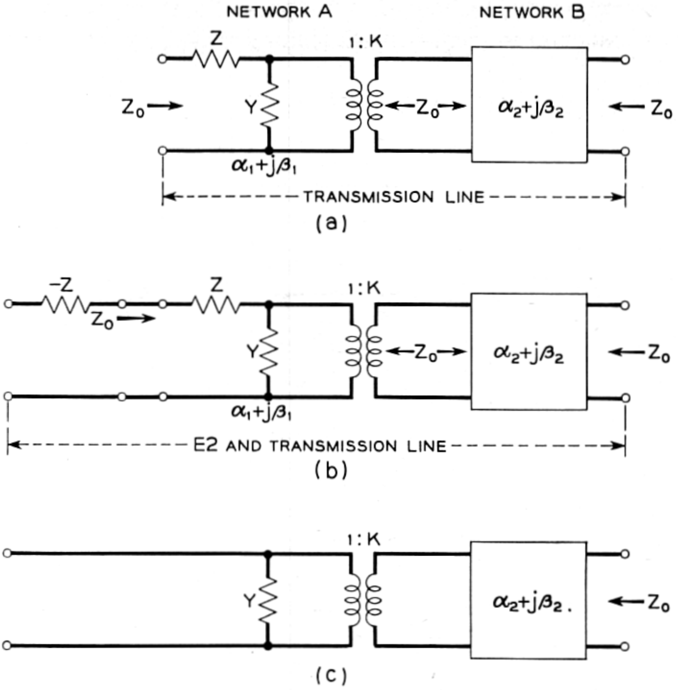

Fig. 9 — Operation of $-Z$ in a transmission line: (a) transmission line, (b) repeater and transmission line, and (c) result of adding repeater.

is, in fact, what is done with the E23 combination repeater. Fig. 10 shows how this is accomplished by using a center tapped line coil for the E2 repeater with the E3 connected as a shunt element to the midpoints of the coil. If the coil is considered to be ideal this arrangement is equivalent to the configuration shown in Fig. 11 in which the coil provides the basic bridge structure: the E2 repeater is the series arm; and the E3, the shunt arm. Incidentally this arrangement of E2 and E3 repeaters is similar to G. Crisson's twin 21-type repeater.[4]

For a bridged-T structure, the image impedance equals the square root of the product of the series and shunt arms and the attenuation (in db) is as indicated on Fig. 11.

If a network is to be inserted in an electrically long line without introducing an irregularity, its image impedance must match the characteristic impedance of the line. This would be the case for the bridged T network if Z_A were set equal to NZ_0 and Z_B were set equal to Z_0 divided by N. Then the square root of the product of Z_A and Z_B would be Z_0.

A network make up of negative impedances is designed to match a line in the same way and Fig. 12 is a representation of such a structure. Here, as a matter of convenience, the shunt arm is shown as an impedance

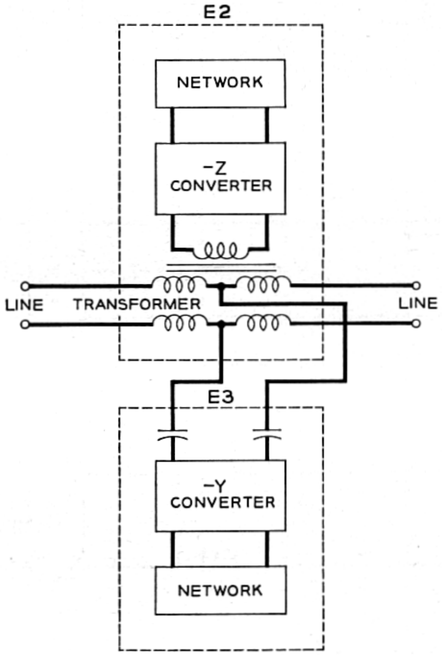

Fig. 10 — The bridged T repeater E23.

with a +180° phase shift instead of an admittance as used previously. The letter N designates a numeric or proportionality constant. It will be observed that the product of the shunt and series impedances is a real or positive impedance and hence the image impedance is a positive impedance, Z_0. The gain is determined entirely by the value of N. Thus if the characteristic impedance of a transmission line is known, together with the gain that the line can support without risk of oscillation, then N is known and the repeater network can be adjusted to give the required gain.

The advantage of the bridged T as compared to a single series negative impedance such as the E2 can be demonstrated by comparing the relative transmission gains obtainable from the two arrangements. Fig. 13(b) shows the insertion loss of a single impedance Z_A connected in series with a transmission line having a characteristic impedance Z_0. If Z_A is a negative impedance such as that produced by the E2 repeater then the repeater gain becomes a function of N as shown in Fig. 13(c). If N equals 2 the gain is infinite and the system will oscillate. Thus N must always be less than 2 where Z_A is a negative impedance of the series or open circuit stable type. Practically, the impedance of the transmission line is not a constant Z_0 but varies with termination, line construction and temperature. Thus N should be decreased until the negative impedance is always less than the sum of the two line impedances in series with it taking into account all possible variations in these impedances.

The same limitations on N apply to the bridged T repeater of Fig. 12

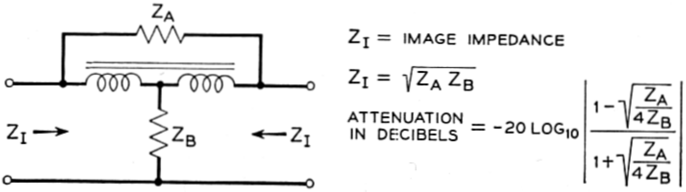

Fig. 11 — Schematic of the bridged T network.

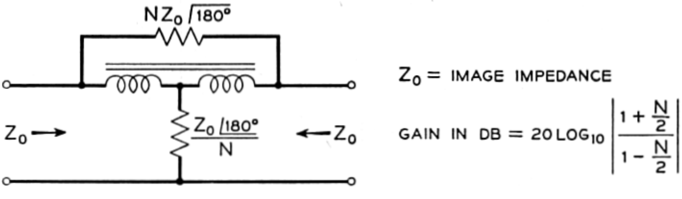

Fig. 12 — Schematic of the bridged T repeater.

as apply to the single series repeater. If N is 2 the gain is infinite and the circuit will sing. This similarity goes further. Assume that a single negative impedance Z_A equal to $NZ_0/\overline{180°}$ is inserted in series in an electrically long line and N is adjusted for stability. If this series element is removed and the bridged T of Fig. 12 is inserted in the same place and adjusted by changing N until the system is stable it will be found that N will have the same value in the bridged T structure as it had for the single series negative impedance.

Thus, if N is the same in the case of the bridged T as in the single series impedance, the gain advantage can be obtained by comparing formulas on Figs. 12 and 13 from which it can be seen that the gain advantage of the bridged T is equal in db to 20 $\log_{10}$ $[1 + (N/2)]$. If a single series repeater can be used in a line to give an insertion gain of 6 db ($N = 1$) then a bridged T can be used to provide 20 $\log_{10}$ $(1 + 0.5)$ or 3.5 db additional. Thus, in this case the series repeater gives 6 db gain as compared to 6 + 3.5 or 9.5 db for the bridged T. These gains are theoretical; in actual lines with simply constructed repeaters the comparison may not be quite so favorable to the bridged T.

THE NEGATIVE IMPEDANCE CONVERTER

So far the discussion of the E2 and E3 repeaters has been in terms of a "black box" which translates a positive impedance into a negative

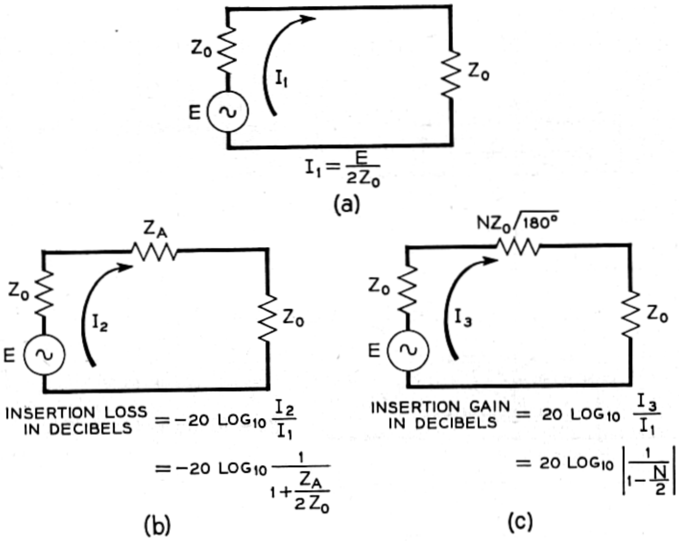

Fig. 13 — Insertion gain of the E2 repeater.

impedance through a multiplying and phase shift operation. It will be interesting to examine these boxes to see what factors determine their characteristics.

THE E2 CONVERTER

The E2 negative impedance converter is the same as the E1. As discussed elsewhere[5] it can be represented schematically as in Fig. 14(a) and also in terms of the equivalent circuit of Fig. 14(b) if the coils are assumed to be ideal. The converter performs much like a transformer. An impedance seen through it is not only transformed in magnitude by the ratio of $| 1 - \mu\beta |$ to $| 1 + \mu |$ it is also modified by the phase shift of this factor which over the operating band of frequencies approximates 180 degrees. The symbol μ stands for the voltage gain of the electron tube and β is the ratio of 1 to $1 + (1/j\omega CR)$. If both C and R are large β approaches unity in magnitude and the ratio of conversion approaches $1 - \mu$ to $1 + \mu$. If μ is large compared to unity then this conversion ratio approaches -1. This ratio of -1 is approximately realized in the E2 converter, and therefore the conversion ratio is not changed appreciably by small variations in μ.

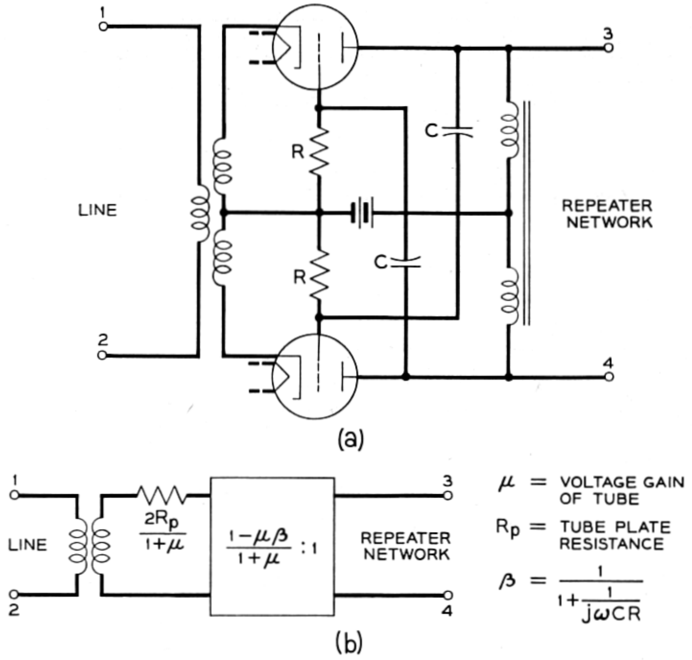

Fig. 14 — E2 Converter; (a) schematic and (b) equivalent circuit.

In addition to the transformation term there is also, as shown in Fig. 14(b), a series term, $2R_p$ divided by $1 + \mu$. Here R_p is the plate resistance of the tube, and μ is the voltage gain as mentioned before. The factor 2 results from the use of two tubes in push pull. If μ is large compared to unity then this series term becomes approximately $2R_p/\mu$. It is entirely dependent upon the characteristics of the electron tube. As the characteristics change from tube to tube with manufacturing variation or in the same tube over a period of time or with variation in battery supply potential, the term $2R_p/(1 + \mu)$ will change accordingly. Percentage-wise this change may be large. This is the largest source of variation in the E2 converter. It can be minimized by operating the converter between impedances much larger in magnitude than $2R_p/(1 + \mu)$ so that variations in this term have relatively small effect. This has been done in the E2 repeater by stepping up the impedance of the transmission line by about 1:9 by means of the transformer shown in Fig. 14.

THE E3 CONVERTER

Theoretically, the same converter used for the E2 and shown in Fig. 14 could have been used for the E3. Instead of connecting the line to

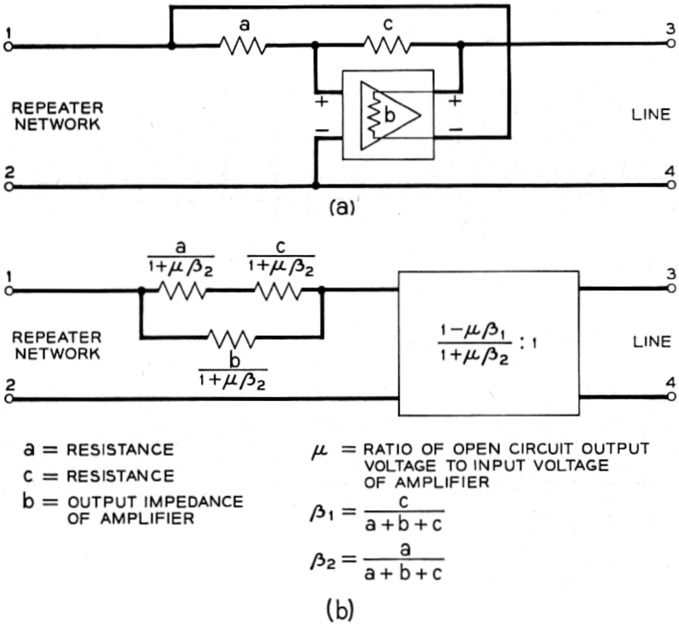

Fig. 15 — E3 Converter; (a) schematic and (b) equivalent circuit.

the converter through terminals 1 and 2, terminals 3 and 4 would be used. However, because the E3 must be designed for connection across a transmission line a coil or transformer input is not practical since the coil would shunt the line at low frequencies and introduce excessive loss to dial pulsing and 20 cps ringing. Without a coil to step up the impedance of the line, variations in $2R_p/(1 + \mu)$ with standard triodes are too large to be neglected. For this reason another converter circuit was designed for the E3 repeater.

This circuit is shown in schematic form in Fig. 15(a). It consists of two resistances, a and c, respectively, and an amplifier poled according to the plus and minus designation on Fig. 15(a). The output impedance of the amplifier has been designated as b. If the input impedance of this amplifier is high compared to other circuit impedances, Fig. 15(a) can also be represented by the equivalent circuit of Fig. 15(b). Here is a conversion factor similar to that in the E2 converter and also a series impedance. The factor μ is the ratio of the open circuit output voltage to the input voltage of the amplifier. In the E3 converter this voltage ratio μ is quite high because the amplifier is a two-stage arrangement. In the design of the E3 both β_1 and β_2 are approximately one half. Thus $\mu\beta_1$ and $\mu\beta_2$ are both large compared to unity so that the conversion ratio $(1 - \mu\beta_1)/(1 + \mu\beta_2)$ is approximately unity and relatively independent of variations in μ. Furthermore, because $\mu\beta_2$ is large compared to b, the series term in the converter circuit is relatively small and variations in this term have little effect on the operation of the converter.

CIRCUIT DESCRIPTION

THE E2 TELEPHONE REPEATER

The circuit function of the E2 telephone repeater can be divided into two parts: the electron tube (negative impedance) converter; and the adjustable two-terminal network associated with the converter.

In order to reduce the effect of variations in the electron tubes to negligible proportions, and at the same time to operate the tubes with load impedances that will permit optimum energy transfer from tube to connected circuit, the impedance of the telephone line is stepped up by means of the input transformer. To insure adequate balance for use in the telephone lines, the low voltage side of the transformer is divided into two equal, balanced windings. Each winding is center-tapped and connected in series with a line conductor. The circuit of the E2 repeater is shown in Fig. 16.

In practice, it is advantageous to limit the conversion bandwidth so

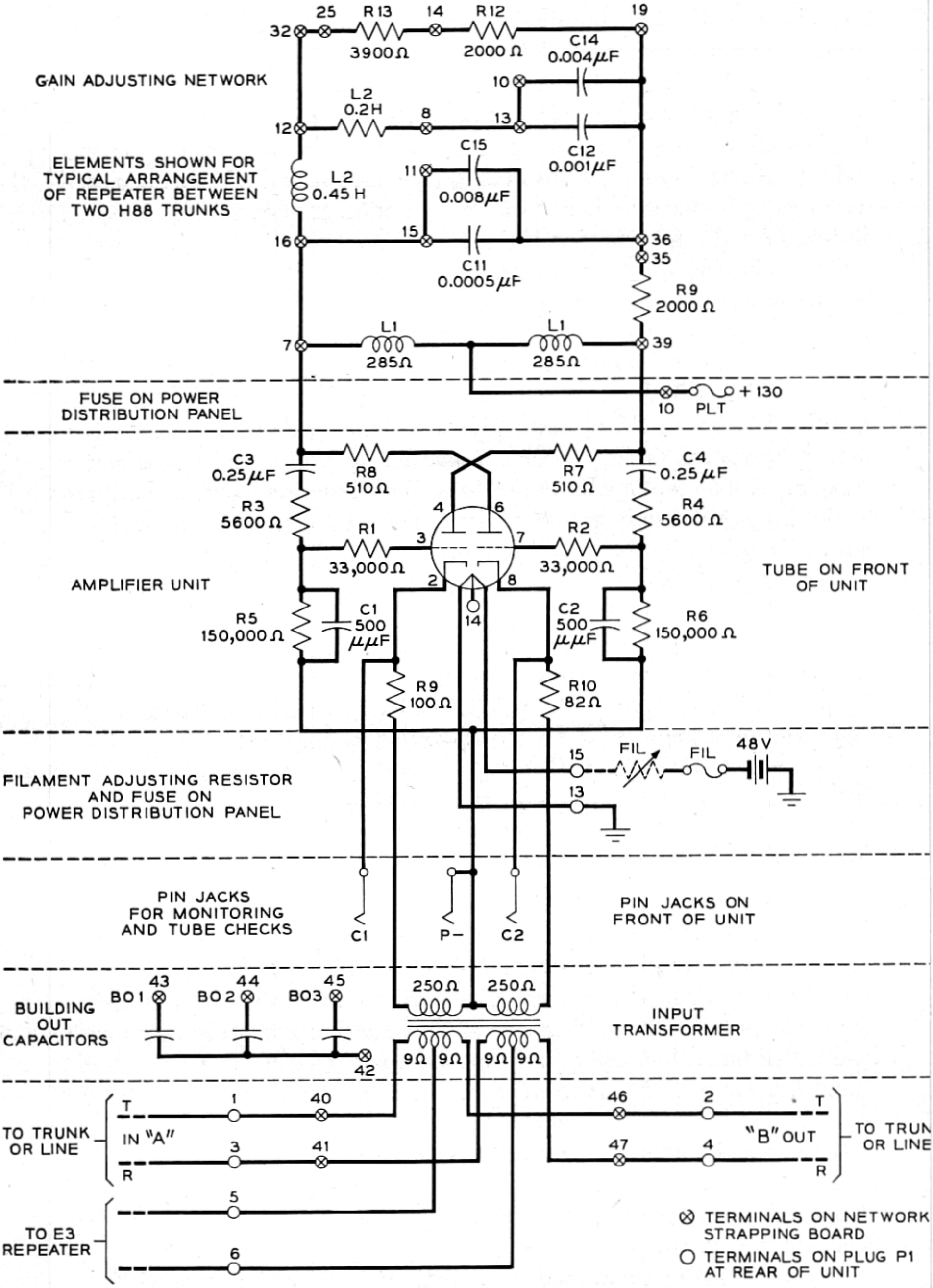

Fig. 16 — Circuit of E2 repeater.

that the line and network impedances do not have to be controlled over an extended frequency band. The conversion gain is limited by reducing β to a small value at low frequencies by capacitors C_3 and C_4 of Fig. 16 in the plate-to-grid coupling network, and at high frequencies by the small capacitors C_1 and C_2 across the grid resistors R_5 and R_6 respectively.

The conversion ratio is affected by small losses inherent in the electron tube and transformer. These are balanced out by a fixed resistor $R9$ connected in series with the gain adjusting network to increase the amount of positive feedback.

The final negative series impedance presented to the line is equal to approximately $-0.1Z_N$ over the frequency band of 300 to 3,500 cycles. The impedance Z_N is determined by the configuration of the gain-adjusting network comprising several inductors, capacitors, and resistors. These components may be arranged in any form to obtain the desired negative impedance, which in turn, introduces the gain and frequency shaping characteristic desired for each type of line facility.

The E2 repeater employs a Western Electric 407A twin-triode electron tube of the 9-pin miniature type. The tube heater circuit can be operated from 24- or 48-volt office battery. The heater current is 100 milliamperes for 20-volt operation, 50 milliamperes for 40 volt operation and the plate current is 11 milliamperes.

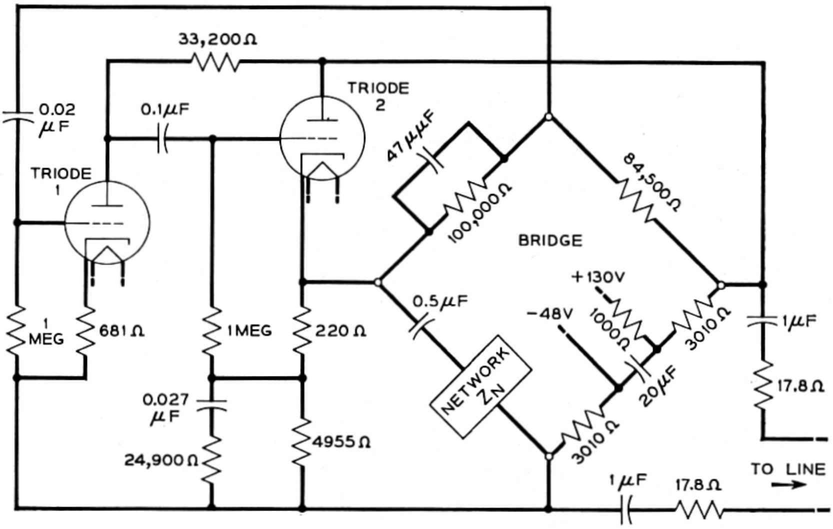

Fig. 17 — Schematic circuit of E3 repeater.

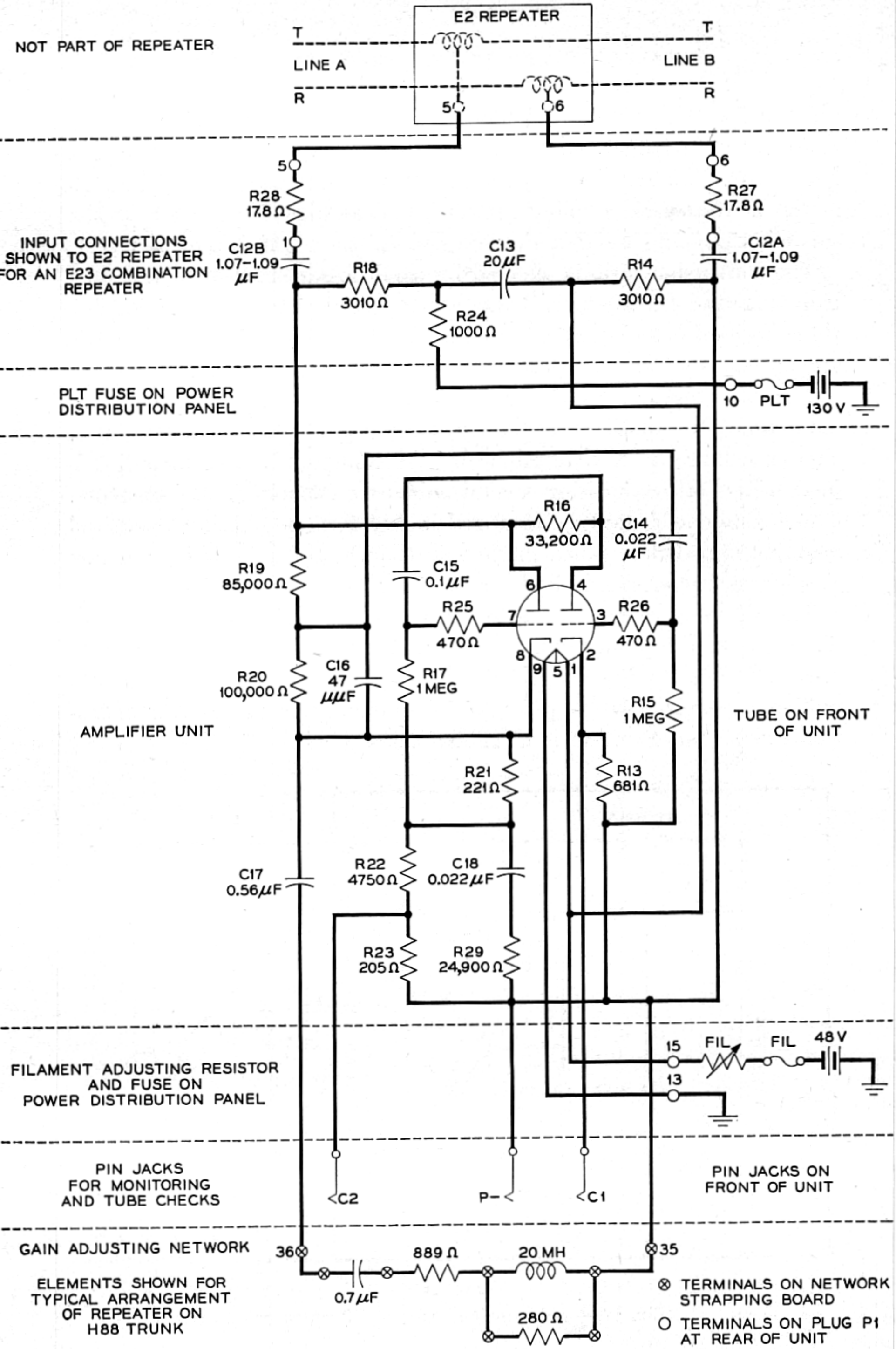

Fig. 18 — Circuit of E3 repeater.

THE E3 TELEPHONE REPEATER

The E3 repeater is a two-terminal high impedance device designed to be bridged across the line in contrast with the E2 repeater which is a low impedance series connected device. Schematically shown in Fig. 17, its circuit is considerably different from that of the E2. The bridged telephone line and an adjustable network form two arms of a bridge connected to output and input circuits of a two-stage amplifier.

The bridge is so connected that a fairly large proportion of the amplifier output current flows into the telephone line and a fairly large proportion of the original line voltage is developed between the grid and cathode of the first tube since these circuits are connected to non-conjugate points of the bridge. The output and input terminals of the amplifier are connected to conjugate points of the bridge in such a manner than when the bridge circuit is balanced no feedback is effective at the input.

It has been shown, in the preceding Section, that the negative impedance generated by this form of converter is equal to the network impedance Z_N divided by a conversion factor. To obtain a practical design of the E3 repeater for the faithful conversion of the network impedances, with a minimum of spurious components, it is necessary to balance out, as nearly as possible, all converted circuit elements associated with the output bridge and connections to the line. Accordingly, the two line capacitors are balanced out by a network capacitor. The battery supply resistors, the resistor and capacitor of the plate-battery filter, and the plate-load resistor of the first-amplifier stage are all balanced out in the network by placing suitable values of resistors and capacitors in the cathode circuit of the second-amplifier stage. All of these elements combine to form an equivalent two-terminal network.

An ideal negative impedance device would convert any impedance in the network over a wide frequency band but it is advantageous to limit the negative impedance, in so far as practicable, to the frequency bandwidth required by the particular application. This is accomplished primarily in the network associated with the converter. The conversion bandwidth of the E3 repeater is restricted at the low frequencies by the design of the resistive-capacitive feedback coupling network, between the output bridge and the input grid, and at the high frequencies by the shunt capacitance connected across one resistive arm of the bridge circuit. The circuit is shown in Fig. 18.

The final negative impedance shunted across the line is equal to $-Z_N/0.94$, within ± 2.5 per cent, over the frequency range of 200 to 5,000 cycles. The magnitude and phase of the negative impedances are controlled by the configuration of the gain-adjusting network, consisting of several inductors, capacitors, and resistors. These components may be arranged in a variety of ways to obtain the gain and frequency shaping characteristics desired for each type of line facility.

The E3 repeater employs a Western Electric 407A twin-triode electron tube of the 9-pin miniature type. The circuit is arranged so that the current for the heater of the tube can be obtained from 24- or 48-volt office battery. The heater power is 2 watts and the plate current is nominally 5 milliamperes.

EQUIPMENT

The objective of the equipment design of the E2 and E3 repeaters was to produce a repeater that would be simpler to manufacture, easier to engineer, install, and maintain, and make more efficient use of the mounting space, particularly on 23-inch bays, than the present E1 repeater. Because of the large demand, savings in manufacturing costs were realized by using a compact aluminum die-cast shell to house the repeater components. To facilitate manufacture, parallel thermoplastic strips were used for the mounting of "pigtail" type of components.[6] Further savings in shop costs were obtained by coordinating the designs of the E2 and E3 repeaters for maximum interchangeability of parts.

Engineering and installation effort has been reduced considerably by avoiding engineered options and by arranging the equipment so that the maximum portion of the assembly and wiring work is performed in the shop. Testing and maintenance routines are simplified by arranging the repeaters as plug-in units that can be removed from their bay positions and plugged into a portable test set located in a more convenient working space. In this way, the network strapping and any repair work which may be required on a repeater need not be performed while the repeater is in place, or is in a congested area. Maintenance and service interruptions are reduced to a minimum length of time by replacing a defective plug-in unit with a spare for immediate restoration of service, and the faulty repeater repaired at a more convenient time.

REPEATER UNITS

Both E2 and E3 repeater units use the same rectangular die-cast chassis, shown in Fig. 19. The front section of each unit carries the electron tube and test pin jacks which must be accessible for testing and routine maintenance. The gain-adjusting network strapping terminals are arranged, in three rows, along the left side of the repeater, and are accessible only after the unit is removed from its mounting shelf.

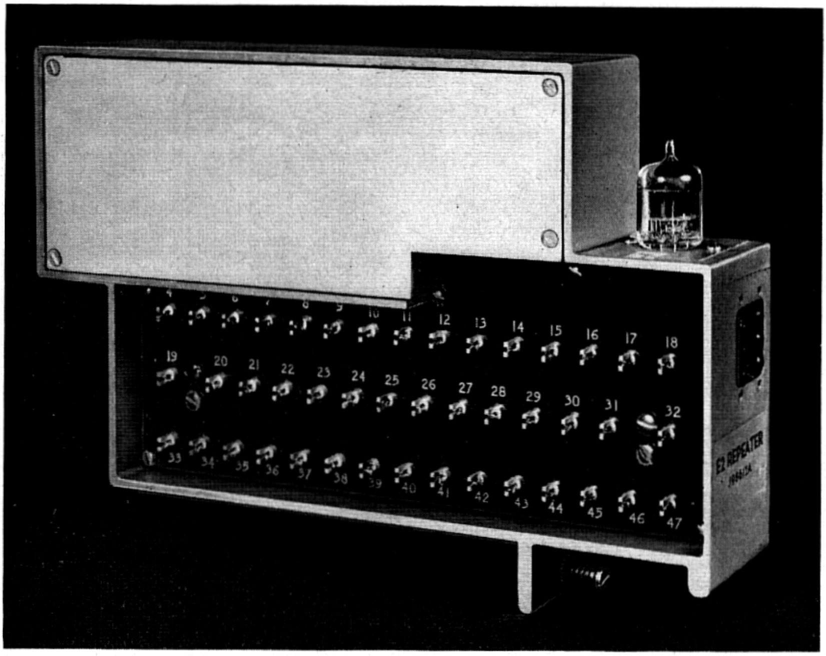

Fig. 19 — Front and side view of E2 repeater.

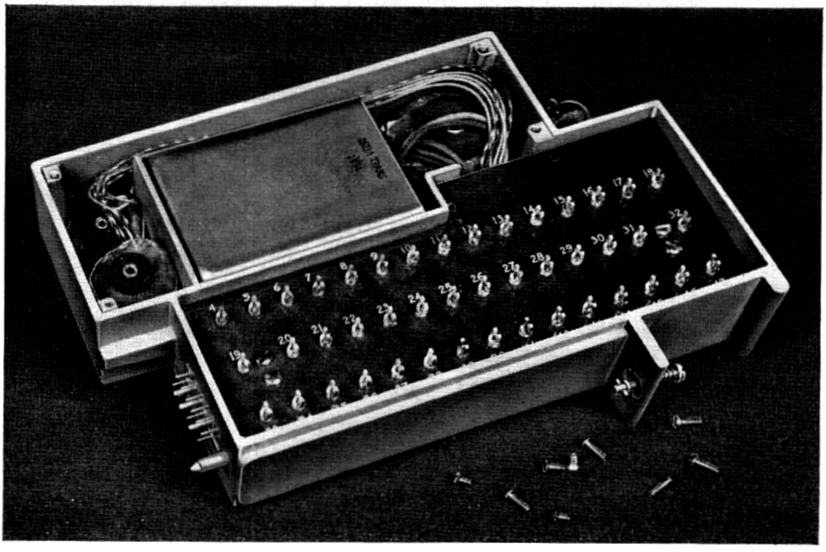

Fig. 20 — Assembly and wiring of E2 repeater.

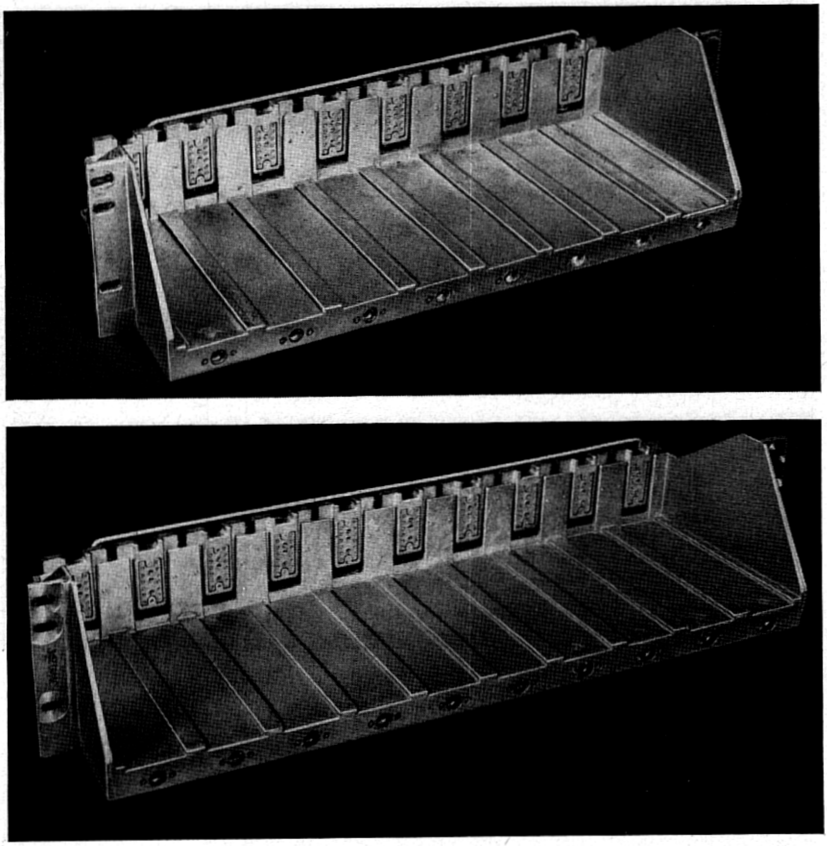

Fig. 21 — Repeater mounting shelves. Upper for 19-inch bays, lower for 23-inch bays.

All external connections, to either type of repeater, are made through a male connector rigidly mounted into the repeater chassis, as shown in Fig. 20. The matching female socket is suspended in the mounting shelf, on a floating assembly, to relieve the strain on contacts and wiring when the repeaters are plugged into a shelf. Both connector units consist of molded rectangular phenolic blocks equipped with 15 gold plated contacts. Proper alignment between the male and female connectors is maintained by using a positioning key and guide pin on the repeater chassis, shown in Fig. 20, and a track on the mounting shelf. After a repeater is seated into its shelf position it is made secure by means of a screwdriver operated quick-acting fastener.

MOUNTING SHELF

An aluminum die-cast shelf, shown in Fig. 21, is used for mounting the repeaters on the relay rack bays. The shelf comes in two widths; one holding 8 repeaters is used for 19-inch bays and the second, containing 10 repeaters, is used on 23-inch bays. Grooves cut into the base of the shelf match a projection on the repeater to act as a track system for positioning the repeater into its connector socket. The shelf connector is mounted in a small die-cast block which, in turn, is fastened to the shelf by shoulder screws to provide a floating assembly. A tapered key, molded into the repeater casting, engages a slot in the connector block to secure the horizontal alignment, and a tapered pin, at the bottom of the repeater casting, raises the connector block for the vertical alignment.

Fifteen mounting shelves can be arranged on standard 11-foot 6-inch relay rack bays. The maximum complement of repeaters will be 120 for 19-inch bays and 150 for 23-inch bays.

POWER DISTRIBUTION PANELS

Fabricated power distribution panels which occupy 1¾-inches of mounting space are used for supplying plate and filament power to the repeater shelves. The primary unit, shown in Fig. 22, is required for furnishing power to the first three repeater shelves and one test-set power outlet. Four sets of plate and filament alarm-type fuses are provided, one set for each shelf and one set for the test power outlet. Four filament-adjusting rheostats are furnished and the panel is equipped with an alarm relay and lamp. Pin jacks are available on the front of the panel to measure the filament voltage.

A supplementary power distribution panel is available, equipped with plate and filament fuses, rheostats and pin jacks sufficient for six additional repeater mounting shelves. One primary and two supplementary power panels are required to fully equip an 11-foot, 6-inch bay with 15 repeater shelves. Both panels are completely wired in the shop to simplify installation. Fig. 23 shows a 19-inch relay bay mounting shelf complete with E2 and E3 repeaters and the two types of power distribution panels.

Repeater Test Set

A new test set has been developed, which will simplify the installation and maintenance of these devices. This test set has been designed

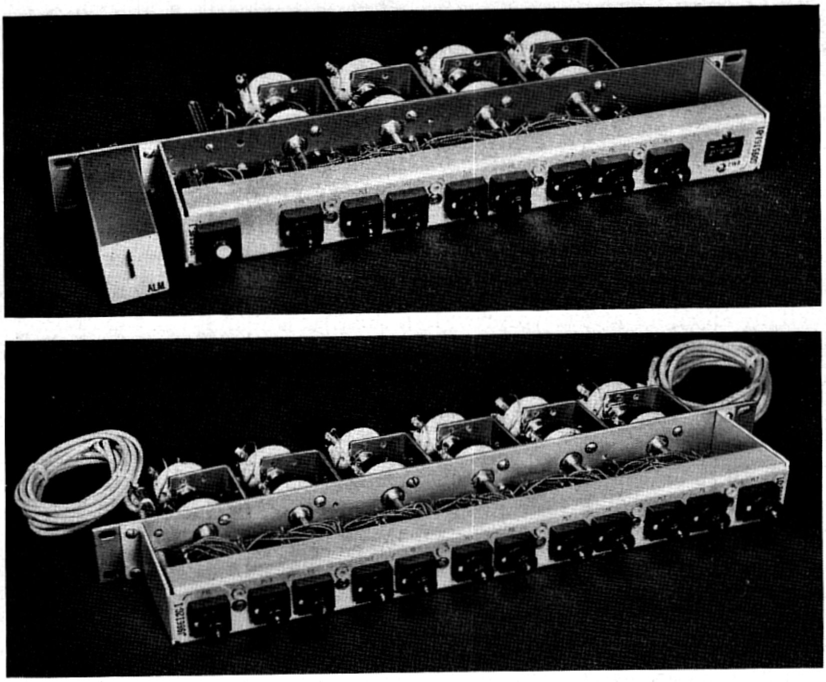

Fig. 22 — Power distribution panels. Upper is primary unit, lower is supplementary unit.

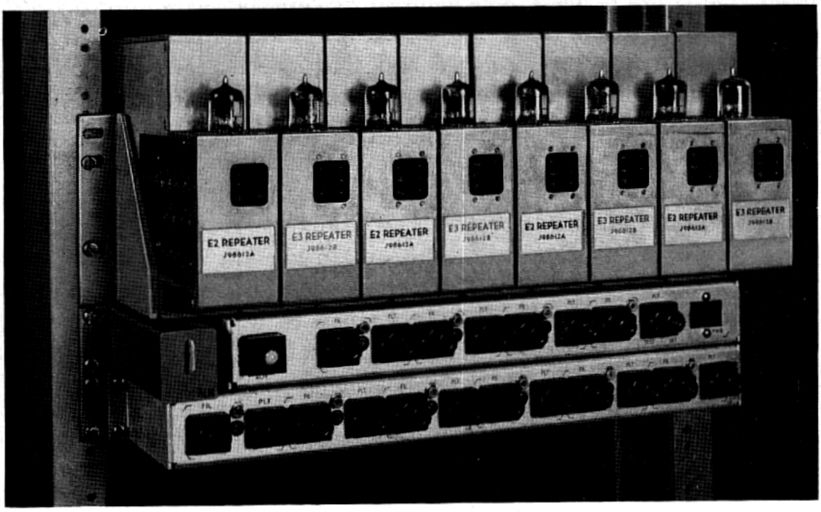

Fig. 23 — Shelf of E2 and E3 repeaters, with power distribution panels, for 19-inch bays.

not only to test the new E2 and E3 repeaters but also the older type of E1 repeater, which has been in use for several years. All test connections which are required to measure individual repeaters or combinations of E1 or E2 and E3 repeaters are made by the operation of a single rotary control function switch. Such a system will avoid the unintentional errors and time consuming operations which attend the setting-up of complicated patch cord connections.

The first five positions of the function switch are arranged to make transmission measurements of an individual repeater or any combination of E1 or E2 and E3 repeaters. Insertion gain and loss measurements are performed with the repeaters working between their normally connected line impedances.

In making transmission and stability measurements, it is sometimes necessary to set up trial connections of the repeater networks during the initial test period or for unusual line conditions. If the actual repeater networks were used, it would require a large number of soldered connections to be made for each condition of the tests. Equivalent jack-ended E2 and E3 networks have been included in the test set, so that with small patch cords, a rapid interconnection of the network components can be made.

As gain and stability of the E-type repeaters are both directly dependent upon impedance variations of the lines, it is sometimes necessary to measure line impedance to determine the causes for low return loss and instability. The last four positions of the function switch are arranged to make positive impedance measurements of lines, negative impedance measurements of the repeaters and return loss measurements between any two lines or impedances. A decade resistance standard has been built into the test set to furnish a direct indication of the magnitude of the unknown impedance. The phase angle of the impedance is determined by a return loss measurement and the angular degrees are read from a chart supplied with the equipment.

Although this test set was designed primarily for tests on E type repeaters, it is possible to connect other types of four-terminal networks into the test set and measure impedances, return loss against known impedances, and insertion gains or losses.

THEORY OF TRANSMISSION MEASUREMENTS

One method of measuring the insertion gain of a negative impedance repeater, without affecting the transmission or stability of the circuit, is to introduce the test voltage, through a low impedance source, in series with the input line and measure the resultant current picked off through a similar low impedance connection in series with the output line. A comparison of the received currents, with and without a repeater, will give an indication of the insertion gain or loss.

The principles involved in making this type of transmission measurement are shown in Fig. 24. The voltage source and the current measuring detector are assumed to have negligible impedances compared to the impedances of the lines Z_1 and Z_2.

In the reference condition of Fig. 24, the driving voltage E_0 and the current measuring device are in series with the two line impedances Z_1 and Z_2. The resultant current will be determined by the source voltage E_0 divided by the vector sum of impedances Z_1 and Z_2:

$$I_0 = \frac{E_0}{Z_1 + Z_2}$$

where $Z_1 + Z_2$ indicates a vector addition of the two impedances.

In the "measure" condition of Fig. 24 the repeater, represented by the network N, is inserted into the circuit between the voltage source and the measuring device, and, although the voltage E_0 is assumed to remain constant, the addition of network N into the circuit will change

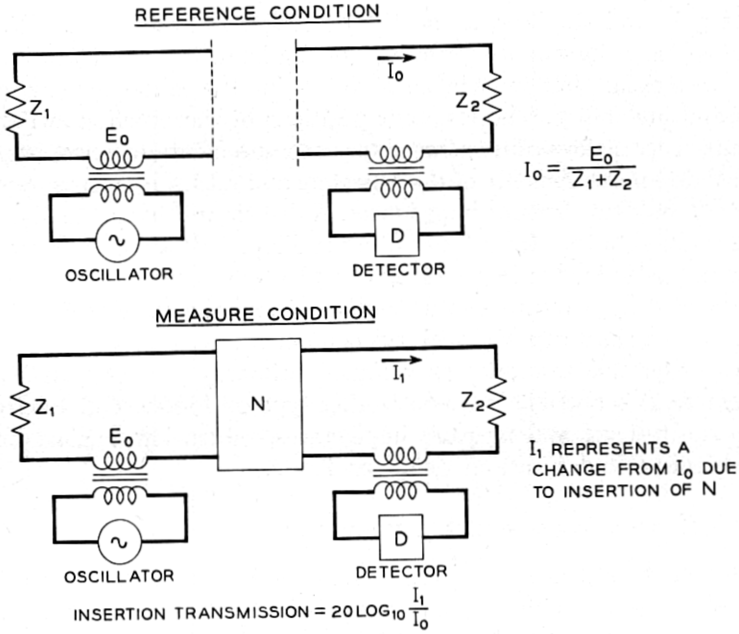

Fig. 24 — Principles of insertion measurements.

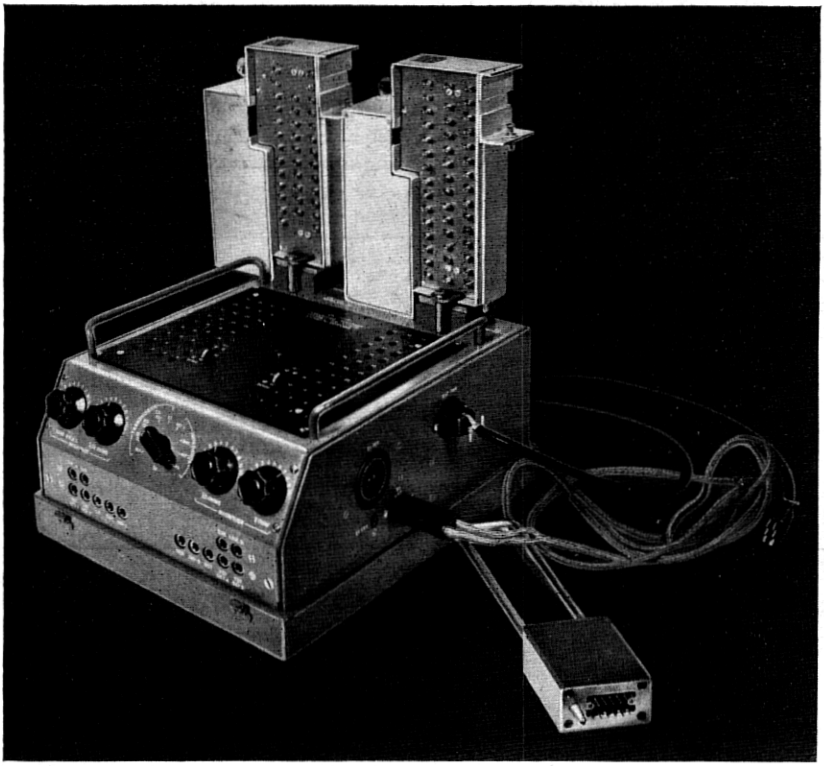

Fig. 25 — Test set showing repeaters and test cords.

the current to a new value I_1. The ratio of the currents I_1/I_0 is a direct measure of insertion gain or loss between Z_1 and Z_2 due to inserting the network. The db change in transmission caused by the insertion of N is

$$\text{Insertion transmission in db} = 20 \log_{10} \frac{I_1}{I_0}.$$

When I_1 is less than I_0, the addition of N has caused an insertion loss, and when I_1 is greater than I_0 the addition of N has caused an insertion gain. In the test set the current indicating device has a db scale so that the change in transmission can be read directly in db.

TRANSMISSION MEASUREMENTS

In setting up to make repeater tests, the E2 and E3 units are removed from their shelf positions and plugged into adapters in the test set, as shown in Fig. 25. A test plug, fashioned to simulate the male connector

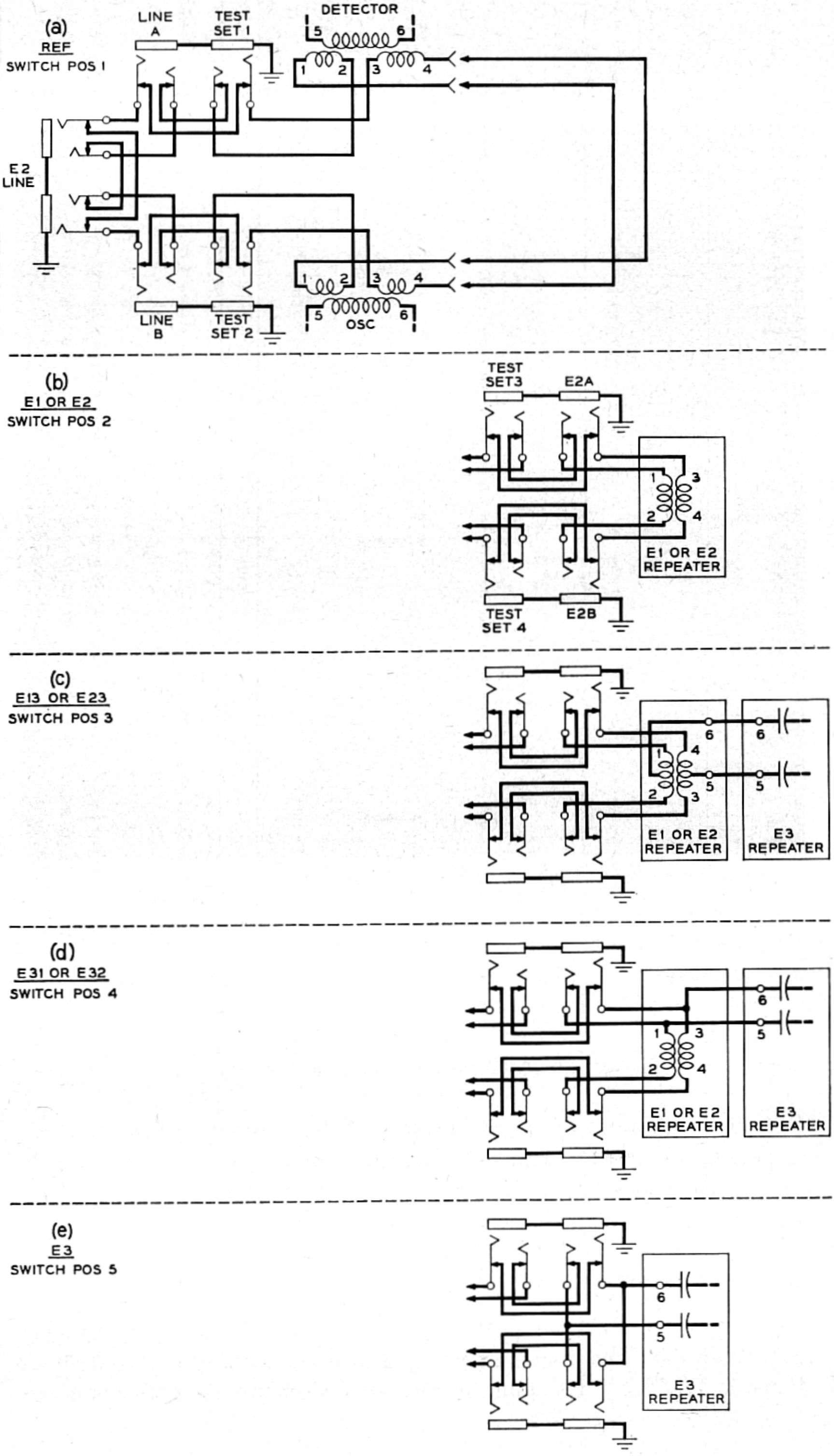

Fig. 26 — Sequence of transmission measurements.

of the repeater, is inserted into the vacant E2 repeater position for picking up the connections to the incoming and outgoing lines. A jack ended cord, connected to the test plug is patched into the test set for applying the line connections to the repeaters under test.

The first position of the rotary function switch arranges the test set for the reference condition. The incoming and outgoing E2 repeater lines provide the terminations, as shown in Fig. 26(a). The low impedance voltage source is obtained by means of an oscillator working through a step-down transformer having an impedance ratio of 600:2 ohms. The low impedance side consists of two equal well balanced windings, one winding being inserted into each side of the line, to form a balanced-to-ground voltage source. The received current is measured by means of a detector working through an identical transformer having one of the 2-ohm windings connected into each side of the line for maintaining the balanced-to-ground circuit.

Switch position 2 connects the E1 or E2 repeater into the test circuit between the sending and receiving impedances as shown in Fig. 26(b). The change in detector reading will indicate the insertion gain or loss of the connected repeater.

The third and fourth switch positions change the arrangements of E1, E2 and E3 repeaters for the insertion measurements of the various repeater combinations, as shown in Figs. 26(c) and (d). Fig. 26(e) indicates the connections for testing the E3 repeater alone on switch position 5.

IMPEDANCE MEASUREMENTS

The second section of the type-E repeater test set has been arranged to measure the impedance of two-terminal networks and the return loss between any two impedances or between an unknown impedance and a specified network. The impedance measuring circuit consists of a hybrid coil arranged in the form of a balanced bridge for measuring return loss. The driving voltage and detecting device are connected across conjugate arms of the bridge and the unknown impedance and a resistance standard are applied across the opposite conjugate arms of the bridge circuit.

Simple transmission measurements made across the hybrid coil, between the oscillator and detector sides of the bridge, are the only determinations required to find the return loss between any two impedances or the magnitude and phase angle of an unknown impedance. Such a device has several advantages over other types of impedance bridges in that no critical balances are required, no calibrations are

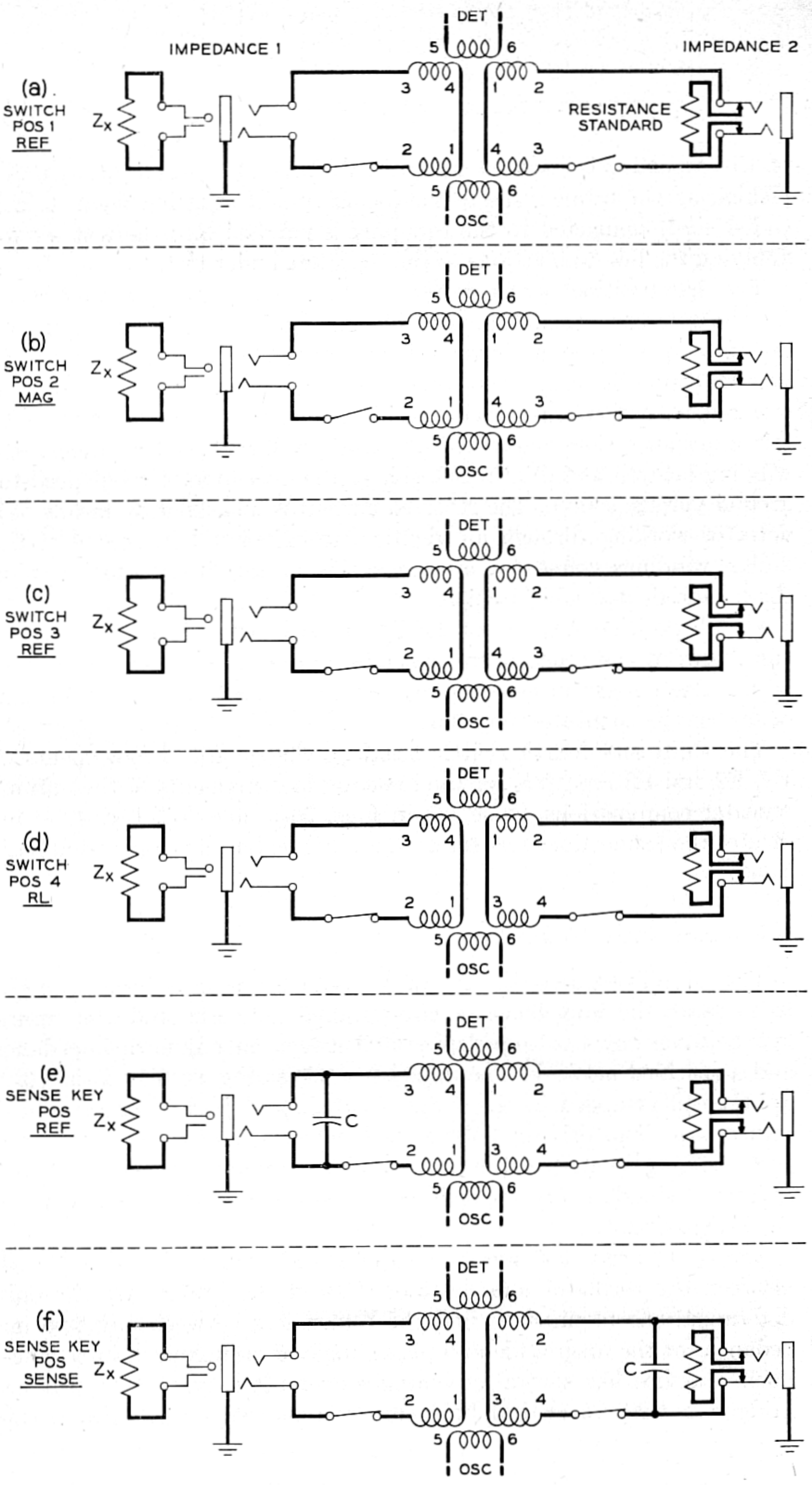

Fig. 27 — Sequence of impedance measurements.

necessary, the critical elements are stable passive networks and changes in the sensitivity of the measuring device, which includes variations in oscillator output and sensitivity of the detector circuit, will not affect the accuracy of measurement.

An impedance reference is established, as shown in Fig. 27(a), when the transmission through the hybrid network is measured with connection to the resistance standard. A second transmission measurement is made through the hybrid coil network with the standard impedance connected instead of the unknown. After replacing the unknown with the resistance standard, the transmission through the hybrid coil is adjusted by varying the resistance standard to obtain the same value of loss, as measured with the unknown impedance. When the two transmissions are equal, the resistance in ohms, as read on the resistance standard, will be the same as the magnitude of the unknown impedance. With the magnitude of the resistance standard and unknown impedance the same, the phase angle of the unknown is readily determined by comparing the transmission through the hybrid coil for two polings of one of the hybrid windings. The first poling, Fig. 27(c), which is used as a reference, provides a measure of the transmission through the hybrid network when the current in the unknown branch and the current in the resistance branch are added vectorially in the detector winding. The reverse poling of one of the coil windings, Fig. 27(d), provides a measure of the transmission through the hybrid when the currents in the resistance and unknown branches are subtracted vectorially in the detector circuit. In addition to being a method of measuring the phase angle of an impedance, this comparison of two measurements with different poling is a return loss measurement of an unknown against a known impedance of equal magnitude. A curve of phase versus return loss may be used for convenient interpretation of the return loss measurement in terms of phase angle. After the phase angle has been ascertained it is necessary to determine the sense of the angle, that is, whether the unknown impedance contains positive or negative reactance. A reference condition is established, Fig. 27(e), by shunting a small value of capacitance first across the unknown impedance and then across the resistance standard and noting the change in transmission through the hybrid network. An increase in the transmission, in going from the reference to measure conditions, indicates a positive reactance and a decrease in transmission indicates a negative phase angle. The reference condition is established to minimize indicational errors at small phase angles of the unknown impedance.

Two additional pieces of information are revealed in the return loss measurement. When the return loss is positive, the unknown impedance contains positive resistance and the phase angle must lie between 0 and ±90 degrees. For negative return losses the unknown impedance contains negative resistance and the phase angle must lie between ±90 degrees and 180 degrees.

ACKNOWLEDGMENTS

The design of the E3 repeater was based upon theoretical work by S. T. Meyers; the design of the test set was based upon theoretical work by H. Kahl and S. T. Meyers. In regard to the theory of negative impedances the contributions of F. B. Llewellyn are gratefully acknowledged.

REFERENCES

1. J. L. Merrill, Jr., A Negative Impedance Repeater, A. I. E. E. Trans., **69,** Part 2, pp. 1461–1466; 1950.
2. J. J. Pilliod, Fundamental Plans for Toll Telephone Plant, A. I. E. E. Trans. **71,** pp. 248–256.
3. O. B. Blackwell, Time Factor in Telephone Transmission, A. I. E. E. Trans., **51,** pp. 141–7.
4. G. Crisson, Negative Impedance and The Twin 21-Type Repeater, B. S. T. J., **31,** pp. 485–513, July, 1931.
5. J. L. Merrill, Jr., Theory of The Negative Impedance Converter, B. S. T. J., **51,** pp. 88–109, Jan., 1951.
6. W. E. Kahl and L. Pedersen, Some Design Features of the N-1 Carrier Telephone System, B. S. T. J., **51,** pp. 418–446, April, 1951.