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Impedance of Smooth Lines, and Design of Simulating Networks

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INTRODUCTION

THE transmission of alternating currents over any transmission line between specified terminal impedances depends only on the propagation constant and the characteristic impedance of the line (at the particular frequency contemplated). In this sense, then, the properties of transmission lines may be classed broadly as propagation characteristics and impedance characteristics. In telephony we are primarily concerned with the dependence of these characteristics on the frequency, over the telephonic frequency range.

Prior to the application of telephone repeaters to telephone lines the propagation characteristics of such lines were more important than their impedance characteristics, because the received energy depended much more on the former than on the latter.

The application of the two-way telephone repeater greatly altered the relative importance of these two characteristics, decreasing the need for high transmitting efficiency of a line but greatly increasing the dependence of the results on the impedance of the line. As well known, this is because the amplification to which a two-way repeater can be set without singing, or even without serious injury to the intelligibility of the transmission, depends strictly on the degree of impedance-balance between the lines or between the lines and their balancing-networks. In the case of the 21-type repeater the two lines must have such impedances as to closely balance each other throughout the telephonic frequency range. In the case of the 22-type repeater, which for long lines requiring more than one repeater is superior to the

21-type, impedance networks are required for closely balancing the impedances of the two lines throughout the telephonic frequency range. Such balancing networks are necessary also in connection with the so-called four-wire repeater circuit.[1]

Smooth lines are fundamental in telephonic transmission; for any telephone line is either a simple smooth line, or a compound smooth line, or a periodically loaded line whose sections are themselves short smooth lines. In any case the characteristic impedances of the constituent smooth lines enter importantly into the impedance of the system. Moreover, the characteristic impedance of the series type of periodically loaded line, at frequencies low relatively to its critical frequency, is closely the same as the characteristic impedance of the corresponding smooth line.

Parts I, II, and III of this paper aim to present in a simple yet comprehensive manner the dependence of the characteristic impedance of the various types of smooth lines on the frequency and on the line constants, by means of description accompanied by equations transformed to the most suitable forms and by graphs of such equations.

Part IV describes the principal networks devised by the writer at various times within about the last ten years, for simulating the impedance of the various types of smooth lines. Of course, the impedance of any line could be simulated, as closely as desired, by means of an artificial model constructed of many short sections each having lumped constants; but such structures would be very expensive and very cumbersome. Compared with them the networks described in this paper are very simple non-periodic structures that are relatively inexpensive and are quite compact; yet the more precise of them have proved to be adequate for simulating with high precision the impedance of most types of smooth lines, while even the least precise (which are the simplest) suffice for a good many applications. The paper includes first approximation design-formulas and outlines a supplementary semi-graphical method for arriving at the best proportioning of the networks. A typical illustrative example is worked out in Appendix E.

It is hoped to devote a succeeding paper to the impedance characteristics of periodically loaded lines, and to various networks devised for simulating and compensating such impedance.

[1]Regarding the broad subject of repeaters and repeater circuits, reference may be made to the paper by Gherardi and Jewett: "Telephone Repeaters," A. I. E. E. Trans., 1919, pp. 1287–1345.

PART I

GENERAL CONSIDERATIONS PERTAINING TO SMOOTH LINES

The exact formula for the characteristic impedance K of any smooth line is usually written in the form

$$K=\sqrt{\frac{R+i\omega L}{G+i\omega C}} \tag{1}$$

R, G, L and C denoting, as usual, the fundamental line constants,[2] namely, the resistance, leakance (leakage conductance), inductance, and capacity, per unit length; ω denoting 2π times the frequency f; and i the imaginary operator $\sqrt{-1}$.

However, this form is neither the simplest nor the most significant. For it involves separately the four quantities R, G, L, and C and is thus a function of not less than four [3] variables, whereas its value evidently depends on only the relative values of these quantities and hence must be expressible as a function of only three independent variables—namely the ratios of any three of them to the fourth.

In deciding just what form or forms of expression to adopt for K we shall here be guided by the following practical considerations:

(A) In telephony we are chiefly interested in the dependence of K on the frequency f; or, stated more generally, in the dependence of some quantity that is approximately proportional to K on some quantity that is approximately proportional to f.

The class of smooth lines is comprised between the following two rather wide extremes, having very different characteristics:

(B) At one extreme are the large gauge open-wire lines, particularly when used at high frequencies. For them R is small relatively to ωL, and G relatively to ωC; and hence K is approximately or at least roughly equal to $\sqrt{L/C}$.

(C) At the other extreme are the small gauge cables, particularly when used at low frequencies. For them R is large relatively to ωL, though G is small relatively to ωC; and hence K is approximately or at least roughly equal to $\sqrt{R/i\omega C}$.

(D) The line constants R, L, C do not change much with frequency over at least the voice frequency range; and hence they, or combinations of them, serve suitably as parameters.

(E) The leakance G, which is nearly always the least important of the four line constants, usually varies greatly with the frequency

[2] Constants as to current and voltage.

[3] Five if ω is regarded separately from L and C.

and hence by itself does not serve very suitably as a parameter. However, in a wide range of applications G is approximately or at least roughly proportional to the frequency; and then a suitable parameter is G/f or preferably $G/\omega C$. This is true of cables except at extremely low frequencies. It is at least roughly true of open-wire lines at very high frequencies, such as carrier frequencies, but usually not at voice frequencies. For most lines the leakance G is usually approximately or at least roughly a linear function of the frequency, namely, $G=G_0+\nu f$, where G_0 is the leakance at $f=0$, and ν is approximately independent of the frequency. For cables, G_0 is small compared with νf except at very low values of f; but for open-wire lines G_0 is usually not negligible except at high values of f.

In the light of these considerations a study of equation (1) suggests the employment of the quantities F, E, k, g, a, b defined by the following six equations. Not all of these substitutions will be employed simultaneously, but it is convenient to set them all down here together.

$$F=\omega L/R, \qquad (2) \qquad\qquad E=\omega C/R, \qquad (3)$$

$$k=\sqrt{L/C}, \qquad (4) \qquad\qquad g=\sqrt{G/R}, \qquad (5)$$

$$a=GL/RC, \qquad (6) \qquad\qquad b=G/\omega C. \qquad (7)$$

Usually F or E will be treated as the independent variable; and k, g, a, b as parameters.

It should perhaps here be emphasized that the approximations mentioned in the foregoing set of five considerations, (A) to (E), are employed merely as guides in the selection of the variables and parameters defined by the above equations (2) to (7), and in the choice of the forms adopted below for the formula for the characteristic impedance. Except where the contrary is definitely indicated, the formulas that will be adopted for the characteristic impedance are rigorously exact; though the variables F and E are never exactly proportional to the frequency, and the parameters k, g, a, b are never exactly independent of the frequency. If the independant variables were exactly proportional to the frequency and the parameters were exactly independent of the frequency, the graphs of the formulas would by a mere change of scales exactly represent the impedance as an explicit function of the frequency.

With particular regard to considerations (B) and (C) it will be found convenient to divide the further treatment of smooth lines into two main parts, pertaining to open-wire lines and to cables respectively; and then, in each of those parts, to present the impedance formulas in the two forms respectively most suitable for the cases where the leakance is approximately proportional to the frequency and approximately independent of the frequency, corresponding to consideration (E).

While the classification of smooth lines into open-wire lines and cables is convenient, there is, of course, no very sharp distinction between the open-wire type of lines and the cable type of lines, since the distinction depends on the line parameters and on the frequency range involved, rather than on the physical form of the line; for, any line at sufficiently high frequencies has the open-wire type of characteristics, and at sufficiently low frequencies the cable type of characteristics. With regard to the relative importance of the fundamental line constants R, G, L, C when the frequency range is that of the voice, it may be said that for the open-wire type of lines L and C are of about equal importance, R of secondary, and G of tertiary importance; while, on the other hand, for the cable type, R and C are of about equal importance, L of secondary, and G of tertiary importance. In illustration of the above remarks it may be noted that smoothly loaded cables (unless loaded very lightly) have the open-wire type of characteristics; as have also periodically loaded cables at low frequencies.

Before proceeding to the separate treatments of open-wire lines and cables, it seems desirable to indicate the general nature of the effect produced on the impedance by leakance.

The General Effect of Leakance

The amount of leakance that is normally allowable as regards its attenuating effects is so small as to produce only very slight effects on the characteristic impedance of either type of line (except at very low frequencies).

In ordinary telephone cables the leakance is so small that, except at very low frequencies, the impedance of such cables is very closely the same as in the limiting case of no leakance; whence that limiting case may be taken as being a good approximation to the actual case. In open-wire lines leakance may be much larger than in cables, yet normally it is small enough so that its effects on the impedance are slight, except at very low frequencies, so that usually the limiting value of zero leakance is still a good approximation when calculating the characteristic impedance. However, during wet weather and in particularly humid climates and locations the leakance in open-wire lines becomes large enough to affect the impedance quite appreciably, even within the voice frequency range, while enormously affecting it at very low frequencies.

The general nature of the effect produced on the characteristic impedance K by any value of the leakance G is readily seen from mere inspection of equation (1), so far as regards the absolute value and angle of the impedance. Thus, increasing G from any initial value decreases the absolute value of the impedance and (algebraically) increases the angle. Starting with $G=0$, the angle is negative and has the value $-\frac{1}{2}\tan^{-1}\frac{R}{\omega L}$; increasing G decreases this negative angle until G has become as large as RC/L, when the angle has become zero and the impedance has become equal to the simple value $\sqrt{L/C}$, and thereby equal also to $\sqrt{R/G}$. Increasing G beyond this transition value RC/L toward infinite values gives to the impedance a positive angle which continually increases toward its limiting value $\frac{1}{2}\tan^{-1}\frac{\omega L}{R}$, while the absolute value of the impedance goes on continually decreasing toward its limiting value of zero.

The statements in the foregoing paragraph hold at all frequencies, though the effects of leakance are usually most pronounced at low frequencies. In fact at zero frequency the characteristic impedance of a line having any finite leakance however small is merely $\sqrt{R/G}$; and at frequencies so low that ωL is small compared with R and ωC small compared with G, the impedance K is, approximately,

$$K=\sqrt{\frac{R}{G}}\left\{1+i\omega\left(\frac{L}{2R}-\frac{C}{2G}\right)\right\}$$

and hence is at least roughly equal to $\sqrt{R/G}$.

Of course, with actual lines the whole physically possible range of variation of G from zero to infinite values is never traversed. On the contrary the leakance G even in open-wire lines seldom reaches a value as large as the transition value RC/L and hence the angle seldom becomes positive; while in cables the angle probably always remains negative and indeed is at least roughly equal to its limiting value of $-\frac{1}{2}\tan^{-1}\frac{R}{\omega L}$, except at very low frequencies.

Although, as already indicated, the effects of normal amounts of leakance are usually very small for both cables and open-wire lines, yet the effects in the two cases differ rather markedly in their nature, owing to the difference in the angles of the impedances of these two types of lines; the angle of cables begin almost $-45°$, while that of open-wire lines, though likewise negative, is much smaller (except at very low frequencies).

To formulate analytically the effects of any value of the leakance G, let K_0 denote the value of K when $G=0$, and let ΔK denote the increment $K-K_0$ due to the presence of the leakance G. A suitable measure of the effect of the leakance is then the ratio $\Delta K/K_0$. In order to obtain for the value of this ratio a formula which will be convenient for use with the formula for K (which involves a radical) it is advantageous to write ΔK in the form $\Delta K=(K^2-K_0^2)/(K+K_0)$, and to introduce for brevity the quantity μ defined by the equation

$$\mu=K^2/K_0^2-1. \tag{7.1}$$

This procedure leads readily to the following simple identity for $\Delta K/K_0$, namely

$$\frac{\Delta K}{K_0}=\frac{\mu}{1+\sqrt{1+\mu}}=\sqrt{1+\mu}-1. \tag{7.2}$$

In particular, when this is applied to the formula (1) for K, the value of μ is found to be

$$\mu=\frac{iG/\omega C}{1-iG/\omega C}. \tag{7.3}$$

Equations (7.2) and (7.3) enable the exact value of $\Delta K/K_0$ to be calculated for any value of $G/\omega C$. For small values of $G/\omega C$, the formula for $\Delta K/K_0$ takes the very simple approximate form

$$\Delta K/K_0=iG/2\omega C; \tag{7.4}$$

and this shows that, to the degree of approximation involved, ΔK is proportional to iK_0 through a proportionality factor $(G/2\omega C)$ which is real and positive. Now, for cables, K_0 has an angle of nearly $-45°$; and hence, by (7.4), it is seen that the addition of small leakance increases the resistance component and decreases the negative-reactance component of the impedance by about equal amounts. For open-wire lines, on the other hand, the angle of K_0 is much smaller, though negative, and hence a small increase in the leakance changes the reactance component of the impedance much more than it does the resistance component; evidently, the change in the negative-reactance component is a decrease, but the change in the resistance component may be of either sign, depending on the frequency. This fact regarding the effect of leakance on the resistance component of the impedance is not completely represented by the approximation (7.4)—which indicates the change as being always an increase—but it can be inferred from a study of the exact formulas (7.2) and (7.3). These would have to be employed also if the effects of large leakance were being studied—or, more generally, large $G/\omega C$. If it were not for a need of these exact formulas, the approximate formula (7.4) would have been derived by the mere application of Taylor's theorem to (1).

Part II

Impedance of Open-Wire Lines

It will be recalled that the characteristic impedance of an ordinary open-wire line depends primarily on its inductance and its capacity, only secondarily on its resistance, and far less still on its leakance; and hence that its impedance is at least roughly equal to $\sqrt{L/C}$.

Of the quantities defined by equations (2), . . . (7), the four most suitable for describing open-wire lines are F, k, b, and a. F is suitable as the independent variable, approximately proportional to the frequency. k is suitable as one parameter. For the other parameter, which evidently must involve the leakance, b or a respectively is the most suitable according as the leakance G is approximately proportional to the frequency or is approximately independent of the frequency. The corresponding suitable forms of the equation for the characteristic impedance K are then

$$K=k\sqrt{\frac{1+iF}{(b+i)F}}, \qquad (8) \qquad\qquad K=k\sqrt{\frac{1+iF}{a+iF}}. \qquad (9)$$

The quantity $k=\sqrt{L/C}$ which occurs in (8) and (9) as a mere factor is significant as being the value that the impedance approaches when the frequency is indefinitely increased[4]; it is also the value the impedance would have at all frequencies if, without changing L and C, the line could be rendered non-dissipative. For ordinary open-wire lines at voice frequencies ($R/\omega L$ small or fairly small compared to unity) it is at least a rough approximation to the value of the impedance. This limiting value $k=\sqrt{L/C}$ will be termed the " nominal impedance " or, more fully, the " nominal characteristic impedance." [5]

The amount $K-k$ by which the characteristic impedance K exceeds the nominal characteristic impedance k will be termed the " excess impedance," and hence its two components the " excess resistance " and the " excess reactance "; (or, more fully, for the three: the " excess characteristic impedance," " excess characteristic resistance," and " excess characteristic reactance," respectively). The latter two

[4] Provided that G/f approaches zero.

[5] Strictly speaking, k varies slightly with the frequency, because of the variations of L and even C.

have respectively the values $M-k$ and N, since k is real; M and N denoting the resistance and reactance components of K. The concept " excess impedance " will be found convenient in various connections, particularly in the description of networks for simulating the impedance of smooth lines.

The ratio K/k of the characteristic impedance K to the nominal impedance k will be termed the " relative impedance " and will be denoted by $z=x+iy$; whence $x=M/k$ will be termed the " relative resistance," and $y=N/k$ the " relative reactance." This complex number z is roughly equal to unity over most of the voice frequency range, and approaches unity as a limit when F is indefinitely increased. Its exact value, written in the two forms corresponding to (8) and (9) respectively, is

$$z=\sqrt{\frac{1+iF}{(b+i)F}}, \qquad (10) \qquad\qquad z=\sqrt{\frac{1+iF}{a+iF}}. \qquad (11)$$

Thus z, which is proportional to the characteristic impedance K (except for the fact that the proportionality factor k is not strictly independent of the frequency), depends merely on the two quantities F and b, or F and a, and hence can be readily represented by tables or graphs.

When z has once been tabulated or graphed the value of K in any specific case (R, G, L, C specified) is readily obtained therefrom by entering such tables or graphs of z with the values of the arguments $F=\omega L/R$ and $b=G/\omega C$ of (10) or the arguments $F=\omega L/R$ and $a=GL/RC$ of (11), and then multiplying the value of z there found by $k=\sqrt{L/C}$. (Graphically this would amount merely to a change of scales if the parameters employed were strictly independent of the frequency.) Thus the function

$$z=\sqrt{(1+iF)/(b+i)F}=\sqrt{(1+iF)/(a+iF)}$$

represents simply and comprehensively the properties of the characteristic impedance of all smooth lines, though it is more suitable for representing open-wire lines than cables.

The two components x and y of z are represented as functions of F by the curves in Figs. 1 and 2 with b and a respectively as parameters. (Explicit formulas for x and y are included in Appendix A.)

The effects produced on $z=x+iy$ by the leakance G are exhibited, in Figs. 1 and 2, through the parameters b and a. These effects may be conveniently represented analytically in a manner formally the same as that already outlined in connection with equations (7.1) and

(7.2); with K, K_0, ΔK (there) corresponding to z, z_0, Δz (here). Thus, by applying (7.1) to (10) and (11),

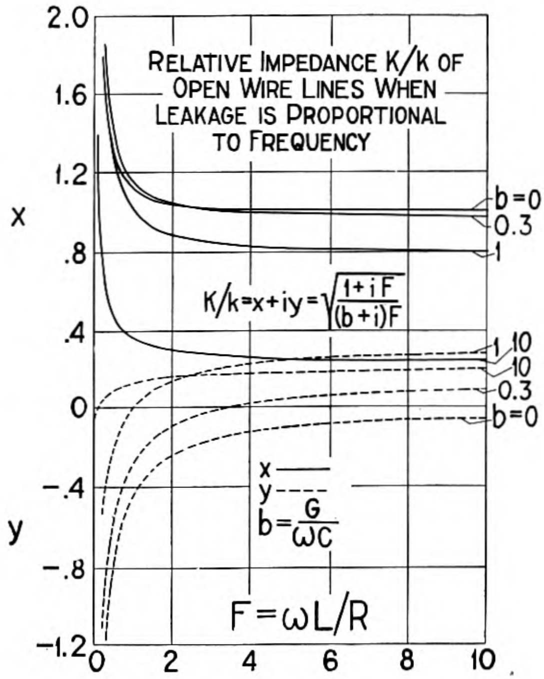

Fig. 1

$$\mu = ib/(1-ib) = ia/(F-ia).$$

Or, approximately, when b and a are small,

$$\mu = ib = ia/F;$$

and thence, approximately, by (7.2),

$$\Delta z/z_0 = ib/2 = ia/2F.$$

This analysis serves to account, approximately, for the nature of the effects of small leakance, as depicted in Figs. 1 and 2 by the curves for small b and small a. To account for the effects of large leakance, as depicted by the curves for large b and large a, recourse to the exact formula for $\Delta z/z_0$ would be necessary; but the curves for large leakance possess hardly more than academic interest, as will be realized from the remarks already made under the heading *The General Effect of Leakance.*

When there is no leakance ($G=0$, and hence $b=0$ and $a=0$) equations (10) and (11) reduce to the same form, namely

$$z=\sqrt{1-i/F}. \tag{12}$$

This limiting form of the equation for the relative impedance z is rather important because it is comparatively simple and yet is a close approximation for the impedance of most actual lines except at very low frequencies (since the effects of normal amounts of leakance are

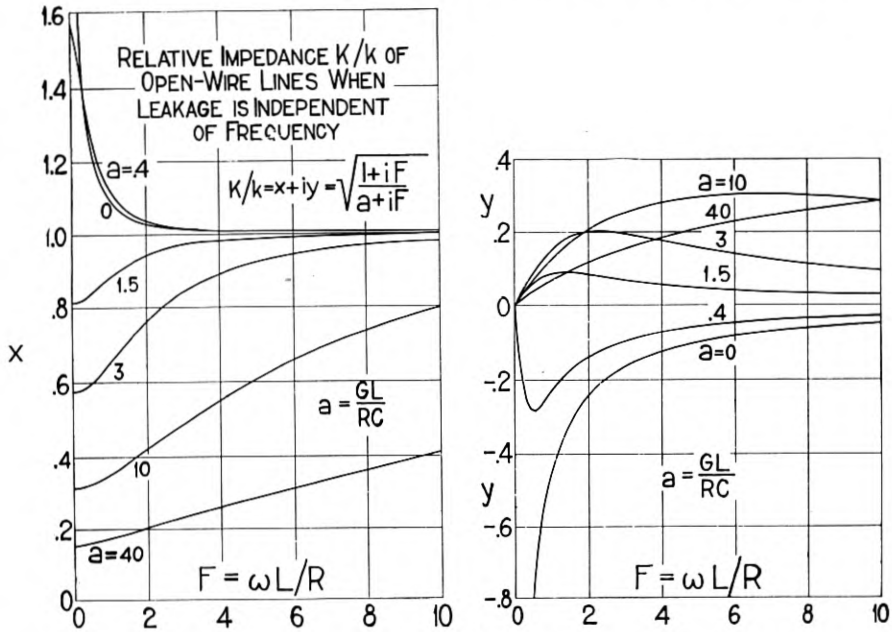

Fig. 2

very small except at very low frequencies). It will therefore now be discussed with some fullness:

For the case of no leakance the formulas for x and y are given under equation (12) in Appendix A; and are graphed in Fig. 1, ($b=0$), and in Fig. 2, ($a=0$). If the wires were devoid of resistance ($R=0$), x would be equal to unity and y would be zero. Thus the effect of wire resistance (in a non-leaky line) is to make x greater than its limiting value unity by the amount $x-1$ (the "relative excess resistance"), and to introduce a negative value of y (the "relative excess reactance," which is equal to the "relative reactance"). Both $x-1$ and $-y$ increase with decreasing F; the increase being slow at large values of F, but more and more rapid as F is decreased. $x-1$

is always smaller than $-y$; and is much smaller except at low values of F, where the two approach equality as F approaches zero. The statements regarding x and y hold also for the effect of wire resistance on the characteristic resistance and the characteristic reactance, since these are (approximately) proportional to x and y respectively, the proportionality factor being the nominal impedance $\sqrt{L/C}$.

Before leaving equation (12) attention will be directed to certain approximate and exact forms of this equation that have been found very useful in devising and proportioning networks for simulating the characteristic impedance of smooth lines, as will appear more fully in the latter part of this paper. At large values of F equation (12) yields immediately the approximation

$$z=1+\frac{1}{8F^2}-i\frac{1}{2F}, \tag{13}$$

whence $x-1$ and y have approximately the values

$$x-1=\frac{1}{8F^2}, \tag{14}$$

$$y=-\frac{1}{2F}. \tag{15}$$

From equation (12) of Appendix A the exact values of $x-1$ and y are known to be

$$x-1=\frac{1}{8F^2}\,\frac{2}{(x+1)x^2}, \tag{16}$$

$$y=-\frac{1}{2Fx}. \tag{17}$$

Thus it is seen that each of the approximations (14) and (15) is always somewhat larger than the exact value, since x is always greater than unity. However, these two approximations are fairly good for values of F as small even as unity, since there x does not exceed 1.1; and they rapidly approach exactness when F is increased, since x rapidly approaches unity. The exact equation for z will now be set down for purposes of reference; by (16) and (17) it is

$$z=1+\frac{1}{8F^2}\,\frac{2}{(x+1)x^2}-i\frac{1}{2Fx}. \tag{18}$$

At small values of F formula (12) shows that z is approximately equal to $z''=x''+iy''$, defined by the equation $z''=1/\sqrt{iF}$. The exact value of the fractional departure $(z-z'')/z''$ is

$$\frac{z-z''}{z''}=\frac{iF}{1+\sqrt{1+iF}}, \tag{18.1}$$

which, at small F, is approximately equal to $iF/2$ merely. Thus, at small F, z exceeds its approximate value z'' by an amount which is proportional to iz'', through a proportionality factor $(F/2)$ which is real and positive; since the angle of z'' is -45° it follows that x is greater than x'' by about the same amount that $-y$ is less than $-y''$. This analysis serves to account for the shape of the curves of x and y at small values of F and no leakance (the curves $b=0$ in Fig. 1, and $a=0$ in Fig. 2). The shape of the curves at any value of F can be accounted for by means of the exact formula (18.1), or a suitable approximation thereof. In fact formula (18.1) shows immediately that

$$x-x''>(-y'')-(-y)$$

and that this inequality increases with F.

Part III

Impedance of Cables

It will be recalled that the impedance of an ordinary cable depends chiefly on its capacity and resistance, relatively little on its inductance, and far less still on its leakance; and hence that its impedance is at least roughly equal to $\sqrt{R/i\omega C}=(1-i)\sqrt{R/2\omega C}$.

Of the quantities defined by equations (2), . . . (7), the four most suitable for describing cables are E, k, b and g. E is suitable as the independent variable, approximately proportional to the frequency. k is suitable as one parameter. For the other parameter, which evidently must involve the leakance, b or g respectively is the most suitable according as the leakance G is approximately proportional to or approximately independent of the frequency. The corresponding suitable forms of the equation for the impedance are then

$$K=\sqrt{\frac{1+ik^2E}{(b+i)E}}, \qquad (19) \qquad\qquad K=\sqrt{\frac{1+ik^2E}{g^2+iE}}. \qquad (20)$$

These two formulas (19) and (20) for cables are less simple than the corresponding formulas (8) and (9) for open-wire lines, because in (19) and (20) neither of the two parameters enters as a mere factor, and hence the number of effective parameters cannot be reduced to less than two. For purposes of mere specific computations this is not much of a complication; but in graphical representation it is enough to prevent the desired simplicity and compactness, if the representation is required to be exact and comprehensive. (Explicit formulas for the two components M and N of K are included in Appendix A.)

The effects of the leakance G, as represented through the medium of the parameters b and g, may if desired be conveniently formulated and analyzed in a manner formally the same as that already outlined under the heading *The General Effect of Leakance.*

In cables, particularly, the effect of leakance is usually extremely small except at very low frequencies. Hence in the graphical representation of formulas (19) and (20) it will suffice very well to confine ourselves to the limiting case of no leakance ($G=0$, and hence $b=0$ and $g=0$), when these two equations reduce to the same form, namely

$$K=\sqrt{k^2-i/E}. \tag{21}$$

The curves in Fig. 3 represent the resistance and reactance components M and N of K as functions of E with k as parameter.

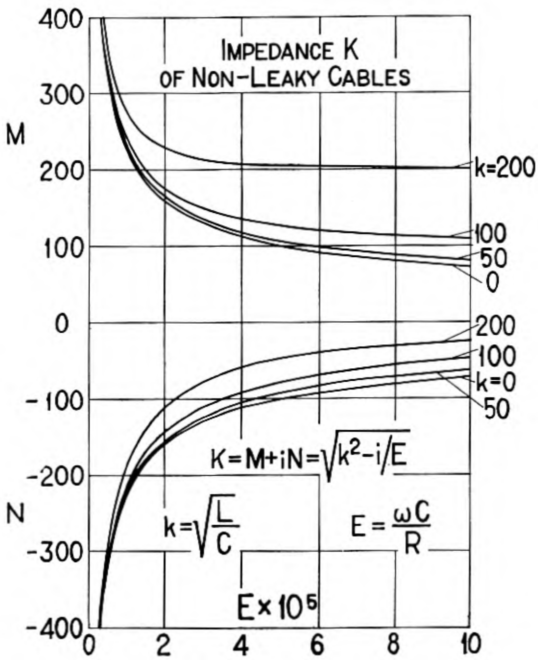

Fig. 3

The effects produced on $K=M+iN$ by the inductance L are exhibited, in Fig. 3, through the parameter k. These effects may be conveniently represented analytically in a manner formally the same as that already employed for the effects of leakance, under the heading *The General Effect of Leakance.* Thus, if K' denotes the value of K, expressed by (21), when $k=0$, then K' here will correspond to K_0 there; hence $\mu=ik^2E$, and thence, when k^2E is small compared to unity,

$$\Delta K/K'=ik^2E/2.$$

This analysis serves to account approximately for the nature of the effects of small inductance as depicted in Fig. 3. When the leakance is not zero but is small, the effects of inductance are still about the same. The general nature of the effect of the inductance L on the characteristic impedance of any smooth line, so far as regards the absolute value and the angle of the impedance, can be readily determined by mere inspection of equation (1), in a manner similar to that already outlined regarding the effect of leakance under the heading *The General Effect of Leakance.*

An alternative mode of representing the characteristic impedance of cables is suggested by the fact, already mentioned, that the impedance of a cable is at least roughly equal to $\sqrt{R/i\omega C}$, whence its absolute value is at least roughly equal to $\sqrt{R/\omega C}$. This suggests that we study a relative impedance consisting of the ratio of K to $\sqrt{R/\omega_1 C}$, where ω_1 denotes any fixed value of ω; and that we adopt the ratio ω/ω_1 as the independent variable. In this mode of treatment it will be convenient to employ the quantities w, r, F_1, b, b_1 defined by the equations

$$w=\frac{K}{\sqrt{R/\omega_1 C}}=\frac{K}{|K_1|}, \tag{22}$$

$$r=\omega/\omega_1=f/f_1, \quad (23) \qquad F_1=\omega_1 L/R, \quad (24)$$

$$b=G/\omega C, \quad (25) \qquad b_1=G/\omega_1 C. \quad (26)$$

Thus, w denotes the relative impedance to be studied; its real and imaginary components will be denoted by u and v, so that $w=u+iv$. r denotes the relative frequency—relative to any fixed frequency f_1. F_1 is one parameter. The other parameter is, respectively, b or b_1 according as the leakance G is approximately proportional to or approximately independent of the frequency.[6] The corresponding forms of the equation for the relative impedance w are

$$w=\sqrt{\frac{1+iF_1 r}{(b+i)r}}, \quad (27) \qquad w=\sqrt{\frac{1+iF_1 r}{b_1+ir}}. \quad (28)$$

These are seen to be of the same functional forms as (19) and (20) respectively; with w corresponding to K, r to E, F_1 to k^2, and b_1 to g^2.

[6] It will be noted that b is the same as already defined by (7); b_1 is related to b; and F_1 is related to F, which has already been defined by (2).

In other respects, however, there are marked differences: K is an impedance, while w is a pure number, being the ratio of K to $\sqrt{R/\omega_1 C}$; E, though approximately proportional to the frequency, is not a pure number (for it is not dimensionless), while r is a pure number, being the ratio of the general frequency to any fixed frequency; of the parameters, k^2 is very different from F_1, and b_1 is very different from g^2. The fact that (27) and (28) are of the same functional forms as (19) and (20) respectively renders formally applicable the material pertaining to equations (19) and (20) given in Appendix A.

As already remarked, the effect of leakance in cables is usually extremely small except at very low frequencies. Hence in the graphi-

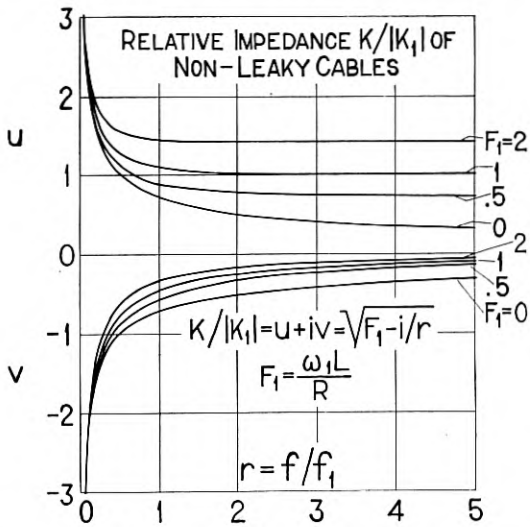

Fig. 4

cal representation of formulas (27) and (28) it will suffice for most purposes to confine ourselves to the limiting case of no leakance ($G=0$, and hence $b=0$ and $b_1=0$), when these two equations reduce to the same form, namely,

$$w=\sqrt{F_1-i/r}. \tag{29}$$

This has the same functional form as (21), with w corresponding to K, r to E, and F_1 to k^2; a circumstance rendering formally applicable the material pertaining to equation (21) given in Appendix A. The curves in Fig. 4 represent the two components u and v of w as functions of r with F_1 as parameter.

Part IV

Networks for Simulating the Impedance of Smooth Lines

Under this heading will be described the various networks devised by the writer, for simulating the characteristic impedance of smooth lines, as mentioned in the latter part of the Introduction. Before proceeding to the systematic description of these networks, some of their practical uses will be mentioned. Foremost of these is their employment for balancing purposes in connection with 22-type repeaters, already spoken of in the Introduction. Another application is for properly terminating an actual telephone line in the field or an artificial line in the laboratory, usually for electrical testing purposes or electrical measurements on the lines. In making certain tests on apparatus normally associated with a telephone line, such line may be conveniently represented for impedance purposes by the appropriate simulating network.

Some of the networks to be shown are potentially equivalent in impedance; but may differ somewhat in cost, space occupied, etc. For the purpose of this paper any two networks will be called "potentially equivalent" if, when the elements of either network are assigned any arbitrary values, the other network can be so proportioned as to have at all frequencies identically the same impedance as the first network. Evidently the mathematical condition for such equivalence is that the expressions for the impedances of the two networks have the same functional forms when the frequency is regarded as the independent variable. The two networks will then have the same number of independent parameters, or degrees of freedom for adjustment; and this number is the same as the minimum number of elements requisite for the construction of a network to have identically the impedance of the given network.

For most of the networks described, there are included design-formulas for the values of the network elements (resistances and capacities). But in any applications requiring the highest simulative precision attainable with such networks, these formulas should be regarded merely as first approximations serving to reduce the requisite detailed design-work down to a relatively small amount but not permitting it to be dispensed with entirely; for the best values of the network elements depend somewhat on the particular frequency-range involved, and on the preassigned weighting of the desired simulative precision with respect to the frequency. Moreover, these formulas completely ignore leakance; while actually leakance may not always be quite negligible. even in the voice frequency-range.

A supplementary semi-graphical method as an aid to finally arriving at the best proportioning of the networks will be found outlined in Appendix C.

The Basic Resistance and the Excess Simulator

The first approximation to a network for simulating the characteristic impedance K of a smooth line is evidently a mere resistance R_1

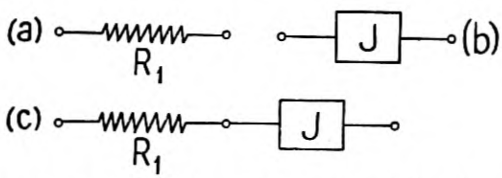

Fig. 5—Synthesis of the General Form of Complete Network. (a). Basic Resistance Element R_1 for Simulating Nominal Impedance. (b). Excess-Simulator J (Abstractly Symbolized) for Simulating Excess Impedance. (c). Complete Network for Simulating Line Impedance

(Fig. 5a) approximately equal to the nominal impedance k of the line, that is,

$$R_1 = \sqrt{L/C}, \tag{30}$$

and this is a very close approximation, for instance, in the case of open-wire lines at the frequencies of carrier current transmission.

Over the voice frequency range, however, a mere resistance does not suffice; since there the excess characteristic impedance $K-k$ is not negligible, particularly at the lower frequencies. But the resistance R_1 equal to the nominal impedance may be retained as the natural basis of a network if it is supplemented by an element or elements such as to approximately simulate the excess characteristic impedance. Such a supplementary network is here termed an "excess-simulator"[7], and is symbolized abstractly by Fig. 5b; while Fig. 5c represents the corresponding complete network consisting of the basic resistance R_1 in series with the excess-simulator, whose impedance is denoted by J. The requisite excess-simulator is obviously less simple in structure and proportioning than the mere basic resistance; whence most of the remainder of this paper will be concerned with various specific types of excess-simulators.

[7] But in practice the term "low frequency corrector" has become rather firmly established. It was suggested by the fact that the excess impedance to be simulated is largest at relatively low frequencies.

The Simplest Excess-Simulator, and Complete Network

The simplest type of excess-simulator is a mere capacity C_1 (Fig. 6b). This is adequate only for those lines whose excess characteristic resistance is negligible; as, for instance, large gauge open-wire lines, and even then not at very low frequencies. The capacity C_1 is cap-

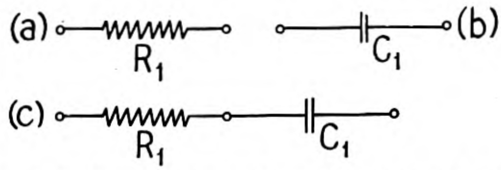

Fig. 6—Synthesis of the Simplest Type of Complete Network. (a). Basic Resistance. (b). Excess-Simulator. (c). Complete Network

able of simulating the reactance N of such a line rather closely, and its proper value for that purpose is approximately

$$C_1=\frac{2\sqrt{LC}}{R}=C\frac{2\sqrt{L/C}}{R}, \tag{31}$$

although the most suitable value depends somewhat on the specific frequency-range involved. The complete network (Fig. 6c) thus consists merely of a resistance R_1 and a capacity C_1 in series with each other, having approximately the values expressed by (30) and (31).[8]

The simple network in Fig. 6c was devised a good many years ago.[9] The majority of present-day applications require such high simulative precision that the excess characteristic resistance of the line is not negligible, and also a mere capacity does not in all cases simulate the excess characteristic reactance quite as closely as desirable. To meet these needs there have been devised the much more precise, yet fairly simple, excess-simulators and complete networks described under several of the following headings.

Two Precise Types of Excess-Simulators, and Their Limiting Forms

Fig. 7 represents two potentially equivalent [10] excess-simulators that in most cases admit of such proportioning as to simulate with

[8] See Appendix B for the derivation of formula (31) for C_1, and incidentally formula (30) for R_1; and for a discussion of the simulative precision of this network; also for the values R_1' and C_1' requisite for exact simulation at any preassigned single frequency.

[9] In 1913. U. S. Patent No. 1,167,694 of January 11, 1916.

[10] In comparing networks as to equivalence I have found very useful the general theorems on equivalence given by O. J. Zobel in his paper on electric wave-filters in the January Number of this JOURNAL, pages 45–46.

the requisite high precision the excess characteristic impedance of the line; the complete network then consisting of either of these excess-simulators in series with the basic resistance element R_1 of Fig. 5a.

In any specific application the most suitable values for the elements constituting either of the two excess-simulators in Fig. 7 depend

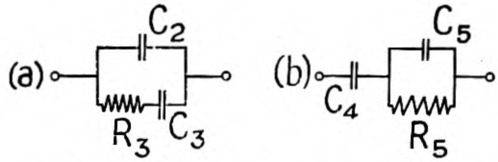

Fig. 7—Two Potentially Equivalent 3-Element Excess-Simulators Possessing High Simulative Precision for Most Applications, Except at very Low Frequencies

somewhat on the particular frequency-range involved, and also on the weighting of the desired simulative-precision with respect to the frequency. As might be expected, therefore, the work of determining closely the best combination of values for the elements of the excess-simulator can hardly avoid a certain amount of tentative detailed design-work; but usually this can be reduced to a relatively small amount by a semi-graphical method such as outlined in the latter part of Appendix C. Moreover, first-approximation values that will usually prove to be rather close, can be quickly found by means of the following approximate design-formulas (32), . . . (37), which are explicit except for containing the single undetermined parameter D. These formulas are such that the excess-simulator will possess high simulative-precision at large and even fairly large values of F, for all physcially admissible values of D $(0 \leqq D \leqq 1)$; and at the lower values of F will have a considerable range of adjustment by means of D, whose optimum value can be readily determined from inspection of Figs. 8 and 9, as described below. The above-mentioned approximate design-formulas for the elements of the two excess-simulators in Fig. 7 are[11]:

$$C_2 = \frac{2\sqrt{LC}}{R}, \tag{32}$$

$$C_3 = \frac{D}{1-D} \frac{2\sqrt{LC}}{R}, \tag{33}$$

$$R_3 = 2\sqrt{\frac{L}{C}} \tag{34}$$

[11] The first part of Appendix C gives the derivation of these formulas, and also the equation of the curves in Fig. 8.

$$C_4 = \frac{1}{1-D}\,\frac{2\sqrt{LC}}{R}, \tag{35}$$

$$C_5 = \frac{1}{D}\,\frac{2\sqrt{LC}}{R}, \tag{36}$$

$$R_5 = D^2 2\sqrt{\frac{L}{C}}. \tag{37}$$

When the excess-simulator is proportioned in accordance with these design-formulas the corresponding complete network consisting of such excess-simulator J in series with the basic resistance $R_1 = \sqrt{L/C}$ will possess the simulative precision represented by the set of graphs in Fig. 8, which shows the percentage impedance-departure δ of the

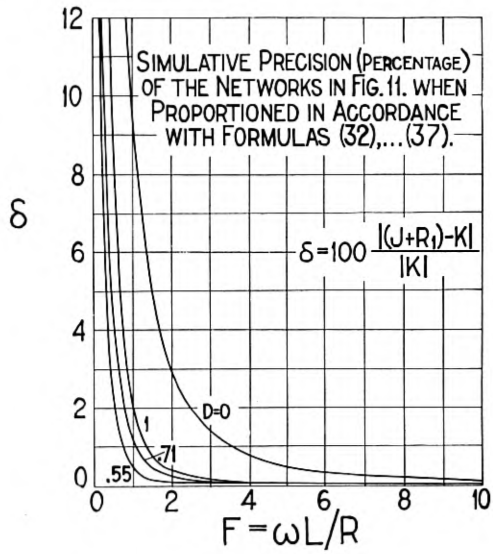

Fig. 8

complete network R_1+J from the line-impedance K, as function of F with D as parameter. In any specific case, where, of course, the F-range would be known, inspection of these graphs (Fig. 8) enables the best value of D to be readily determined, and the corresponding resulting precision δ to be seen as function of F. The curves show that the best value of D is determined by the lowest value of F contemplated, since the departure δ is largest at small values of F and rapidly decreases toward the larger values of F. It will be noted that the curves for the limiting values $D=0$ and $D=1$ have been included in Fig. 8; the corresponding limiting forms of the excess-simulators are considered a little further on.

Fig. 9, derived from Fig. 8, represents the optimum value of D as function of F; and shows also the corresponding minimum departure δ_m of the complete network. If D is chosen to be the optimum

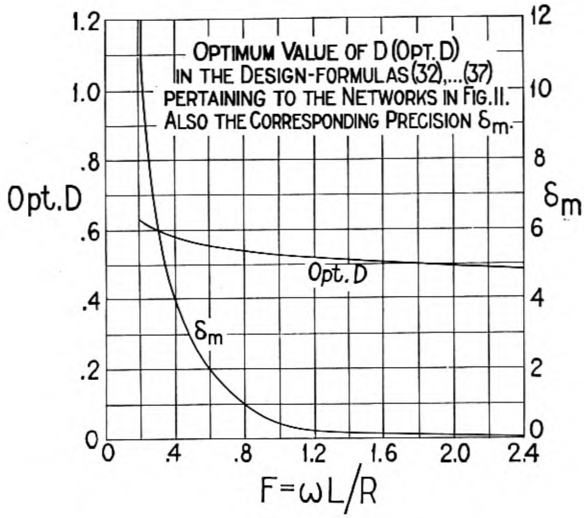

Fig. 9

value at any fixed F, the resulting network will have at that F exactly the departure shown on Fig. 9, but at all other values of F will, of course, have departures larger than those on Fig. 9.

It should be noted that these statements regarding the departures pertain to the network when the excess-simulator is proportioned in accordance with formulas (32), . . . (37). As those are only first-approximation formulas, the ultimate precision attainable will usually be better, and may be adjusted to possess a somewhat different distribution over the frequency-range.

Although the two excess-simulators in Fig. 7 are potentially equivalent as regards impedance there is a slight choice between them from the viewpoints of cost and space occupied. For it is readily seen by mere inspection of the networks at zero frequency that when they have equal impedances the total capacity C_2+C_3 of the excess-simulator in Fig. 7a is equal to merely the capacity C_4 of the excess-simulator in Fig. 7b, thus leaving C_5 in excess. As regards the relative magnitudes of their various elements the two excess-simulators can be readily compared by means of the following equations (38) derived from (32), . . . (37):

$$\frac{C_4+C_5}{C_2+C_8}=\frac{1}{D}=\frac{C_5}{C_2}=\frac{C_4}{C_3}=\sqrt{\frac{R_3}{R_5}}. \tag{38}$$

Fig. 10 represents the two limiting forms of the excess-simulators in Fig. 7, corresponding to the limiting values 0 and 1 of the parameter D occurring in the design-equations (32), . . . (37). For $D=0$ the limiting form is that in Fig. 10a, and will be recognized as

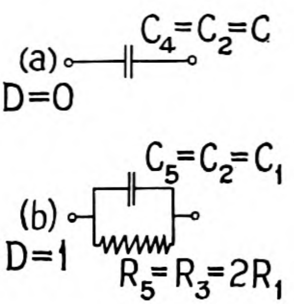

Fig. 10—The Two Limiting Forms of the Excess-Simulators in Fig. 7, Corresponding to the Limits 0 and 1 of the Parameter D

the simple excess-simulator already shown in Fig. 6b consisting of a mere capacity C_1 having the value expressed by (31); while for $D=1$ the limiting form is that in Fig. 10b, and is thus of the same form as one mentioned below, under the heading *Modifications for Very Low Frequencies*, as being capable of furnishing approximate simulation extending down to zero frequency. The departure-curves for these two limiting forms ($D=0$ and $D=1$) are included in Fig. 8, as already mentioned; and from them it is seen that the form in Fig. 10b ($D=1$) possesses much higher simulative precision than the form in Fig. 10a ($D=0$)—as would be expected.

Four Precise Types of Complete Networks, and Their Limiting Forms

Figs. 11a and 11b represent the two potentially equivalent complete networks that can be constructed from the basic resistance R_1 of Fig. 5a, and the excess-simulators in Figs. 7a and 7b respectively; and hence having for their elements approximately the values expressed by equations (30), (32), . . . (37).

Figs. 11c and 11d represent two other complete networks that also are potentially equivalent to those in Figs. 11a and 11b[12].

Appendix D gives the three sets of formulas expressing the values of the elements constituting the networks in Figs. 11b, 11c, 11d re-

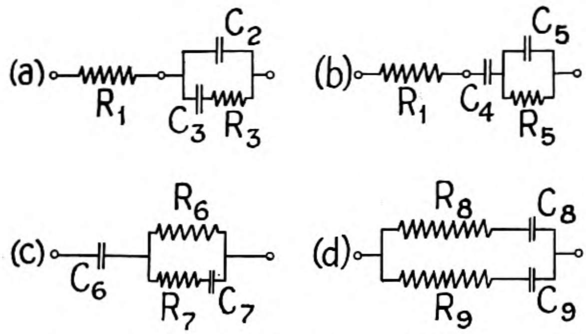

Fig. 11—Four Potentially Equivalent 4-Element Complete Networks Possessing High Simulative Precision for Most Applications, Except at Very Low Frequencies

spectively, in terms of the elements constituting the network in Fig. 11a, when those four networks have equal impedances.

Although the four complete networks in Fig. 11 are potentially equivalent as regards impedance there is some choice among them from the viewpoint of cost and space occupied. For it is readily seen by mere inspection of the networks at zero frequency that, when they have equal impedances,

$$C_2+C_3=C_8+C_9=C_4=C_6. \tag{39}$$

Thus the networks in Figs. 11a and 11d have the same total capacity; and this is less than the total capacity of the network in Fig. 11b by the amount C_5, and is less than the total capacity of that in Fig. 11c by the amount C_7. Similarly by mere inspection of the networks at infinite frequency it is seen that

$$G_6+G_7=G_8+G_9=G_1, \tag{40}$$

the G's being the reciprocals of the R's and thus being the corresponding conductances.

Before leaving Fig. 11 it may be noted that the network in Fig. 11d has the same form as though obtained by connecting in parallel two networks having the same form as Fig. 6c but with elements R_1', C_1' and R_1'', C_1'', say. Now it is known that, in most applications, the

[12] In connection with Figs. 11b and 11c the network shown in U. S. Patent No. 1,240,213 of September 18, 1917 may be of some interest.

network in Fig. 11d has much higher simulative precision than that in Fig. 6c. These considerations suggest the possibility of attaining still higher precision by connecting in parallel several such networks, having constants R_1', C_1'; R_1'', C_1''; R_1''', C_1''', ...

Fig. 12 represents the two limiting forms of the network in Fig. 11, corresponding to the limiting values 0 and 1 of the parameter D occurring in the design-equations (32), . . . (37). For $D=0$ the limiting form is that represented in Fig. 12a, and this will be recognized

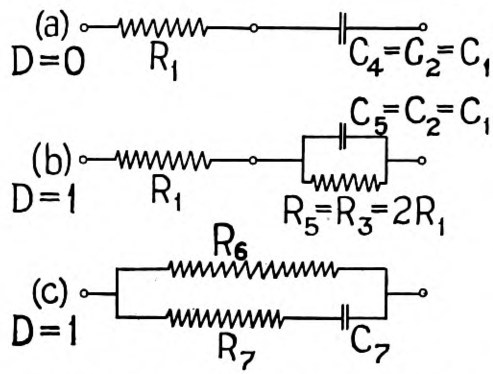

Fig. 12—The Two Limiting Forms of the Networks in Fig. 11, Corresponding to the Limits 0 and 1 of the Parameter D. Networks (b) and (c) are Potentially Equivalent

as the simple 2-element network already shown in Fig. 6c; while for $D=1$ the limiting forms are the two potentially equivalent 3-element networks represented in Figs. 12b and 12c, and are thus of the same forms as two mentioned below, under the heading *Modifications for Very Low Frequencies*, as being capable of furnishing approximate simulation extending down to zero frequency. The values of the elements of the network in Fig. 12c in terms of the elements of the network in Fig. 12b, for equivalence of these two networks as regards impedance, are

$$R_6 = R_1 + R_3 = 3R_1, \tag{41}$$

$$R_7 = R_1(1 + R_1/R_3) = 3R_1/2, \tag{42}$$

$$C_7 = \frac{C_2}{(1+R_1/R_3)^2} = \frac{4C_2}{9}. \tag{43}$$

Thus the network in Fig. 12c requires only four-ninths as much capacity as the network in Fig. 12b.

Modifications for Very Low Frequencies

Thus far the present paper has dealt with the characteristic impedance of smooth lines as distinguuished from their sending-end impedance, strictly speaking. The two are closely equal when the lines are electrically long, which is usually the case for the telephonic frequency range; but at very low frequencies the sending-end impedance of even a rather long line may depend very greatly on the distant terminating impedance and hence depart widely from the characteristic impedance. In case the terminating impedance is conductive to direct current the sending-end impedance of even a strictly non-leaky line would have a finite value at zero frequency; its resistance component evidently being equal to the total line-wire resistance plus the terminating resistance, while its reactance component would, of course, be zero. Actually, on account of line leakance, the resistance component would be somewhat less; and in case the distant terminating impedance permits no passage of direct current the sending-end impedance of the line at zero frequency would depend largely on the line leakance.

Most of the simulating networks thus far described were devised primarily with regard to the voice range of frequencies, without reference to frequencies very far below that range. At very low frequencies these networks become unsuitable because their impedance is not only much too large but also has not even approximately the proper angle. There have not been many occasions for modifying the networks so as to extend their range of simulation down toward zero frequency; but it seems likely that in most cases the requisite modification in the network impedance could be attained, at least roughly, by shunting the excess-simulator (Fig. 5b) with a mere resistance S' approximately equal to the zero-frequency sending-end resistance of the line diminished by the resistance R_1 of the basic resistance element. Clearly this modification will give the network the desired impedance at zero-frequency, without affecting its impedance at infinite frequencies; since the impedance of the unshunted excess-simulator is infinite [13] at zero-frequency and is zero at infinite frequencies. At the intermediate frequencies the resulting modification would doubtless be slight except toward the lower frequencies, where it would increase more and more rapidly as zero-frequency is approached. Of course, the addition of the modifying element S' would usually entail some alterations in the proportioning of the

[13] Except for the limiting form in Fig. 10b.

original network, as indicated by Fig. 13a, where the altered values of J and R_1 are denoted by J' and R_1' respectively.

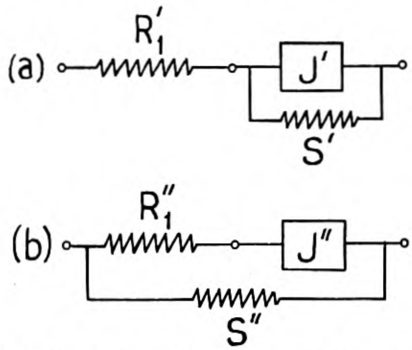

Fig. 13—Two Potentially Equivalent Modifications for Extending Range of Simulation Down to Zero Frequency. (a). Modification by Shunting the Excess-Simulator J'. (b). Modification by Shunting the Complete Network $R_1''+J''$

Fig. 13b represents an alternative but potentially equivalent form of modification, obtained by shunting the original form of network (Fig. 5c) with a resistance S''; and the conditions for equivalence are

$$S''=S'+R_1', \tag{44}$$

$$R_1''=R_1'(1+R_1'/S'), \tag{45}$$

$$J''=J'(1+R_1'/S')^2. \tag{46}$$

Since the shunts S' and S'' are potentially equivalent in their effects their simultaneous application would be potentially equivalent to the application of either alone.

Thus far the suggested modifications have been stated only with reference to the excess-simulator regarded abstractly. When the specific structure of the excess-simulator is regarded, the modifications can take several different forms which, for any one excess-simulator, are equivalent as regards impedance. Certain of these are noted in the following paragraphs:

Among the modified excess-simulators will evidently be found one having the limiting form already depicted in Fig. 10b.

Fig. 14 represents by (a) and (b), respectively, the 3-element excess-simulators in Figs. 7a and 7b modified by the shunt resistance S', and thereby converted to 4-element excess-simulators. Figs. 14c and 14d represent two other 4-element excess-simulators that are potentially equivalent to those in Figs. 14a and 14b as regards impedance.

Before leaving Fig. 14 it may be noted that the excess-simulator in Fig. 14d has the same form as though obtained by connecting in series two of the simple form of modified excess-simulator in Fig. 10b having elements C_2', R_3' and C_2'', R_3'', say. This observation suggests

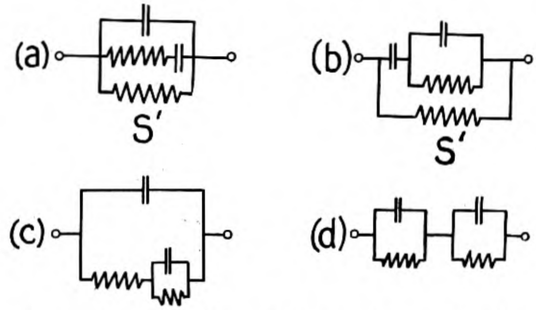

Fig. 14—Four Potentially Equivalent 4-Element Excess-Simulators Embodying Shunt-Resistance Modifiers for Extending the Range of Simulation down to Zero Frequency

the possibility of attaining still higher simulative precision for a modified excess-simulator by connecting in series several such simple modified excess-simulators.

Among the modified complete networks will evidently be found two having respectively the forms already depicted in Figs. 12b and 12c.

Fig. 15 represents four potentially equivalent complete networks derived from Fig. 11d by application of a shunt resistance S''. The

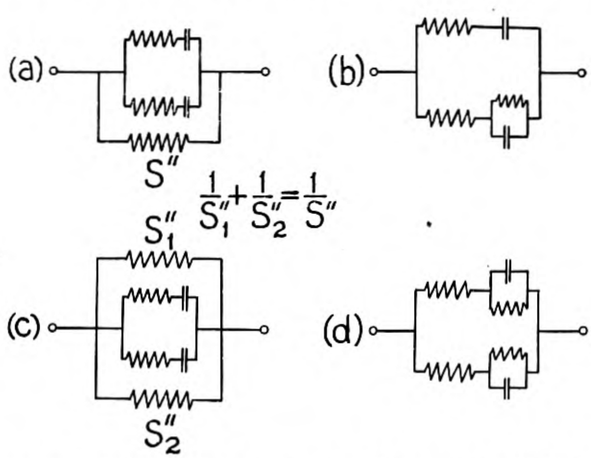

Fig. 15—Four Potentially Equivalent Complete Networks Embodying Shunt-Resistance Modifiers for Extending the Range of Simulation Down to Zero Frequency

forms in Figs. 15c and 15d, though each containing a superfluous element, are of interest because they have the same forms as though obtained by connecting in parallel two networks of the forms already depicted in Figs. 12c and 12b respectively.

Modifications For Leaky Lines

For lines whose leakance is not quite negligible a study of the formulas and graphs of the line impedance indicates that the effects of such leakance can be sufficiently taken into account by a mere slight reproportioning of the network without the addition of any further element, except that a small series inductance might be a slight improvement in those cases where the leakance increases rapidly with the frequency.

Appendix A

Equations of the Components of the Line Impedance

This Appendix contains the equations for the rectangular components and the equation for the angle of the relative impedance z and of the impedance K, corresponding to most of the various forms of the equations employed in this paper for expressing z and K. It thereby includes the equations for all the graphs employed in representing z and K. It contains also the equations for the network of curves of z and K in the complex plane for certain of the more important limiting cases involving not more than one parameter.

With regard to the notation it will be recalled that $z=x+iy$ and $K=M+iN$. The angles of z and K will be denoted by $ag\, z$ and $ag\, K$, respectively, "ag" being an abbreviation for "angle of".

Equation (10):

$$z=\sqrt{\frac{1+iF}{(b+i)F}},$$

$$x=\sqrt{\frac{b+F+\sqrt{(1+b^2)\,(1+F^2)}}{2\,(1+b^2)\,F}},$$

$$y=-\frac{1-bF}{2(1+b^2)Fx},$$

$$ag\, z=-\tfrac{1}{2}\tan^{-1}\frac{1-bF}{b+F}.$$

Equation (11):

$$z=\sqrt{\frac{1+iF}{a+iF}},$$

$$x=\sqrt{\frac{a+F^2+\sqrt{(1+F^2)(a^2+F^2)}}{2(a^2+F^2)}},$$

$$y=-\frac{(1-a)F}{2(a^2+F^2)x},$$

$$ag\, z=-\tfrac{1}{2}\tan^{-1}\frac{(1-a)F}{a+F^2}.$$

Equation (12):

$$z=\sqrt{1-i/F};$$

$$x=\frac{1}{\sqrt{2}}\sqrt{1+\sqrt{1+1/F^2}},$$

$$y=-1/2Fx=-\sqrt{x^2-1},$$

$$x-1=\frac{1}{8F^2}\,\frac{2}{(x+1)x^2},$$

$$ag\, z=-\tfrac{1}{2}\cot^{-1}F.$$

The relation $y=-\sqrt{x^2-1}$ can be written in the form

$$\frac{x-1}{-y}=\sqrt{\frac{x-1}{x+1}},$$

which shows that $x-1$ is always smaller than $-y$; and is very much smaller except at small values of F, where the two approach equality as F approaches zero.

The locus of z in the xy-plane is the hyperbola $x^2-y^2=1$. For any preassigned value of F the corresponding values of x and y on this locus can be accurately calculated by means of the above equations for x and y. For any pair of values of x and y situated on this locus the corresponding value of F is given by $F=-1/2xy$.

Equation (19):

$$K=\sqrt{\frac{1+ik^2E}{(b+i)E}},$$

$$M=\sqrt{\frac{b+k^2E+\sqrt{(1+b^2)\,(1+k^4E^2)}}{2(1+b^2)E}},$$

$$N=-\frac{1-bk^2E}{2(1+b^2)EM},$$

$$ag\, K=-\tfrac{1}{2}\tan^{-1}\frac{1-bk^2E}{b+k^2E}.$$

Equation (20)

$$K=\sqrt{\frac{1+ik^2E}{g^2+iE}};$$

$$M=\sqrt{\frac{g^2+k^2E^2+\sqrt{(1+k^4E^2)\,(g^4+E^2)}}{2\,(g^4+E^2)}},$$

$$N=-\frac{(1-g^2k^2)E}{2(g^4+E^2)M},$$

$$ag\,K=-\tfrac{1}{2}\tan^{-1}\frac{(1-g^2k^2)E}{g^2+k^2E^2}.$$

Equation (21):

$$K=\sqrt{k^2-i/E};$$

$$M=\frac{1}{\sqrt{2}}\sqrt{k^2+\sqrt{k^4+1/E^2}},$$

$$N=-1/2EM=-\sqrt{M^2-k^2},$$

$$M-k=\frac{1}{8E^2}\,\frac{2}{(M+k)M^2},$$

$$ag\,K=-\tfrac{1}{2}\cot^{-1}k^2E.$$

The relation $N=-\sqrt{M^2-k^2}$ can be written in the form

$$\frac{M-k}{-N}=\sqrt{\frac{M-k}{M+k}},$$

which shows that $M-k$ is always smaller than $-N$, though the two approach equality when E approaches zero.

The network of curves of K in the MN-plane are the equi-k curves consisting of the family of hyperbolas $M^2-N^2=k^2$, and the equi-E curves consisting of the family of hyperbolas $MN=-1/2E$.

Appendix B

On the Simple Type of Complete Network (Fig. 6)

The network in Fig. 6c consisting of a resistance R_1 and capacity C_1 in series with each other and having the values expressed by equations (30) and (31) was originally arrived at by working with values of F large or at least fairly large compared with unity; for then, by equation (12), the characteristic impedance K has approximately the value.

$$K=k-ik/2F. \tag{1-B}$$

This represents K as having a resistance component k that is independent of frequency, and a reactance component $-k/2F$ that is negative and inversely proportional to the frequency f (since $F=\omega L/R$) and thus leads exactly to the values of R_1 and C_1 expressed by (30) and (31), whence the impedance of this network is exactly equal to the approximate value of the line impedance expressed by (1-B).

To obtain more precise and comprehensive knowledge regarding the simulative precision of this network its exact impedance $k-ik/2F$ will here be compared with the exact value of the line impedance (when leakance is neglected). For this purpose it is convenient to employ the line impedance in the form

$$K=xk-ik/2xF, \tag{2-B}$$

obtained by means of the relation $y=-1/2Fx$ found under equation (12) in Appendix A. The equation (2-B) shows that to exactly simulate the line impedance by a resistance R_1' and capacity C_1' in series with each other these would have to possess the values

$$R_1'=x\sqrt{L/C}, \tag{3-B}$$

$$C_1'=\frac{2x\sqrt{LC}}{R}, \tag{4-B}$$

which differ only by the factor x from the values of R_1 and C_1 expressed by (30) and (31). Thus the ideal resistance R_1' and capacity C_1' for exactly simulating the line impedance would vary with F in precisely the same way as x varies with F. Moreover the ratio of these ideal values to the fixed values of R_1 and C_1 expressed by (30) and (31) is merely x. By reference to Fig. 1 (with $b=0$) it will be seen that, except at small values of F, the factor x is nearly independent of F and is only slightly greater than unity. Thus the values of R_1 and C_1 determined by means of equations (30) and (31) are slightly too small at all frequencies; while the values determined by means of equations (3-B) and (4-B), for any specified frequency (by inserting the appropriate value of x), are slightly too small at lower frequencies and slightly too large at higher frequencies.

Since (3-B) can, by (30), be written in the form

$$R_1'=R_1+(x-1)\sqrt{L/C}, \tag{5-B}$$

and since x is always greater than unity, it is seen that the simulation can be somewhat improved by supplementing the excess-simulator with a small series resistance element R_{11}, the ideal value of which would be

$$R_{11}=(x-1)\sqrt{L/C}. \tag{6-B}$$

Actually, since x varies with frequency, R_{11} is limited to some compromise value. In practice R_{11} would usually be combined with the basic resistance R_1, though the functions of the two are distinctly different. (If the requisite value of R_{11} were negative, R_1 would merely be decreased by that amount.)

Appendix C

On the Precise Types of Excess-Simulators (Fig. 7)

The two sets of formulas (32), (33), (34) and (35), (36), (37), representing first-approximations to the proper values of the elements constituting the excess-simulators in Figs. 7a and 7b respectively, were originally obtained by working with values of F large or at least fairly large compared with unity; for then, by (13), the excess characteristic impedance $K-k$ has approximately the value

$$K-k=\frac{k}{8F^2}-i\frac{k}{2F}, \tag{1-C}$$

while, at large or fairly large values of T, the impedance $J=P+iQ$ of each excess-simulator in Fig. 7 can be expressed approximately by the equation

$$J=\frac{P_0}{T^2}-i\frac{(1+t)P_0}{T}, \tag{2-C}$$

derived from the exact equation (16-C) below, in which t, P_0, and T have the values defined by the following two sets of equations (3-C), (4-C), (5-C) and (6-C), (7-C), (8-C) for the excess-simulators in Figs. 7a and 7b respectively:

$$t=C_2/C_3, \quad (3\text{-C}) \qquad\qquad t=C_5/C_4, \quad (6\text{-C})$$

$$P_0=\frac{R_3}{(1+t)^2}, \quad (4\text{-C}) \qquad\qquad P_0=R_5, \quad (7\text{-C})$$

$$T=\frac{\omega C_2R_3}{1+t}, \quad (5\text{-C}) \qquad\qquad T=\omega C_5R_5, \quad (8\text{-C})$$

P_0 thus being the value of P at $\omega=0$. Comparison of the approximate equations (1-C) and (2-C) gives immediately

$$P_0/T^2=k/8F^2, \tag{9-C}$$

$$(1+t)P_0/T=k/2F, \tag{10-C}$$

as the two conditions that are necessary and sufficient for (approximate) equality of J and $K-k$ at large values of F and T. This pair of equations is equivalent to the more convenient equations (11-C),

$$\frac{T}{F}=\frac{4}{1+t}=\sqrt{\frac{8P_0}{k}}. \tag{11-C}$$

Thus the ratio of T to F is fixed as soon as either t or P_0/k is fixed. It will be convenient to adopt $\sqrt{P_0/2k}$ as the arbitrary quantity and to denote it by D, so that

$$D=\sqrt{P_0/2k}, \tag{12-C}$$

whence

$$P_0=2D^2k, \tag{13-C}$$

and

$$t=\frac{1}{D}-1, \tag{14-C}$$

and

$$T=4DF. \tag{15-C}$$

Since only positive values of t and D are physically admissible, equation (14-C) shows that the admissible range of D is 0 to 1.

From (13-C), (14-C), (15-C) and the defining equation $F=\omega L/R$ the two sets of equations (32), (33), (34) and (35), (36), (37) follow readily from the two sets of defining equations (3-C), (4-C), (5-C) and (6-C), (7-C), (8-C), respectively.

The formula for plotting the curves in Fig. 8 depends on the exact equation for J/P_0 which is

$$\frac{J}{P_0}=\frac{1}{1+T^2}-i\frac{t+(1+t)T^2}{T(1+T^2)}. \tag{16-C}$$

By substituting herein the values of P_0, t, and T expressed by (13-C), (14-C), (15-C) the equation for J/k becomes

$$\frac{J}{k}=\frac{2D^2}{1+16D^2F^2}-i\frac{1+16D^2F^2-D}{2F(1+16D^2F^2)}, \tag{17-C}$$

which is thus the exact formula for the relative impedance J/k of each of the excess-simulators in Fig. 7 when these are proportioned in accordance with the formulas (32), . . . (37).

A semi-graphical method will now be outlined in the remainder of this Appendix. In this method the ratio T/f is of frequent occurrence and will be denoted by d. Then, recalling that $P+iQ=J$, it will be seen from equation (16-C) that P/P_0 depends only on f and d; while Q/P_0 depends on f, d, and t. These observations are the basis for the method now to be described for evaluating the three parameters P_0, d, and t which implicitly determine the elements of the excess-simulators in Fig. 7.

In the first step of this method the two parameters d and P_0 are so chosen that the resistance component P of the excess-simulator will be approximately equal to the excess resistance $M-k$ of the line-impedance K, over the specific f-range contemplated, or else will differ therefrom by a nearly constant amount, which can be approximately simulated by a mere series resistance element. In the second step of the method the remaining parameter, t, is so chosen that the reactance component Q of the excess-simulator will be approximately equal to the reactance N of the line impedance, when d and P_0 have the pair of values already chosen in the first step. The technical procedure in these two steps may now be formulated explicitly as follows:

First, over the contemplated f-range, plot a set of curves representing P/P_0 as function of f with d as parameter; and on the same sheet a set of curves representing $(M-k)/P_0$ as function of f with P_0 as parameter. To evaluate d and P_0 choose (by interpolation, if necessary) such P/P_0-curve and $(M-k)/P_0$-curve as most closely coincide. A preliminary idea regarding the useful ranges of d and P_0 can be readily obtained from the approximate formulas (15-C) and (13-C), together with Fig. 8.

Second, on another sheet plot as function of f that particular N/P_0-curve having as parameter the value of P_0 already found in the first step. With this value of P_0 and the corresponding value of d, as found in the first step, plot also a sufficient set of Q/P_0-curves as function of f with t as parameter to find the one that coincides most closely with the single N/P_0-curve already plotted. To abridge this step tentative values for t can be readily obtained from the approximate formula (14-C), together with Fig. 8. But the useful range of t can be demarcated more closely by solving for t the equation obtained by equating the expressions for Q and N; the value for t thus found is [14]

$$t=-\frac{dfN}{P_0}-\frac{d^2f^2}{1+d^2f^2}.$$

This may even be plotted, as function of f, to see whether the requisite value of t varies much in the contemplated f-range.

If the best compromise value of t found in the second step is unsatisfactory as regards simulation of N by Q, it will be necessary to revert to the first step, choose some other pair of values for d and

[14] It will be recalled that the line-reactance N is practically always negative.

P_0, and with these repeat the second step. In this connection it should be noted that, in the first step, it is not necessary to choose the P/P_0-curve and $(M-k)/P_0$-curve which most closely coincide; on the contrary it suffices to choose two curves that are closely parallel (that is, have closely equal slopes at each f). For, corresponding to the nearly constant distance between such two curves, it will only be necessary to supplement the excess-simulator with a series resistance element R_{11}—which will thus in the complete network be also in series relation to the basic resistance R_1 and hence can be merged therewith (even when the requisite R_{11} is negative, provided it is less than R_1 in absolute value).

After the parameters t, P_0, and $d=T/f$ have been evaluated, the values for the elements of the excess-simulators in Figs. 7a and 7b can be readily obtained from the two sets of equations (3-C), (4-C), (5-C) and (6-C), (7-C), (8-C), respectively; it thus being found that

$$C_2=d/2\pi(1+t)P_0,$$
$$C_3=d/2\pi(1+t)tP_0,$$
$$R_3=P_o(1+t)^2,$$

$$C_4=d/2\pi tP_0,$$
$$C_5=d/2\pi P_0,$$
$$R_5=P_0.$$

The requisite value for the supplementary series resistance element R_{11} is evidently

$$R_{11}=P_0\left(\frac{M-k}{P_0}-\frac{P}{P_0}\right).$$

which will be approximately independent of f if the curves of P/P_0 and $(M-k)/P_0$ chosen in the first step are approximately parallel. If the requisite value of R_{11} is negative, the basic resistance R_1 will merely be decreased by that amount.

For the limiting form of excess-simulator in Fig. 10b the design-procedure is considerably simpler, because the parameter t is fixed $(t=0)$. The two remaining parameters d and P_0 can be evaluated by inspection of two sheets of curves plotted as functions of f: One sheet containing a set of curves of P/P_0 with d as parameter, and curves of $(M-k)/P_0$ with P_0 as parameter; and the other sheet, curves of Q/P_0 with d as parameter, and curves of N/P_0 with P_0 as parameter.

Instead of f as the independent variable it may be more convenient to employ some quantity proportional to f (for instance, F or E); likewise, instead of P, P_0, Q, M, N, some quantities proportional to them (for instance, their ratios to k).

Appendix D

Relative Values of the Elements in the Four Precise Types of Complete Networks (Fig. 11)

The following three sets of formulas express the values of the elements constituting the networks in Figs. 11b, 11c, 11d, respectively, in terms of the elements constituting the network in Fig. 11a when those four networks have equal impedances. These formulas involve the two ratios ξ and ζ pertaining to the network in Fig. 11a and defined by the equations

$$\xi = C_3/C_2, \quad \zeta = R_1/R_3.$$

For Fig. 11b,

$$\frac{R_5}{R_3}=\left(\frac{\xi}{1+\xi}\right)^2, \qquad \frac{C_4}{C_3}=\frac{1+\xi}{\xi}, \qquad \frac{C_5}{C_3}=\frac{1+\xi}{\xi^2}.$$

For Fig. 11c,

$$\frac{R_6}{R_3}=\zeta+\left(\frac{\xi}{1+\xi}\right)^2, \qquad \frac{C_6}{C_3}=\frac{1+\xi}{\xi},$$

$$\frac{R_7}{R_3}=\zeta+\left(\zeta\frac{1+\xi}{\xi}\right)^2, \qquad \frac{C_7}{C_3}=\frac{1}{(1+\xi)\left(\frac{\xi}{1+\xi}+\zeta\frac{1+\xi}{\xi}\right)}$$

For Fig. 11d,

$$\frac{R_8}{R_3}=\frac{2\zeta\tau}{(\eta+\tau)-2(1+\xi)},$$

$$\frac{R_9}{R_3}=\frac{2\zeta\tau}{2(1+\xi)-(\eta-\tau)},$$

$$\frac{C_8}{C_3}=\frac{2\xi-\zeta(1+\xi)(\eta-\tau)}{2\xi\zeta\tau},$$

$$\frac{C_9}{C_3}=\frac{\zeta(1+\xi)(\eta+\tau)-2\xi}{2\xi\zeta\tau},$$

where $\eta=1+\xi+\frac{\xi}{\zeta}$, $\quad \tau=\sqrt{\left(1+\xi+\frac{\xi}{\zeta}\right)^2-4\frac{\xi}{\zeta}}.$

Appendix E

Illustrative Example

The example contained in this Appendix serves two purposes. First, it illustrates the use of two types of the general line-impedance graphs contained in Parts II and III of the paper; second, it illustrates the first-approximation design of a simulating network by means of the method in Part IV.

The specific example chosen pertains to a well-insulated open-wire line consisting of two horizontal parallel copper wires, of No. 12 N. B. S. gauge, having per loop-mile the constants

$R=10.4$ ohms, $L=.00367$ henry, $C=.00835\text{x}10^{-6}$ farad,

the leakance G being regarded as negligible. This particular type and gauge of line was chosen because it is rather extensively employed in practice, and also because its excess impedance is far from being negligible even as regards its resistance component.

For the illustratve purposes contemplated, it will be supposed that it is desired to evaluate the resistance and reactance components M and N of the characteristic impedance K of this line over the frequency-range from 200 to 2500 cycles per second; and also to design a network for approximately simulating this impedance over that frequency-range, and to determine the simulative precision of such network.

The procedure and results are indicated by the following table together with the supplementary description coming thereafter.

f	F	x	$-y$	M	$-N$	r	u	$-v$	δ_0	δ
200	.444	1.32	.86	876	570	.222	1.87	1.22	——	3.0
300	.666	1.19	.64	790	425	.333	1.69	.91	16.6	1.3
500	1.110	1.08	.42	717	279	.555	1.53	.60	8.1	.3
800	1.776	1.04	.27	691	179	.888	1.48	.38	3.6	.1
1200	2.664	1.02	.19	676	126	1.332	1.45	.27	1.7	.1
1600	3.552	1.01	.14	670	93	1.776	1.43	.20	1.0	.1
2000	4.440	1.01	.12	670	80	2.220	1.43	.17	.6	.1
2300	5.106	1.01	.10	670	66	2.553	1.43	.14	.5	.1
2500	5.550	1.01	.10	670	66	2.775	1.43	.14	.4	.1
∞	∞	1	0	663	0	∞	$\sqrt{2}$	0	0	0

The first column in the table is a set of values of the frequency f distributed over the specified range 200 to 2500.

The columns headed $F, x, -y, M, -N$, show the successive steps in evaluating the characteristic impedance $K=M+iN$ by means of

Fig. 2 [15], with $a=0$ (since the leakance G is neglected). The F-column was obtained from the f-column by means of the equation $F=\omega L/R=.00222f$. Next the values of x and y were read from the curves $a=0$ in Fig. 2. Finally M and N were obtained from $M=kx$ and $N=ky$, with $k=\sqrt{L/C}=663$ ohms (whence M and N are in ohms). From the table it will be noted that at $f=200$ the excess resistance is about one-third as large as the nominal impedance, and the reactance is about nine-tenths as large as the nominal impedance.

The columns r, u, $-v$ show the steps in evaluating M and N by means of Fig. 4. After choosing F_1 (in Fig. 4) equal to 2 [16], the r-column was obtained from the f-column by means of the equation $r=f/f_1=2\pi Lf/RF_1=.00111f$. Next the values of u and v were read off from the curves $F_1=2$ in Fig. 4. Finally the values of M and N were obtained from $M=|K_1|u$ and $N=|K_1|v$, with $|K_1|=\sqrt{R/\omega_1 C}=\sqrt{L/CF_1}=469$.

The two last columns (δ_0, δ) of the table show the percentage precision of certain simulating networks designed in accordance with the first-approximation methods of this paper, and having for their elements the values given in the last paragraph of this Appendix.

δ_0 pertains to the simple 2-element network in Fig. 6c when proportioned in accordance with equations (30) and (31). The values of δ_0 were read from the curve $D=0$ in Fig. 8. The precision at the lower frequencies could be considerably improved by the addition of a small resistance R_{11} (as already noted in connection with equation (6-B) of Appendix B), but with a corresponding sacrifice in the rest of the range.

δ pertains to the 4-element networks in Figs. 11a and 11b when proportioned in accordance with (30), (32), (33), (34) and (30), (35), (36), (37) respectively; and δ pertains also to the networks in Figs. 11c and 11d when these are proportioned, by Appendix D, so as to be equivalent to the network in Fig. 11a. The values of δ were read from the curve $D=0.55$ in Fig. 8, this value of D being known from Fig. 9 to be about the best.

The values of the elements of the networks to which δ_0 and δ pertain will now be set down, each preceded by a reference to the corresponding diagram and design-formulas:

Fig. 6c—Formulas (30), (31); Precision δ_0.

$R_1=663$ ohms, $\qquad C_1=1{,}063\text{x}10^{-6}$ farad.

[15] Or Fig. 1, with $b=0$; but Fig. 2 is plotted to a larger scale.

[16] $F_1=1$ would be somewhat preferable for reading off values; but the principles are more clearly exhibited by choosing for F_1 some other value than unity.

Fig. 11a—Formulas (30), (32), (33), (34); Precision δ.
$R_1 = 663$ ohms, $C_2 = 1.063 \text{x} 10^{-6}$ farad, $C_3 = 1.300 \text{x} 10^{-6}$ farad, $R_3 = 1326$ ohms.

Fig. 11b—Formulas (30), (35), (36), (37); Precision δ.
$R_1 = 663$ ohms, $C_4 = 2.362 \text{x} 10^{-6}$ farad, $C_5 = 1.932 \text{x} 10^{-6}$ farad, $R_5 = 401$ ohms.

Note:—To furnish sufficiently high precision for most engineering applications the curves and the cross-section lines in the line-impedance charts would evidently have to be drawn at much closer intervals than has been done in the present paper, where the purpose of the charts is mainly qualitative, or only roughly quantitative, to exhibit the general nature of the functions involved.

Practical Application of Carrier Telephone and Telegraph in the Bell System

By ARTHUR F. ROSE

IN 1918 it was announced that the engineers of the Bell System had perfected carrier current telephone apparatus to such a point that four talking circuits had been added to one pair of wires already in use for telephone and telegraph communication and were being used commercially between Pittsburgh and Baltimore for providing needed telephone facilities. Since that time the growth of carrier application in the Bell System has been quite rapid. The purpose of this paper is to summarize the applications of carrier up to the present time and give a few typical examples where it has been found economical to provide circuits by means of carrier rather than by other types of facilities.

Principles of Operation

The theory of carrier current systems, together with a historical sketch, was presented by Messrs. Colpitts and Blackwell before the American Institute of Electrical Engineers in February, 1921, and was published in Volume XL of the Transactions of the Institute. For those who do not wish to go into the detailed theory given in that paper, it may suffice to say that in a carrier current system a number of telephone or telegraph messages are simultaneously superposed on a single pair of wires by means of high frequency currents of different frequencies on which the individual messages are impressed. It is from this principle that the carrier current systems get their name, as the individual high frequency currents may be said to "carry" the telegraph or telephone messages. By using different frequencies for the carrier currents, the individual messages retain distinctive features which enable them to be separated one from another at the receiving end of the circuit.

On account of the much higher frequencies that are used in carrier operation, the carrier currents are attenuated more rapidly than the ordinary low frequency voice currents. This requires that repeaters be located at frequent intervals in a carrier system. In these repeaters all the carrier channels are amplified together although the ordinary voice frequency channel is separated out and amplified in its own repeater.

The telephone and telegraph carrier systems although alike in their essentials differ very materially in the details of their operation. With the present equipment the frequencies employed in carrier telephony are much higher than in carrier telegraphy, thereby requiring more frequent repeater stations. In both telephone and telegraph systems it is necessary to provide for two way operation. This may be accomplished by using different carrier frequencies in the two directions or by using the same frequency in each direction with directional selectivity obtained by the three-winding coil (hybrid coil) used in repeater work. In this latter case it is necessary to provide networks

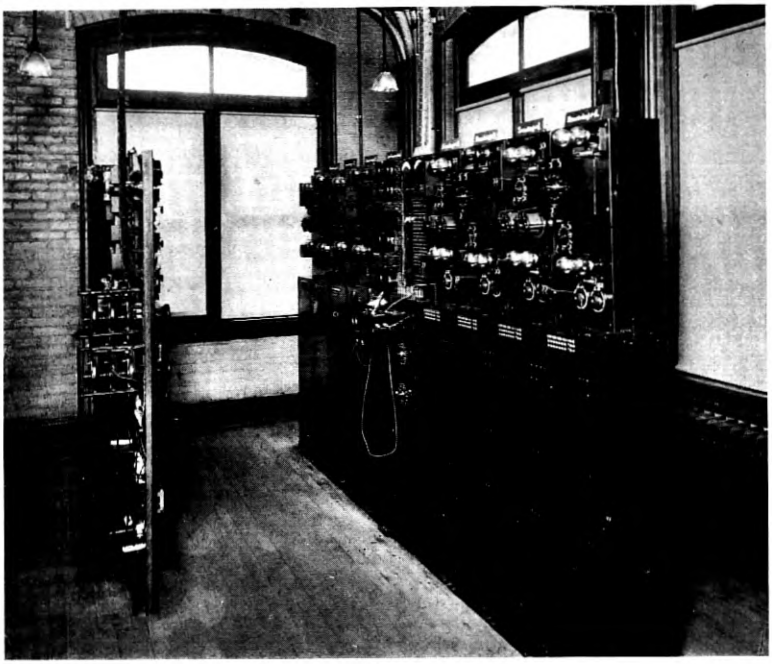

Fig. 1

to balance the lines over which the carrier system is operated. In the past both of these methods have been used but the tendency is now in the direction of eliminating balance entirely on account of its attendant maintenance difficulties and of providing for directional selectivity entirely by means of different frequencies in the two directions.

In order to show the variations in equipment arrangements which have been used in carrier systems, Figs. 1, 2 and 3 have been included. Fig. 1 shows one terminal of the original Pittsburgh-Baltimore carrier telephone system. In this picture it will be noted that the apparatus is mounted on racks about 6 feet high and occupying about one square foot of floor space, which are lined up in rows as space permits. Fig. 2 shows a terminal of a later type of carrier telephone equipment which was installed between Harrisburg and Detroit. In this case the ap-

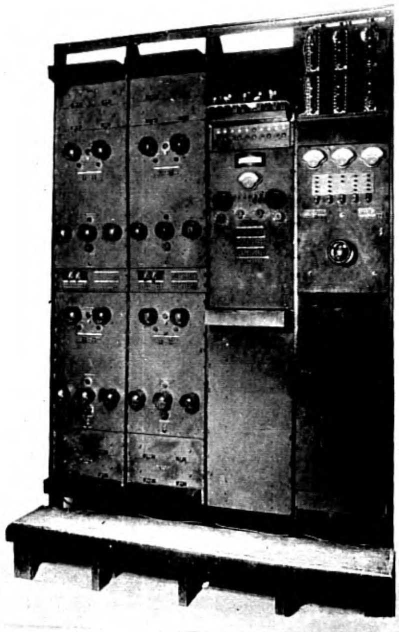

Fig. 2

paratus for a complete terminal (4 channels) is mounted on four relay bays as shown. The carrier telegraph equipment shown in Fig. 3 is a typical installation of the latest apparatus. Here rack construction is used although the individual panels are considerably larger than the older telephone equipment.

Present Development

As pointed out by Mr. Vail in his original announcement of the successful development of the carrier equipment, carrier systems are economical only for the longer circuits in the plant. The cost of the terminal equipment is so great that short circuits cannot economically be provided by carrier apparatus. Repeaters, for amplifying the high frequency currents must also be installed at frequent intervals.

The permissible distance between these repeaters depends on the gauge of wire employed in the circuits on which the carrier circuits are superposed. For this reason the large gauge circuits of the Bell System have been equipped first with the result that practically all the existing carrier installations are installed on the 165 mil wires

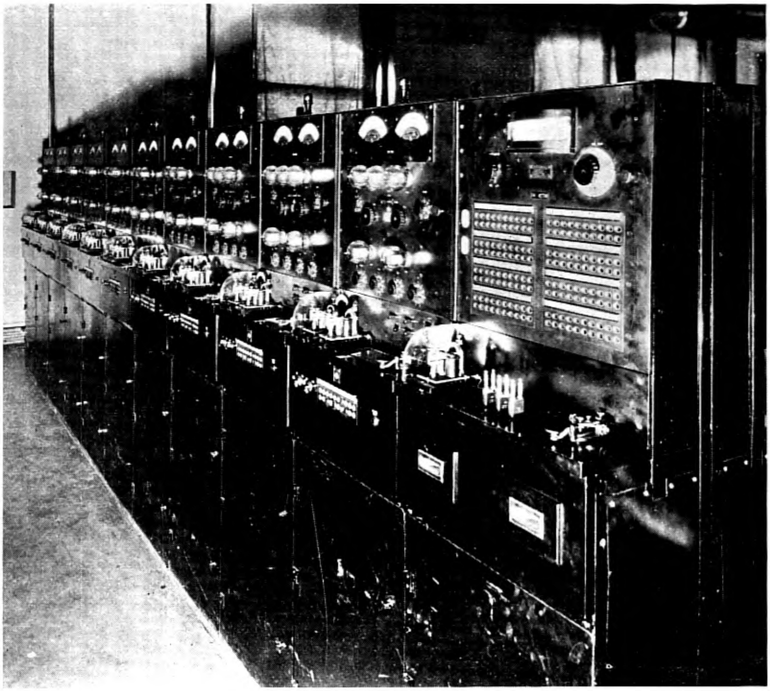

Fig. 3

which are the largest generally in use throughout the Bell plant. This wire is largely used on the important backbone routes of the country and it is on these that the existing carrier circuits are superposed. In looking over the map of Fig. 4, which shows all the existing carrier installations, this fact will be noted and also that the carrier systems in most cases provide circuits over 250 miles in length.

It is of interest to note that the application of carrier very completely covers the important cross country routes. In the west the circuits from Portland to Los Angeles are equipped, the transcontinental line from San Francisco east to Harrisburg, and the eastern coast route from Bangor to Atlanta with the exception of the all cable sections between Boston and Washington. As each line on the map represents several channels the number of circuits obtained by carrier

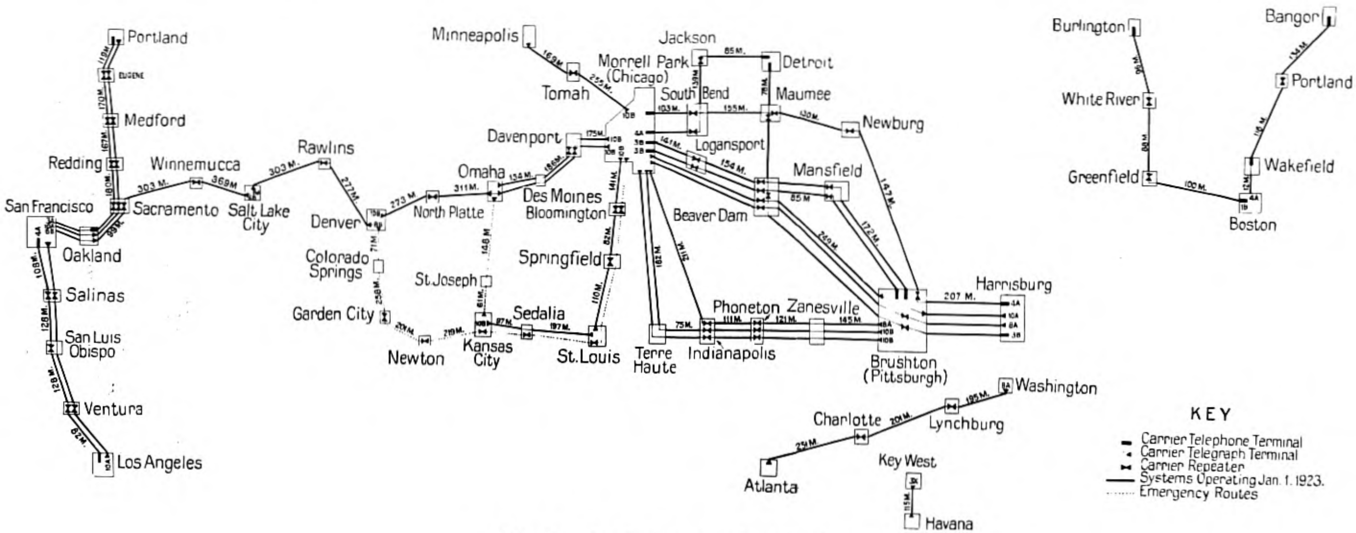

Fig. 4—Carrier System Installations

does not appear as large as is actually the case. In order to give a better idea of the extent of the carrier application the following table has been prepared which lists all the systems shown on the map and totals the channel miles obtained by each system. The telegraph channels if placed end to end would circle the globe 3 times and the telephone channels would extend somewhat more than half way round.

Carrier Telephone System	Channels	Miles	Channel Miles
Harrisburg-Chicago	4	742	2,968
Boston-Bangor	4	250	1,000
San Francisco-Los Angeles	4	446	1,784
Harrisburg-Detroit	3	605	1,815
Boston-Burlington	1	284	284
Oakland-Portland	3	735	2,205
Pittsburgh-Chicago	6	552	3,312
Chicago-Detroit	4	327	1,308
Total	29	3,941	14,676

Carrier Telegraph System	Channels	Miles	Channel Miles
Washington-Atlanta	8	647	5,176
Harrisburg-Chicago	18	749	13,482
Oakland-Portland	10	735	7,350
Chicago-Omaha	20	495	9,900
Chicago-Pittsburgh (Via Terre Haute)	20	634	12,680
Chicago-Pittsburgh (Via Indianapolis)	8	588	4,704
Key West-Havana	3	115	345
Chicago-Minneapolis	10	424	4,240
Chicago-St. Louis	10	333	3,330
St. Louis-Kansas City	10	294	2,940
Omaha-Denver	10	584	5,840
Denver-Salt Lake	8	580	4,640
Salt Lake-Oakland	6	771	4,626
San Francisco-Los Angeles	10	446	4,460
Total	151	7,395	83,713

Typical Cases—Telegraph

It will perhaps be of interest to consider several typical cases of carrier installations in order to see the economies involved in providing circuits by carrier rather than by other methods. Taking first the carrier telegraph systems as the considerations involved there are usually very simple, we shall consider the Pittsburgh-Chicago section. There are at present three carrier telegraph systems actually in operation between Pittsburgh and Chicago. They provide a total of twenty-eight full duplex channels. These give service which could not be given otherwise as all the open-wire facilities between Pittsburgh and Chicago are completely equipped with direct current composited telegraph sets (to give all possible telegraph channels). The layout of the carrier telegraph systems between these points is shown in Fig. 5.

The above example is representative of the conditions under which carrier telegraph will be installed. In cases where open wire or cable facilities are available which can be composited with the ordinary direct current methods, the telegraph facilities can be obtained as a by-product most cheaply in this way. As soon as these facilities are all in use or an insufficient number of spare circuits remains, carrier telegraph can properly be used provided the returns from the special contract telegraph service are sufficient to meet the annual charges on the apparatus itself.

One of the carrier systems listed in the above tables is the Key West-Havana carrier system. The details of the telephone and telegraph channels obtained for the submarine cables were described in detail in the paper on the "Key West-Havana Submarine Telephone and Cable System" published in the journal of the A. I. E. E., dated March, 1922. On account of the considerable length of this cable and its high attenuation, the carrier equipment is special although resembling in principle the carrier telegraph apparatus used in our ordinary land installation. Without the carrier equipment it would have been possible to obtain only one telegraph channel on each of the three submarine cables by means of direct current composite sets. With the carrier apparatus it is possible to obtain 4 telegraph channels in addition to the single telephone channel.

Typical Cases—Telephone

The most important application at the present time of carrier telephone apparatus is probably between Pittsburgh and Chicago where the existing open wire leads are so congested that the additions of further circuits would require extensive construction work and possibly an entirely new pole line. An engineering study of this situation resulted in the drawing up of plans for an aerial toll cable which will largely replace the open wire. Work is already well advanced on the installation of this cable and it will be completed

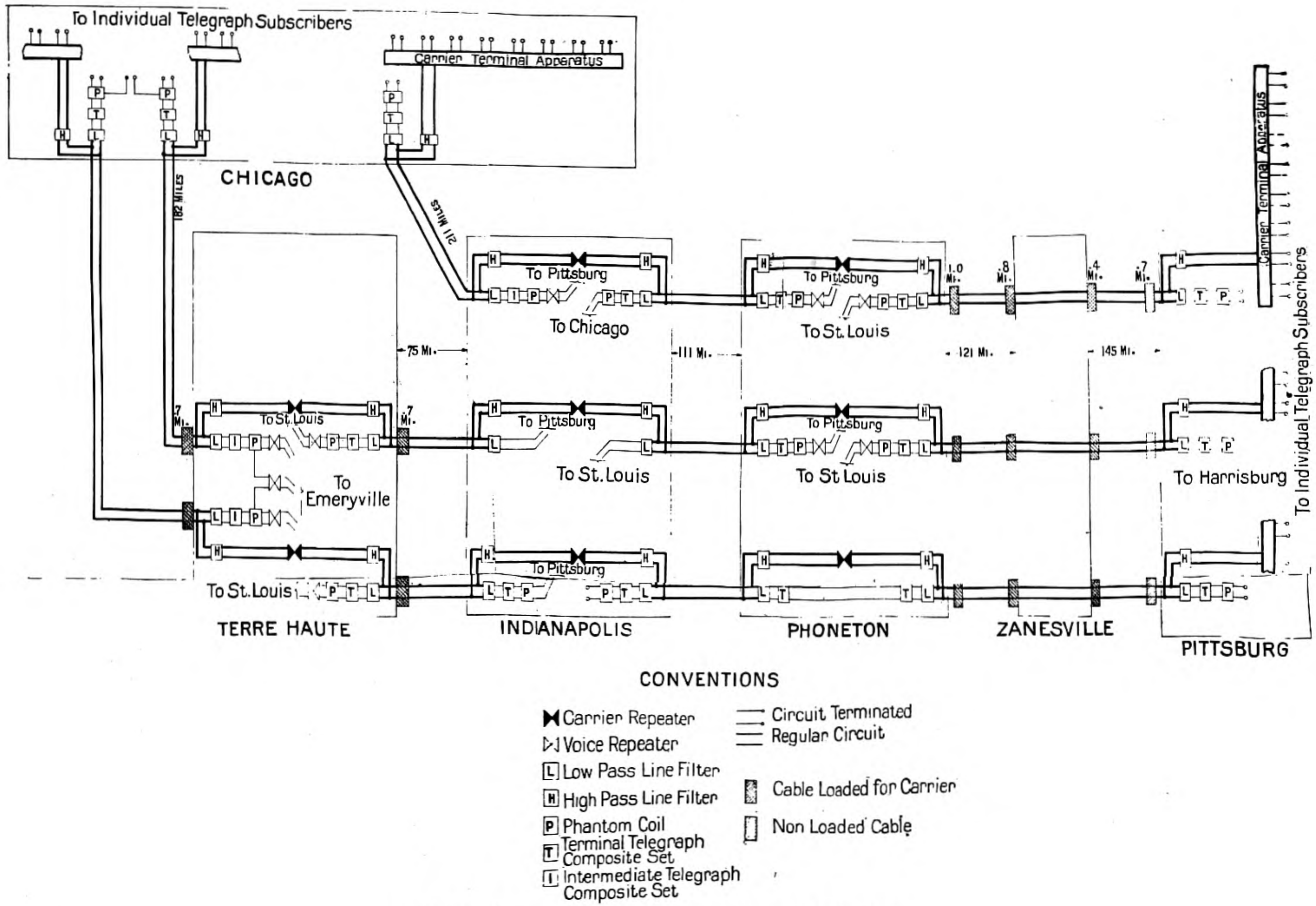

Fig. 5—Chicago-Pittsburgh Carrier Telegraph Systems

within the next few years but in the meantime, the use of carrier apparatus enables the traffic growth to be taken care of without stringing wire which, under the circumstances,would be very expensive.

There are, at present, operating between Harrisburg and Chicago, one 4-channel telephone system and between Pittsburgh and Chicago, two 3-channel systems, providing a total of 10 carrier telephone channels. These will be supplemented by at least two additional systems before the cable is completed. As soon as the cable is installed the carrier systems will probably be removed from service here and reinstalled in other locations.

In most cases the problem of providing additional circuits is not as difficult as in the section between Pittsburgh and Chicago. For this reason the relative economies of providing circuits by carrier and by the other methods must be more carefully considered. Even where no congestion exists, however, it will be found that where the circuits are long enough the carrier circuits will be cheaper than any other method of providing the facilities. The circuits to be provided must usually be several hundred miles in length before this is the case; also, since the cost of a carrier channel goes down as the number of channels installed at one time is increased it will usually be found that an installation of 3 channels will prove in for considerably shorter distances than would be necessary if a lesser number of channels are installed. In the practical case a complete system consisting of either three or four channels is usually installed at one time.

A typical case of a carrier telephone installation where the existing open wire lead is not already full but where the circuits required are long, is the Oakland-Portland system which in conjunction with a short cable between Oakland and San Francisco provides San Francisco-Portland circuits. The detailed layout is shown on Fig. 6. Here the cost study showed a considerable saving in annual charges in favor of the carrier although there was room for stringing open wire on the existing pole line. This system was put in service by the Pacific Telephone and Telegraph Company in 1921 and has since given very satisfactory service.

Another type of carrier installation is one installed to defer a proposed cable project. A long toll cable project involves the investment of such large sums of money that deferring the annual charge on the cable circuit for one year will frequently be sufficient to pay for and maintain a carrier system over the same period. Additional carrier systems may then be added to further defer the cable if this appears economical. The addition of a second system to a lead usually involves some considerable line expense for transposition work,

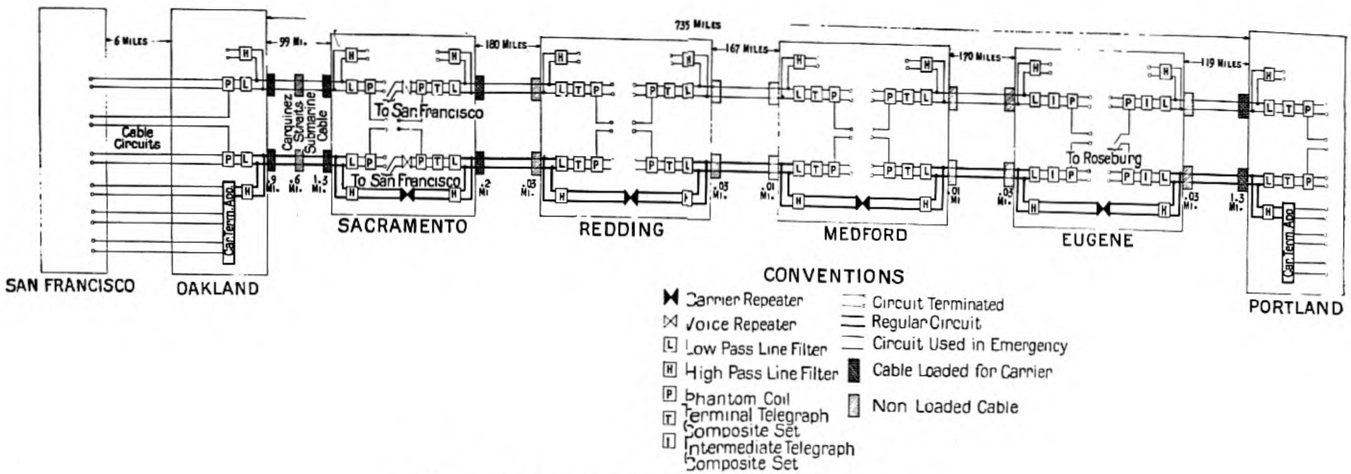

Fig. 6—Oakland-Portland Carrier Telephone System

however, and this may prove out the further addition of carrier. Even if it appears economical to install additional carrier systems, a point will soon be reached where the cumulative annual charges of the carrier systems will exceed that of the cable. The first few systems prove in over the cable because the carrier provides only for the immediate circuit requirements while the cable must take care of growth and therefore includes many idle facilities when first installed. Where carrier is used to provide facilities in place of a toll cable it should always be considered an intermediate and temporary step between open wire and cable plant.

The use of carrier as outlined above may effect further economies after the apparatus has been removed as the equipment may be reused at some other point to advantage. A typical example of the use of carrier apparatus to defer a cable is the Boston-Bangor carrier system which was put in to defer the installation of the first section of the Boston-Portland cable. The layout of this system is given in Fig. 7. It will be seen that this system is fairly short but the first

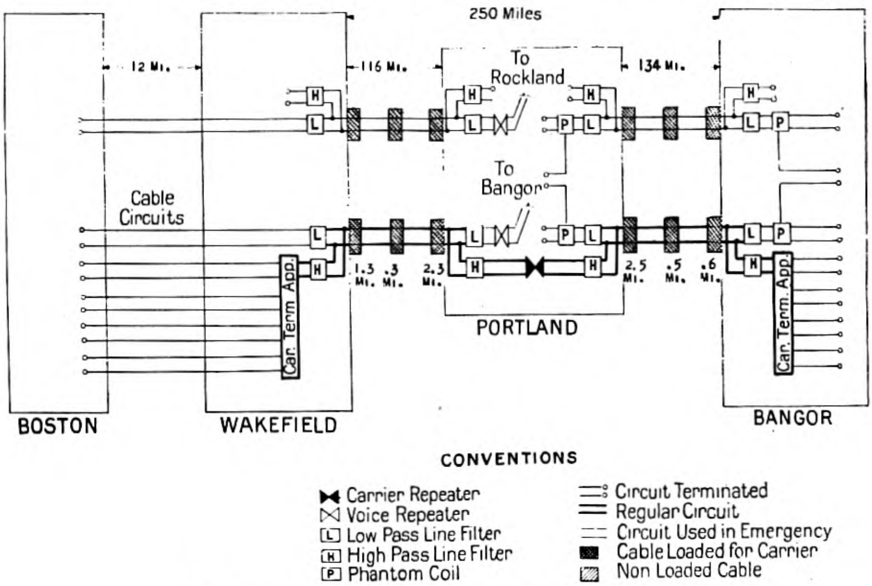

Fig. 7—Boston-Bangor Carrier Telephone System

year's annual charge on the first 50 miles of the Boston-Portland cable would have been sufficient to pay the entire first cost of this carrier project. It is possible that further carrier may be installed on this route before the cable is finally installed. The present system has deferred the cable somewhat longer than was originally expected as the growth of traffic has not been quite as rapid as was expected at the time of the war emergency.

Another example of line congestion enabling the carrier to be proved in on somewhat shorter than the ordinary economical length is in case a considerable amount of line reconstruction is involved if open-wire circuits are added to an existing lead. A case of this kind was the Boston-Burlington system where a very considerable amount of line reconstruction work would have been involved if an effort had been made to add a phantom group to the existing lead. The use of the carrier system on the existing 104 mil circuits enabled this work to be eliminated from consideration and it is possible that the work will not need to be done until this section of the line is relieved by cable or other means.

There are many cases in which the use of carrier can be considered a stop-gap to take care of the transient period between open wire and cable facilities. This has been true in the case of the former Baltimore-Pittsburgh system where the original apparatus has been removed from service as cable facilities are now available between these points via Philadelphia, Reading and Harrisburgh. This does not mean that the equipment is no longer of value, since it usually can be used again on some other location. Even the experimental panels which were used in the Pittsburgh-Baltimore system will probably be reinstalled within the next year. It is now thought that this apparatus will be used between Chicago and Minneapolis in connection with some additional panels to provide for new telephone circuits there.

Expected Development

Looking forward for the next ten years, it is expected that carrier telephone facilities will be installed at the rate of about 5,000 to 10,000 channel miles and telegraph facilities at the rate of from 20,000 to 30,000 channel miles per year. In the meantime development work may produce cheaper systems which will prove in on shorter circuits, thereby extending the field of use so that the rate of application may possibly be doubled or trebled. Even now the number of channel miles in service constitutes an important part of the total facilities of the Bell System and present a very interesting picture of rapid growth when compared with the beginning between Baltimore and Pittsburgh in 1918.

Machine Switching Telephone System for Large Metropolitan Areas

By E. B. CRAFT, L. F. MOREHOUSE and H. P. CHARLESWORTH

Synopsis: From the earliest forms of telephone switchboards to the modern types, the development of the switchboard has been marked by the increasing use of automatic methods to supplement the manual operation wherever this would result in better service to the public or more efficient operation.

In addition to all that has been done in developing and introducing automatic operations with manual switchboards, it has been found desirable and practicable to go further in the direction of introducing automatic operation in the telephone plant and a machine switching system has been developed in which the bulk of the connections are established without the aid of an operator.

The complexity of a large metropolitan area and the exacting requirements which a machine switching system must meet are outlined briefly, and the system which has been developed to meet these requirements is described.

The application of the system to a typical large metropolitan area and the means provided for permitting its gradual introduction into the existing plant are discussed.

IT is the purpose of this paper to outline briefly certain important developments in connection with machine switching telephone systems and to discuss the application of the results of these developments to the problem of providing telephone service in large metropolitan areas.

The telephone was invented in 1876. Almost immediately thereafter it was recognized that, for it to attain its greatest field of usefulness, switchboards and switching centers would have to be established for effecting interconnection between subscriber's lines.

Professor Bell's vision of the future was given in a statement to prospective investors. He said:

> "It is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings, country houses, shops, manufactories, etc., etc.—uniting them through the main cable with a central office where the wires could be connected as desired, establishing direct communication between any two places in the city. Such a plan as this, though impracticable at the present moment, will, I firmly believe, be the outcome of the introduction of the telephone to the public. Not only so, but I believe in the future wires will unite the head offices in different cities, and a

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man in one part of the country may communicate by word of mouth with another in a distant part.

"Believing, as I do, that such a scheme will be the ultimate result of the telephone to the public, I will impress upon you all the advisability of keeping this end in view, that all present arrangements of the telephone may be eventually realized in this grand system."

Early Developments

The only apparatus available at that time for this purpose was that employed in telegraph, messenger, fire and burglar alarm services. Some of this apparatus, such as wire, insulators, batteries, annunciators, etc., was found to be useful in the new art; other apparatus had

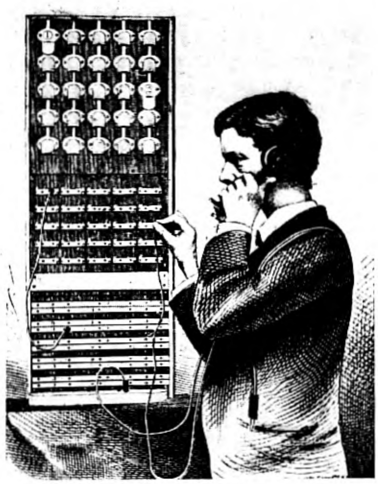

Fig. 1—Early Type Switchboard

to be developed. The switchboards of that day employed this apparatus. They were small in size, and could accommodate only a limited number of lines.

It soon became evident that the requirements of the telephone exchange service demanded signaling and switching equipment different from that employed in any of the other branches of the electrical industry, and it became necessary to create an entirely new art, involving many branches of science, before commercial telephone service could be given on an adequate scale. The switchboards grew from small boards, capable of handling a few lines, as shown in Fig. 1, to the very complex arrangements providing signaling, switching, and transmission facilities for as many as ten thousand lines in a single board, of the type shown in Fig. 2.

As the subscribers increased in number it was found that beyond a certain point it was no longer practicable or economical to have all of the subscribers' lines brought to one center. It was therefore, necessary to have several centers, the number depending upon many factors, the most important of which are the size and telephone needs of the community.

Fig. 2—Modern Type Common Battery Switchboard

The consequence of all this is that in large metropolitan areas the number of centers is large, and the trunking system complex, as each center must be provided either directly or indirectly with trunks to every other center.

As an illustration, take the New York Metropolitan area, shown in Fig. 3, where the telephone plant is of the greatest intricacy because of the very large number of subscribers served. There are at the present time 158 central office switchboards, many of them having equipment for 10,000 lines. These offices and the associated plant provide for intercommunication between 1,400,000 telephones, and approximately two trillion possible connections. It is estimated that by the year 1940 there will be 300 central office switchboards within the New York Metropolitan area, serving some 3,300,000 telephones—or nearly two and a half times the present number.

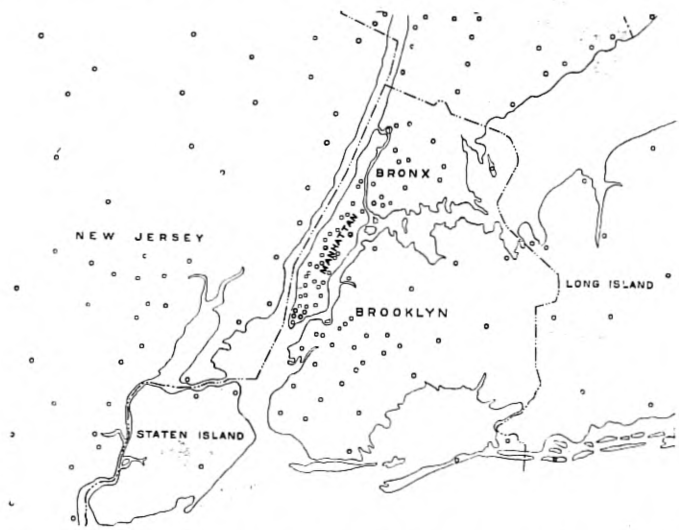

Fig. 3—Map Showing Location of Central Offices in New York Metropolitan Area

Manual Switchboards

The system most commonly employed today for connecting subscribers' lines together is the so-called "manual" system; that is, a system in which operators are employed to make the actual connections between subscribers' lines, although so many of the functions are performed automatically that, except in name, it is to a large degree automatic.

It is a long step from the early switchboards to the modern common battery multiple manual switchboards. The history of the development of switchboard equipment and apparatus shows that enormous progress has been made in this art in a comparatively few years. As the telephone subscribers have grown in number and as the amount and complexity of the traffic have increased, it has been only by the most intensive development that it has been possible to keep ahead of the demand for telephone service, and that telephone engineers have been able to get the speed, efficiency and accuracy that are obtained today in so-called manual operation. It is worthy of note in this connection that the attainment of these ends was made possible by the extensive introduction of automatic features.

A very brief description at this point of the type of manual switchboard more commonly employed will be helpful.

In this switchboard the subscriber's line terminates at the central office in so-called "jacks." Associated with each line is a lamp, individual to it, which automatically lights when the subscriber removes his receiver from the hook. This serves as a signal to the operator that a connection is desired.

The operator answers this call by inserting one end of a cord in the jack associated with the calling subscriber's line, operates a listening key which connects her telephone set to the subscriber's line, and asks for the number desired. When this is obtained the operator completes the connection by inserting the other end of the cord in the jack of the desired subscriber's line, and the subscriber's bell is rung. Suitable lamp signals are provided so that the operator may know when the called subscriber answers, when either subscriber desires further attention, or when either or both of them have finished talking and have hung up their receivers.

If the subscriber desired is connected to a distant office, the operator receiving the call would, instead of plugging directly into the subscriber's line, directly connect the subscriber's line to a trunk terminating in the desired office, where the connection would be completed by a second operator, known as the "*B*" operator, as shown in Fig. 4.

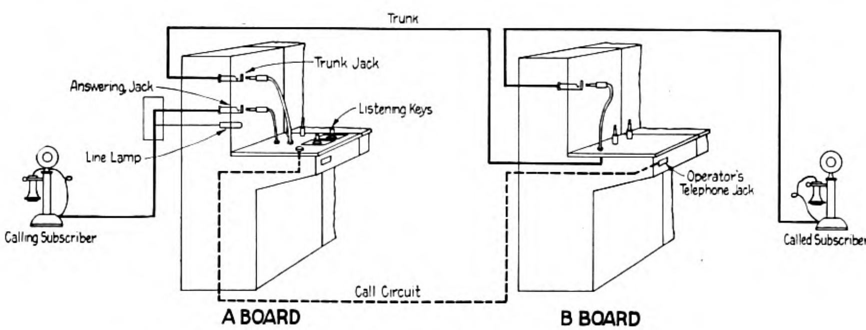

Fig. 4—Diagram Showing Manual Interoffice Connection

Such communication between the two operators as is necessary to establish this connection takes place over a special pair of wires known as a "call circuit."

The method, of which the above is a bare outline, is that used in completing ordinary connections. Different arrangements and different operating methods have to be provided for handling short haul toll calls, long distance calls, calls from coin boxes, and calls of many other kinds.

In the simplest types of manual systems, the subscriber, in order to signal the central office, turns a crank thus operating a magneto generator. This throws a drop in front of an operator at the central office. In the switchboards developed to meet the needs of the larger areas, electric lamps are substituted for the drop, and relays automatically controlled by the subscriber bring them into play at the proper time. Electric lamps which serve as visual signals to the operator to indicate the status of the connection are also associated with the cords that the operator uses for connecting subscribers together. The operation of these lamps is automatic and is under the control of the switchhook at the subscriber's station.

Many other arrangements of an automatic character have been developed and are used as occasion requires—not merely because they are automatic in character but only when it has been established that they make for better service to the public or for efficiency and economy of operation, or both. Among these may be mentioned automatic ringing, automatic listening, and many forms of automatic signaling. Many of these arrangements are highly ingenious and contribute greatly to the efficiency and economy of operation. Thus, the trend of switchboard development has been more and more in the direction of automatic operation and automatic methods.

In addition to all that has been done in developing and introducing automatic operation with so-called manual switchboards, it has been felt for a long time that in large and complex telephone areas, such for example as New York City, the time would ultimately come when it would be desirable to go further in the direction of introducing automatic operation in the telephone system. This whole matter has been the subject of much thought on the part of engineers of the Bell System and, as a result, there has been developed and recently put into operation a system in which the work of establishing most of the local connections is done entirely by machinery.

The introduction of this system will eventually make a considerable reduction in the telephone company's requirements for operators which are becoming more difficult to fulfill year by year. Operators will be required, however, to handle toll and many special classes of local calls and for this reason, together with the constant growth of the business and the considerable period of time that will be required to introduce the new system completely, we can expect little or no reduction in the present operating forces for some time to come, and no operator will find herself out of employment on account of the introduction of the machine switching system.

Machine Switching

It is the purpose of this paper to describe this system sufficiently in detail to give a general picture of it, but because of the limitation as to space no attempt will be made to go into the intricacies of circuits and apparatus, which doubtless would be of interest only to the telephone engineering specialists.

Among other requirements, the following must receive special consideration in the design of a machine switching system.

The functions to be performed by the telephone subscriber in getting a connection must be simple and easily understood.

It must work efficiently and with accuracy and speed, and, of course, must be capable of handling the various types of calls that the subscriber wishes to make.

The system must not require modifications in the existing rate structure, otherwise than desirable. If the rate structure calls for message register operation, coin boxes, etc., means must be provided for automatically operating the register and collecting the coins on such calls, and for preventing a charge on calls not answered, calls for free lines, busy lines, etc.

The system should employ, as nearly as practicable, the conventional numbering scheme.

It should work with the existing telephone network, so that its introduction does not require wholesale number changes and extensive rearrangement or the abandonment of existing switchboards or other plant. Its introduction must, of necessity, be on a gradual basis.

It must be sufficiently flexible in design to care for growth and such changing traffic conditions as occur from time to time.

In large telephone areas, such as the New York Metropolitan area, there is a great variety of calls to be handled and many different classes of service furnished the public, such as message rate, flat rate, official, coin box, non-attended pay station, attended pay station, special services such as information, etc. Not only individual lines but party lines, and private branch exchanges must be cared for, and provision must be made for thousands of toll messages which must be recorded, supervised and timed.

A call originating in a machine switching office in New York City may have as its destination any one of a great number of points. It may be for another subscriber in the same office or for one in another nearby machine switching or manual office; it may be for one of a large number of suburban toll points, or it may be to some point in a distant city.

The machine switching system, which is the subject of this paper, meets these requirements. After long-continued laboratory experi-

Fig. 5—Desk Stand Equipped with Dial

ments, supplemented by field trials, power-driven apparatus of the panel type has been found to be the most suitable, and is now in successful operation in New York City and in other large cities in the country.

General Plan of Operation

At the expense of some repetition it seems desirable in order to give as clear an understanding as possible as to the operation of the system, to first give a brief outline of how the call is handled and a description of the more important elements of the equipment, before going into a detailed description of the operation of the system.

The subscriber's station is equipped with the usual form of telephone instrument and, in addition, with a calling device known as a "dial," mounted at the base of the desk stand, as shown in Fig. 5. This dial has ten finger holes, bearing letters and figures, as shown in Fig. 6.

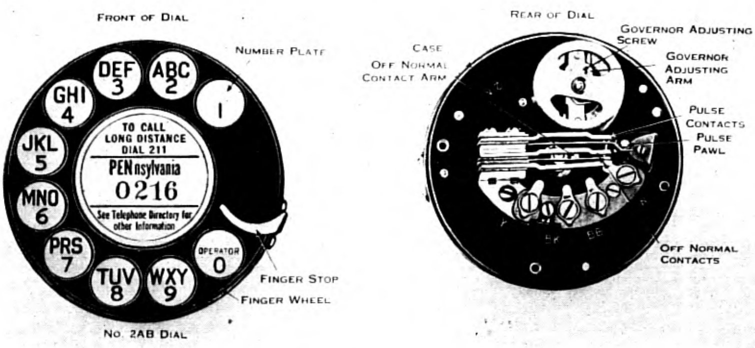

Fig. 6—Subscriber's Dial

In making a call the subscriber will, of course, first refer to the telephone directory. He will find in the directory a listing that is only slightly different from that to which he is accustomed. Typical samples of this new form of telephone listing for New York City are shown in Fig. 7. As will be noted, these conform to the present

Argent Co, 1400 Bway............**GRE** eley **5513**
Argentina Brazil & Chile Shipping Co
70 Wall. **HAN** over **0307**
Argentine Genl Consulate, 17 Batry pl..**REC** tor **6946**
Argentine Impt & Expt Corp, Prod Ex...**BRO** ad **1768**
Argentine Mercantile Corp, 42 Bway.....**BRO** ad **5066**
Argentine Naval Commission, 2 W 67..**COL** mbus **5623**
Argentine Quebracho Co, 80 Maiden la....**JOH** n **1652**
Argentine Railway Co, 25 Broad.......**BRO** ad **1383**
Argentine Trading Co, 1164 Bway......**MAD** Sq **1871**
Argeres Bros, Restrnt, 86 6th av......**SPR** ing **5337**
Argero A, Grocer, 119 9th av........**CHE** lsea **6255**
Arghis A, Tobacco, 74 Wall.........**HAN** over **6311**
Argirople Theodore, Jwlr, 406 8th av..**FAR** ragut **9772**
Argo Packing Corpn, 705 Greenwich...**FAR** ragut **4505**
Argon Dress Co, 24 E 12..........**STU** yvsnt **2011**
Argonaut Supply Corp, 50 Union sq..**STU** yvsnt **7476**
Argonne Steamship Co, 17 Battery pl...**REC** tor **2493**
Argos Ad-Art Co, 1133 Bway........**FAR** ragut **5986**
Argosy The (A Pub), 280 Bway......**WOR** th **8800**

Fig. 7—Typical Examples of New Form of Listing Telephone Numbers

manual listings, except that the first three letters of the office name are set out prominently. This numbering system will be discussed later in this paper.

Having secured the desired telephone number from the directory, which we will assume is "ACAdemy 1234," the subscriber will first remove his receiver from the hook and will hear the so-called "dial tone," which indicates that the apparatus is ready to receive the call. He will then insert his finger in the hole over the letter A, rotate the dial until the finger comes in contact with the metal stop shown in the picture, then release the dial, which will automatically return to normal. He will repeat this operation for the letters C and A, and in turn for the four numerals, *1, 2, 3, 4.*

This operation of dialing on the part of the subscriber is exactly the same, whether the telephone number he desires is in a manual or a machine switching office. Similarly, the method employed by a subscriber who is connected to a manual office in getting a subscriber connected to a machine switching office, is the same as though the desired subscriber were connected to another manual office.

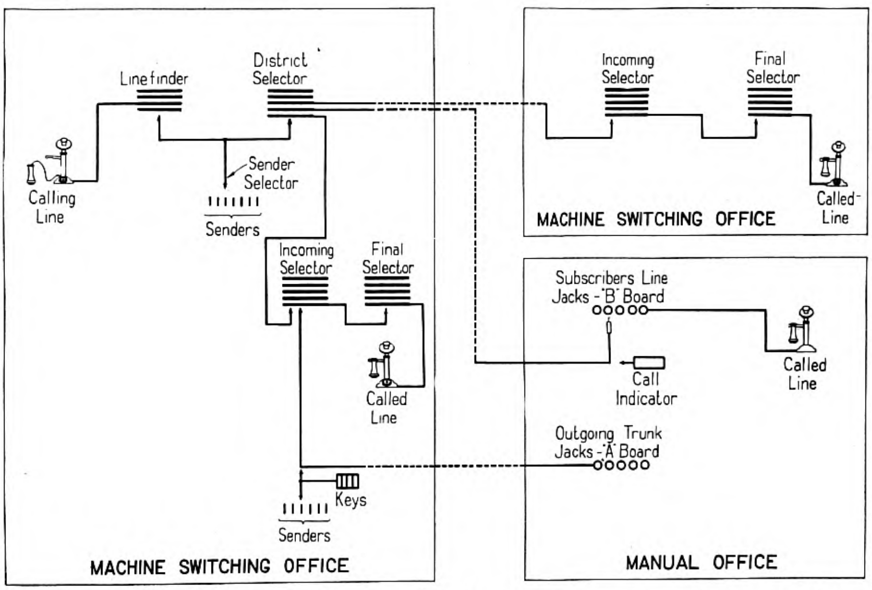

Fig. 8—Diagram Showing Connections from Machine Switching to Machine Switching, Machine Switching to Manual and Manual to Manual Switching

The progress of a call originating in a machine switching office is briefly as follows:

As will be seen from Fig. 8, the line of the calling subscriber, whom we will assume to be a subscriber in the Academy office, appears in a so-called "line finder" frame. When the subscriber's receiver is removed from the switchhook preparatory to dialing, the line is selected by a "line finder" and connected to an idle "sender" by means of a "sender-selector."

Upon completion of these operations which take but a fraction of a second, the dial tone is sent to the calling subscriber as previously mentioned. When the subscriber dials, electrical impulses on a decimal basis are transmitted to the sender which receives and registers them, translating them in turn to the proper basis for the control of the selectors which are not operated on a decimal basis. The sender automatically causes the particular "district selector" which is permanently associated with the line finder originally used, to select a trunk to the office desired.

Assuming that the call is for a subscriber in the same office, Academy, the trunk chosen will terminate at an "incoming selector" frame and the sender above referred to will cause the call to be routed through the incoming selector to a final selector, and thence to the particular line desired. When the connection is thus completed, audible signals will be sent back to the calling subscriber to indicate that the station is being rung or that the line is busy.

If the call had been for a subscriber in another machine switching office, namely, Pennsylvania, the call would be routed from the district selector to the office desired, either directly or through an "office selector" in case the total number of trunks to all offices is too large to be placed on the district selector multiple. These trunks terminate on incoming selectors at the Pennsylvania office which select the subscriber's line through final selectors, as described above.

If the call is for a subscriber connected to, say, the Worth Office, which is a manual office, the call would be routed from a district selector directly or through an office selector to the "B" board in the Worth Office, where the number desired appears in front of the operator at a "call indicator position" in the form of visible numbers on the keyshelf. The operator is advised of the trunk to which the call is connected by suitable signals, and the call is completed by plugging this trunk into the desired subscriber's line.

Calls originating in a manual office and intended for a machine switching office reach the machine switching office over trunks from the "A" operators in the manual office. At the machine switching end these trunks terminate in incoming selectors, which have access to the final selectors on which the subscriber's lines are located. The selectors are under the control of a special group of senders, and operators are provided with suitable keys for setting up in these senders the number of the desired subscriber. These operators at the machine switching office receive the information as to the desired number from "A" operators in the distant manual office, exactly as is done in the case of manual operation.

The introduction of machine switching equipment does not require radical changes in private branch exchanges. The private branch exchange is provided with dials, and calls to the central office are dialed by the private branch exchange attendant or by the extension user in the same way that the ordinary subscriber dials. No change in the private branch exchange is required for handling incoming calls. An idle trunk in the private branch exchange group is selected by the mechanism in the machine switching office, in much the same way as an individual subscriber's line is selected.

Numbering System

One of the unique advantages of the plan developed for designating telephone numbers, to which reference has already been made, is that it does not necessitate the abandonment of the existing manual listings. It requires no change except that the first three letters of the office name are set out more prominently. Simple as this change in the form of listing appears, until it was developed by the Bell System no satisfactory method of designating telephone numbers for machine switching offices in large cities was known.

Many plans had been proposed, to all of which there were serious objections. Some of them required changing the whole system of manual designation, others the use of combinations difficult for the subscriber to use. In small cities a numbering plan employing only digits is sometimes practicable, but in such a large area as we are considering, such a plan would involve seven digits. The subscriber's number would take the form of say 786-3549. Such numbers would be difficult for operators to use and for the subscribers to carry in mind and would require that every subscriber's number in the entire area be changed before the first machine switching office could be cut into service. With the new system, the subscriber's number and office in general remains as before. It is necessary to change only a few conflicting office names in order to make them fit into the system.

Description of the Equipment

A detailed description of each unit employed in this system would be impracticable, in this connection, but a brief description of the more important ones will be of interest.

Sender. The use of the sender makes practicable the introduction of machine switching in large metropolitan areas where, of necessity, the service conditions are extremely complex. It is, in effect, the brains of the system, dealing with the subscriber and controlling the selection until the destination is reached, as an operator deals with the subscriber and controls the selection in a manual system. The number dialed conveys the same information to the sender in a machine switching system as the number spoken by the subscriber does to an operator in a manual system.

The sender is an arrangement of relays, sequence switches, and selectors, so worked out as to perform the following more important functions:

1. It receives a succession of electrical impulses from the subscriber's dial which are on a decimal basis, stores them and translates them to a non-decimal basis, corresponding to the particular group of lines and trunks that is involved in the path of the call.

2. It controls selecting mechanisms which build up the connection to the called party in such a manner that each mechanism is given the exact time required to perform its functions without any waste of time, independently of the rate received from the dial.

3. It makes the central office designations entirely independent of the arrangement of the trunk groups on the selector frames. This is a very important matter, inasmuch as it allows the selectors to be used to full efficiency. It provides the desired flexibility for growth and permits any desirable rearrangement of the trunks on the selector frames that the telephone company may find desirable at any time.

4. The sender is capable of distinguishing the class of office at which the connection terminates. That is, if the call is to terminate at a mechanical office, the sender will arrange to govern the selection accordingly. If the call is to terminate at a manual office, the sender recognizes this and arranges to send out impulses to the call indicator equipment in the manual office.

5. For the completion of certain calls, traffic conditions require the introduction of tandem centers as discussed later. The sender recognizes calls to be routed via tandem centers and arranges to handle these correctly. The tandem center may be manual or it may be mechanical, and the control must be determined accordingly.

6. Certain senders are arranged to serve lines supplied with coin boxes. These senders are arranged to make a test to determine whether a coin has been deposited and do not allow the connection to be cut through so that conversation can take place until the coin is deposited. If the subscriber does not deposit the coin, after a reasonable time has elapsed the sender connects an operator to the subscriber, and this operator notifies the subscriber of his omission. After the

coin has been deposited, the sender allows the called subscriber to be rung and permits the conversation. In case the called subscriber is busy or does not answer, or if the call is to a free line, the sender returns the coin to the calling party. If the called party answers, the sender causes the coin to be collected.

The sender makes a test of the calling line after the subscriber has completed dialing, to insure the deposit of the coin, and recognizes whether a coin has actually been deposited or whether some abnormal condition exists, in which case the call will be routed to an operator who causes an investigation to be made.

7. In large areas, such as the New York Metropolitan area, there are distant points, connection to which requires toll charges. In such cases the subscriber is instructed to dial a special operator who will ascertain his wishes, complete the call, and make the proper charge. Should a subscriber attempt to dial outside of his own local service area, his call will automatically be routed to an operator.

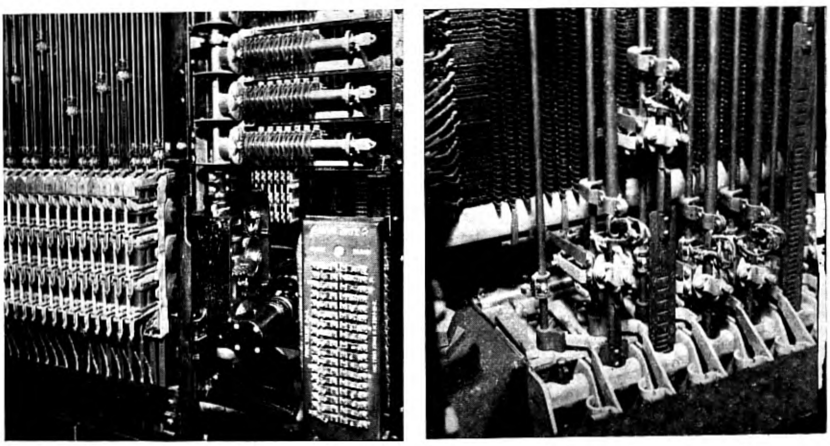

Fig. 9—Views of the Selector

Panel Type Selecting Mechanism. An important mechanism of a machine switching system is the selector and its associated multiple bank. It is a device by means of which trunks or lines are connected together as required. It performs the same function as the switchboard cord and plug which in a manual exchange can be plugged by the operator into any one of a number of jacks which are the terminals of trunks or lines.

Fig. 9. shows the mechanical elements of the selectors. The movable member corresponds to the cord and plug of the manual system

and the fixed terminals or multiple, to which the movable member can make connection, corresponds to the jacks of the manual system.

Fig. 10 shows the fixed terminals or multiple to which the selectors connect. This multiple consists of flat punchings about 3½ feet long and 1 inch wide overall. Each of these strips has lugs on each side with which the selectors can make contact. In this particular panel, three hunderd of these strips are piled one above the other, separated by insulation, and securely bolted together, forming a panel about 15 inches high. This panel provides a multiple consisting of "tip," "ring" and "sleeve" connection for one hundred lines appearing sixty times; that is, thirty on each side. The insulating material consists of special impregnated paper and is of such a nature that,

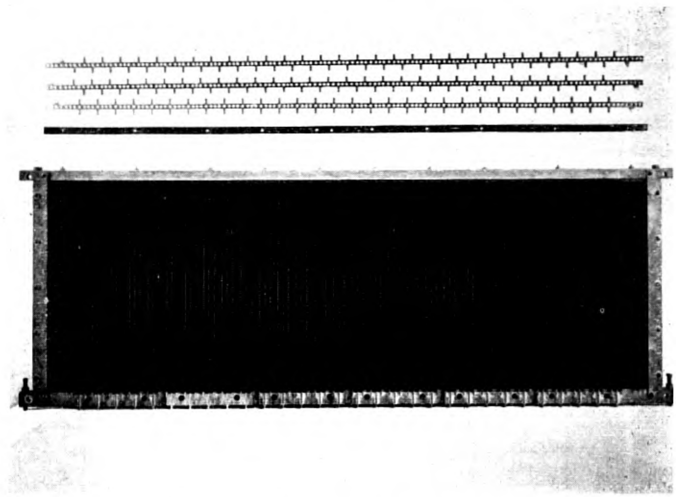

Fig. 10—Selector Multiple Bank

after the panel is assembled and baked, it becomes inert and is not adversely affected by any conditions met with in a central office. It is this panel which has given the name to the system.

The selector (see Figs. 9 and 13) consists of a metal tube supported in bearings allowing vertical motion and carrying five sets of brushes. Each one of the five sets of brushes is arranged to make connections to the tip, ring and sleeve terminals of the panel banks before which it normally stands, and the tip, ring and sleeve contact members of all five of these brushes are multipled together. They are normally free from contact with the terminals, but any set may be tripped mechanically, so that that set will contact successively over terminals as the selector rises.

A friction clutch is provided at the base of each selector, so arranged that the selector can be raised or lowered by power supplied by a constantly rotating small motor, common to 60 selectors. A magnet is also provided for tripping, by means of a rotating rod, any one of

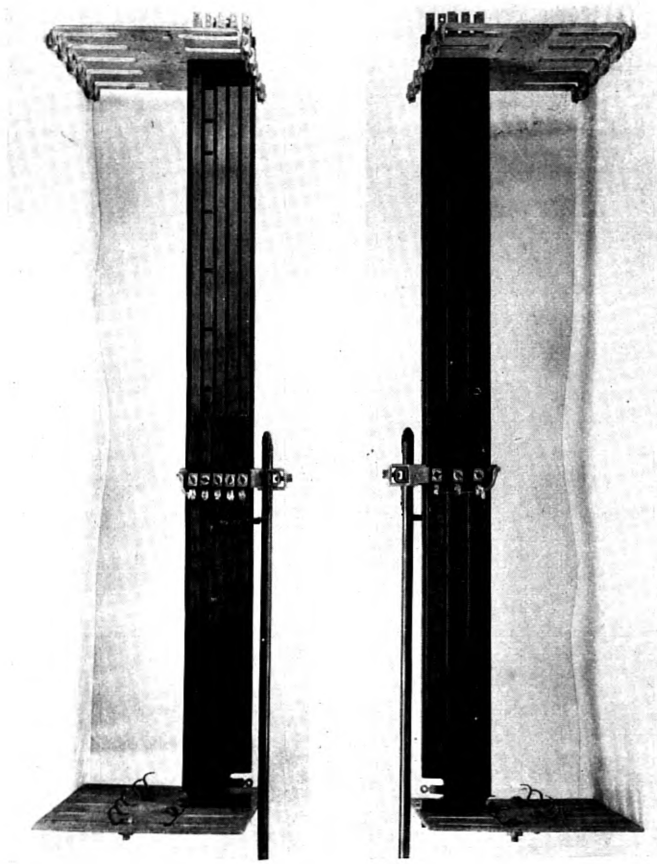

Fig. 11—Commutator for Controlling Vertical Movement of Selecting Mechanism

the five sets of brushes into mechanical engagement with the terminals. In choosing a trunk or line, that one of the five sets of brushes which has access to the panel in which the desired trunk or line happens to be, is tripped so that it makes contact with the bank terminals before it. The selector then moves upward, under the proper control, until the tripped brush engages the desired line or trunk. The selector is then held in this position by a pawl associated with the clutch. When the connection is to be taken down, the pawl is withdrawn, and the selector is carried back by means of the power drive controlled by the clutch. When the selector reaches its normal position the tripped brush is reset.

Selectors used for different purposes are arranged to move their brushes upward at different speeds. The speed most commonly employed moves the brushes over the terminals at the rate of 60

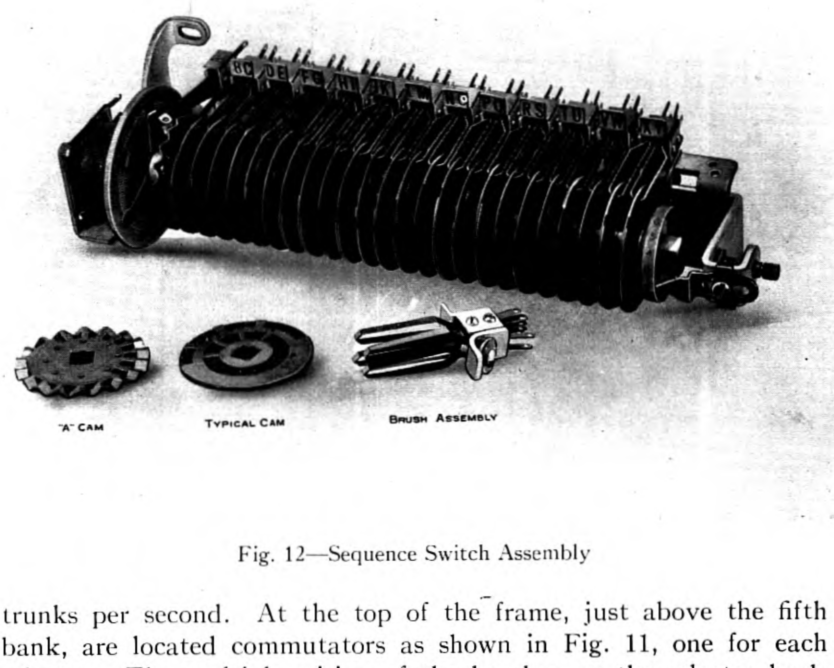

Fig. 12—Sequence Switch Assembly

trunks per second. At the top of the frame, just above the fifth bank, are located commutators as shown in Fig. 11, one for each selector. The multiple wiring of the brushes on the selector leads to other brushes which move over strips on these commutators, and thereby completes the connection from the movable selector to the rest of the circuit, thus avoiding flexible wire connections with their attendant troubles. This commutator, also, performs the more important service of controlling the travel of the selector. Brushes moving over conducting segments separated by insulation produce impulses which, when sent back to the sender, indicate to it the exact position of the selecting mechanism.

Sequence Switch. Another device of great importance is the "sequence switch," shown in detail in Fig. 12. It is operated through

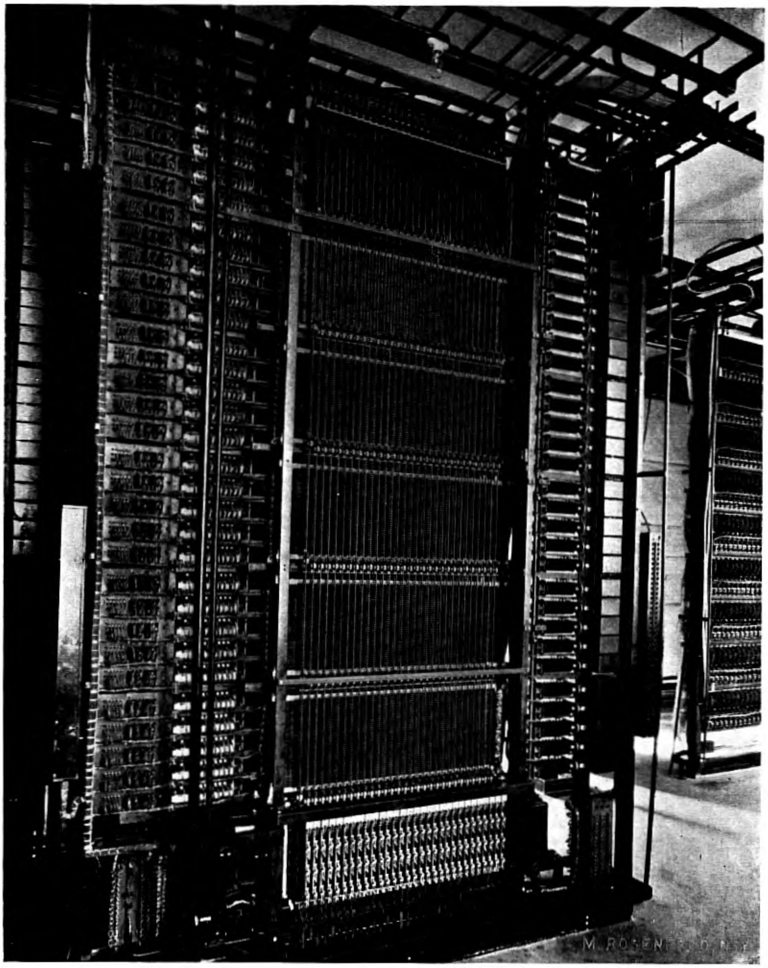

Fig. 13—Selector Frame Completely Equipped

an electromagnetic clutch from the same motor that drives the selectors.

The sequence switch may be described as a circuit controller or device whose function is to establish in a definite sequence such circuit conditions as are required in the operation of the system. It is made up of circular disks called cams mounted rigidly on a shaft. The plates of the cams are cut so that brushes come in contact with the plates only when the circuit is to be closed. The sequence switch can be stopped at any one of eighteen different positions as required, by the simple opening of the electromagnetic clutch.

There are many of these sequence switches used in this system, and the arrangement of cutting the cams varies, depending upon the particular circuit combinations which it is desired to establish.

Selector Frames. Fig. 13 shows thirty selectors with all of the associated mechanism mounted upon one side of a frame ready for operation in an exchange. Both sides of the frame are alike. Five panels of 100 lines each are mounted in this frame, one above the other giving a total capacity of 500 trunks or lines. Thirty selectors, each capable of making connection with any one of the 500 trunks or lines, are placed adjacent to each other on each side of these panels; the entire frame thereby having a capacity of sixty selectors, each of which has access to 500 trunks or lines.

Immediately to the right of the selectors are the sequence switches and, under protective covers, such relays as are used in connection with the selectors upon the frame shown.

Selecting apparatus of this general type, but differing in details of design, is used during the different stages of the call as line finders, district selectors, incoming selectors and final selectors, reference to which has been made before. Fig. 14 shows a section of a machine switching office with some of the typical frames.

The use of apparatus of the substantial construction just described is made possible only through the use of the sender which receives impulses from the subscriber at the rate they are dialed and receives impulses from the selecting mechanism at the rate it is traveling. This obviates the necessity for restrictions in the design of either the dialing circuit or the selecting circuit, such as would be necessary if they were tied together.

Power Supply Arrangements. Since most of the operations normally required in handling a call in a machine switching office are carried out mechanically, it is evident that a considerably larger amount of power is required than with the manual system. Selectors and sequence switches are propelled mechanically by rotating shafts driven continuously by small motors mounted on each frame.

The use of small motors on each frame gives a flexible and reliable source of power particularly since the motors now being used are of the special "duplex" type developed for the purpose. They consist of two motor elements in one frame, one element being normally driven from the commercial power service and the other being driven by the telephone reserve storage battery to which it is automatically

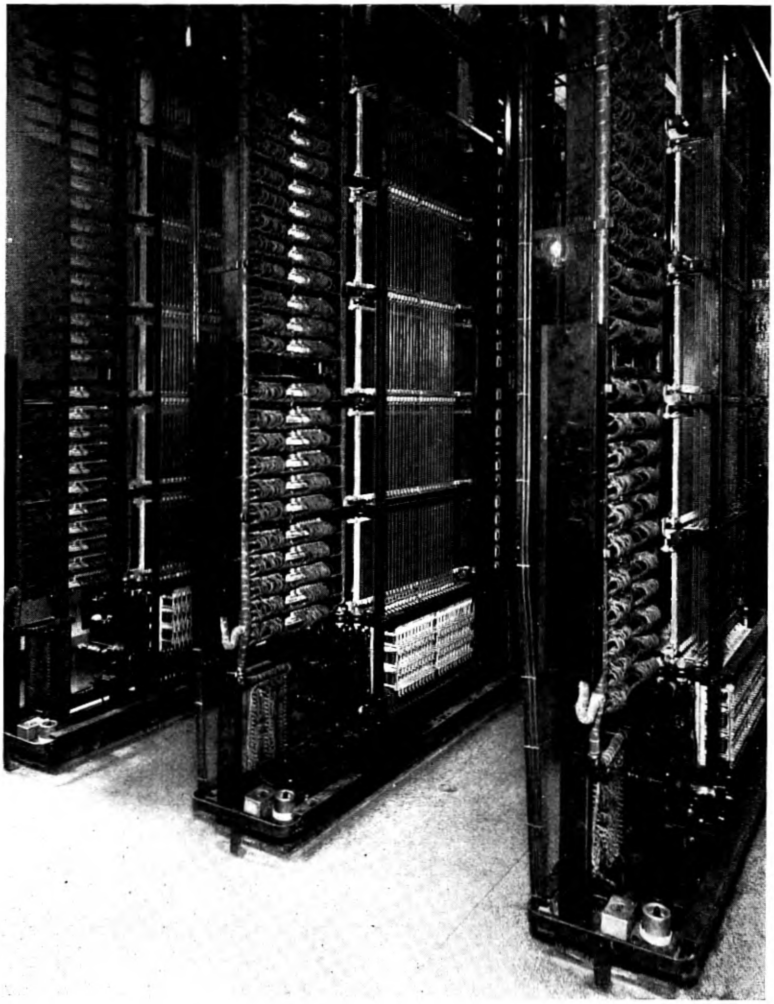

Fig. 14—Group of Typical Selector Frames

connected by a relay inside the motor when the regular power fails. A power failure, therefore, causes no interruption to the drive. The selectors are arranged so that not more than half in any one group are driven by the same motor which insures continuous service in case of motor failure.

The main power requirement is for direct current at about 24 and 48 volts which is furnished from motor generator sets (Fig. 15) of special construction to reduce noise, converting the commercial alternating or direct power current into current which is regulated as to voltage and is free from variations which would cause noise in the telephone circuits.

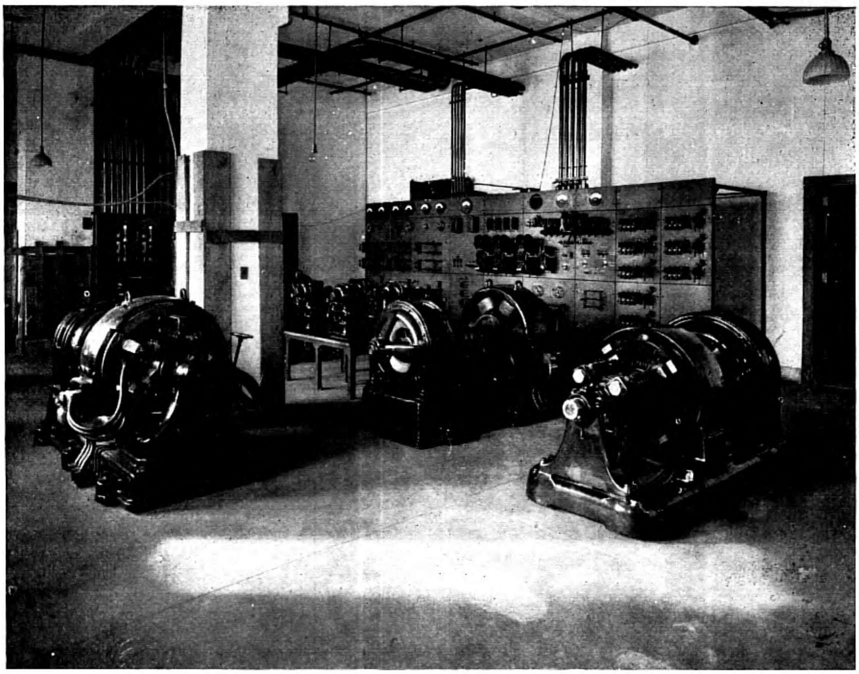

Fig. 15—Power Machine and Control Equipment for Two 10,000-Line Units

Storage batteries (Fig. 16) floating across the current supply busbars insure regulation. In addition to stabilizing the voltage and reducing noise interference from the machines and between telephone circuits, the batteries perform the important function of keeping the exchange in operation during interruptions to the commercial power service. Small motor generators furnish current for ringing subscribers' bells and drive commutators supplying various tones and signals. Batteries or machines supply current for operating coin boxes and pulse machines provide impulses for the operation of certain of the machine switching apparatus.

Whenever practicable, two or more commercial power services from independent generating stations are secured, either of which will keep the office supplied. Where independent generating systems are not available a reserve gas engine supply (Fig. 17) is installed to take the place of the incoming power service, such engine also being equipped for emergency operation on gasoline.

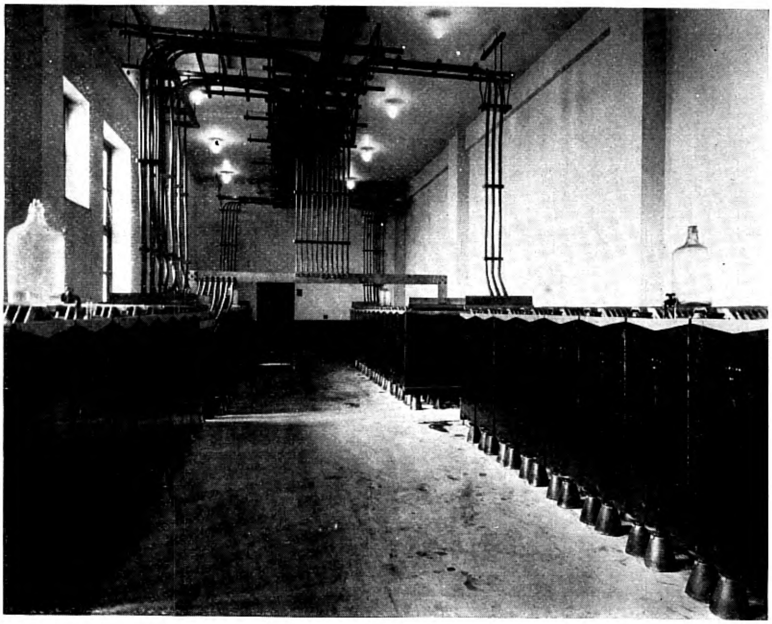

Fig. 16—Battery Room for Two 10,000-Line Units

All of the essential power machines and batteries are provided in duplicate and are arranged to come into action automatically wherever this is necessary to insure continuity of service in the event of loss of power or trouble with any of the power equipment. Alarms are provided to detect variations in battery voltage, blowing of fuses, stopping of machines or any failure of service on all power busses which feed energy to the telephone or signaling circuits. The power plant is thus designed to give an uninterrupted energy supply at all times even when the usual sources of power may have been temporarily discontinued.

Detailed Plan of Operation

The following will give in some detail the plan of operation for handling typical calls between various types of offices in a large metropolitan area such as New York City.

Calls Originating in Machine Switching Offices. Fig. 18 shows schematically the path of a call originating in a machine switching office. The pair of wires of a subscriber's line is attached to one of the sets of fixed terminals in a panel bank appearing before a group of selectors of the type which has been described. By putting fewer

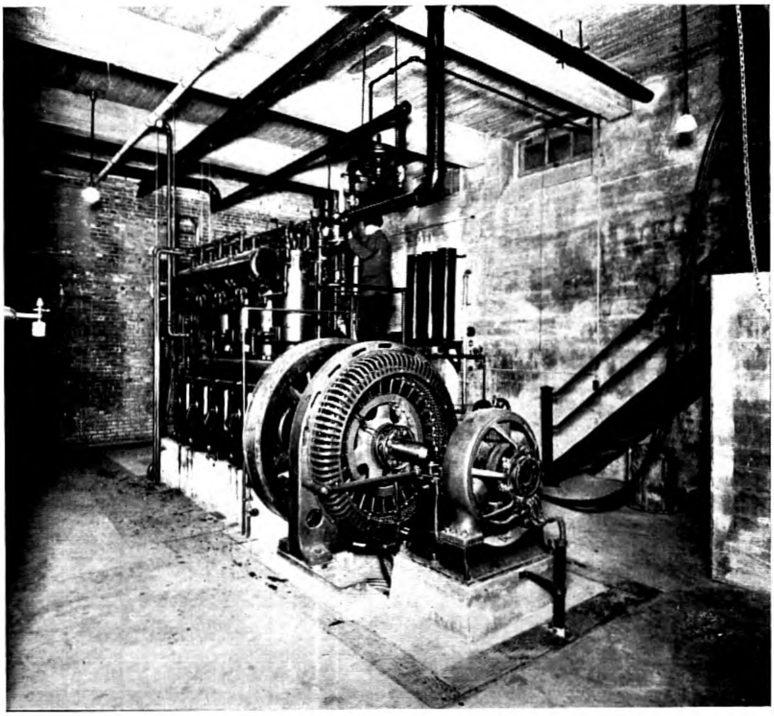

Fig. 17—165 H. P. Gas Engine Generating Set for Emergency Use

lines in these panels and increasing the number of selector brushes, we attain the speed necessary at this stage of the connection. These selectors are called "line finders," since their function is to find calling lines. The terminals correspond to the answering jacks and the selectors to the "A" operators' answering cords of the manual system.

When the subscriber removes his receiver, he closes the circuit of his line, causing a relay at the central office in series with his line, to operate. This relay causes an idle line finder, having access to his line, to trip the proper brush and then move upward to his line. At the same time a sender selector attached to that line finder is choosing,

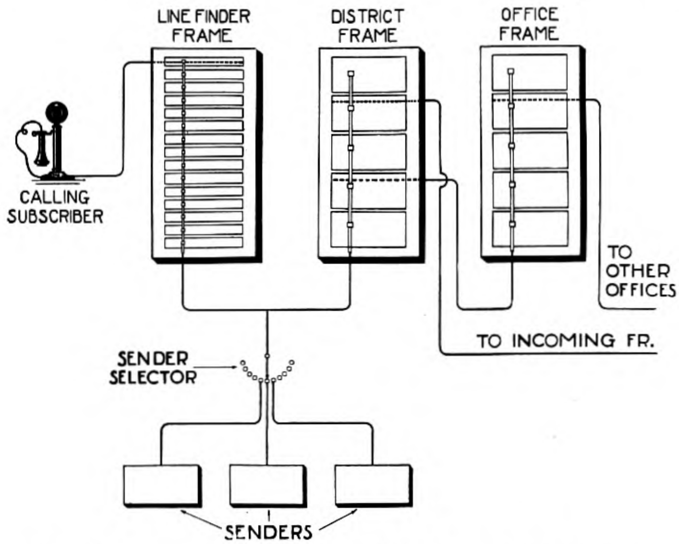

Fig. 18—Diagram of Line Finder, District and Office Frames

out of a common group, an idle sender. The sender selector is a small selector of a type in which the brushes are driven by a magnet over contacts arranged as shown in Fig. 19.

The sender having been attached in this manner to the calling line, a low humming sound, known as the dial tone, is heard by the subscriber, advising him that the mechanism is ready for him to dial. The entire sequence of events just described takes place in a fraction of a second, so that ordinarily the subscriber finds the dial tone when the receiver reaches his ear. The subscriber now dials the required letters of the office name, and the numerals of the called number.

The pulses from the dial come over the subscriber's line through the line finder and sender selector to the sender which records and translates them to control the setting up of the connection. As soon as the connection has been established, the sender is released and is ready to be used for a new call, being kept in use only a few seconds for each call.

The first step in completing the connection is to choose an idle trunk in the proper direction. To the nearby offices there are groups of direct trunks, whereas the more distant offices are reached through tandem centers described later.

The line finder leads to the movable element of a panel selector known as a "district selector." This district selector has capacity for 450 working outgoing trunks, the other 50 trunks being used for control purposes. In a small city 450 trunks would be sufficient to

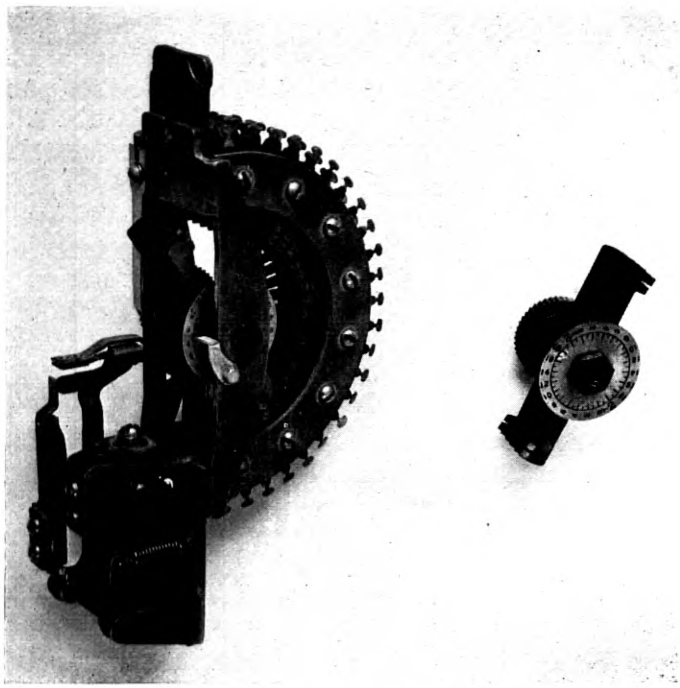

Fig. 19—Sender Selector

reach all points, but in the case of the New York offices 450 outgoing trunks are not sufficient. Accordingly, only a few of the trunk groups outgoing from these offices leave directly from the district selectors. To obtain access to the remaining trunks there are, on every district selector frame, groups of trunks leading to so-called "office selectors." These office selectors are of the panel type and each has a capacity for 450 outgoing trunks.

The path of a call through a district and office selector will now be traced. The district selector starts upward under the control of the sender. As the district selector moves upward, it produces pulses by means of the brushes which slide over the commutator at the top of the selector. These pulses are transmitted back to the sender, and are there counted. When the sender has counted the number of pulses which indicates to it that the district selector has proceeded to the proper position, the sender opens the fundamental circuit to the selector and causes it to stop. This method of controlling the movment of the selector is termed the reverse control method.

The first selection made chooses the set of brushes to be tripped into engagement with the terminals. Assume, as shown in Fig. 18, the desired trunk appears on the second panel from the bottom. Therefore, the district selector is allowed to make two pulses and is then stopped by the sender. The brush-tripping device is thus set in position to trip the second brush, and the selector is started again by a signal from the sender, which operation completes the process of tripping the brush.

The selector now continues upward, making a pulse for every group of trunks which it passes over, until, having reached the desired group, as indicated by the number of pulses counted by the sender, it is again stopped by the sender at the beginning of this group. The selector is now started again, and this time under its own control, hunts for an idle trunk in the group. Busy trunks are grounded on the third or signaling terminals, whereas idle trunks are open. A testing relay, associated with the selector, keeps the selector moving upward until a trunk with an open third wire is found, whereupon the selector stops, makes connection with this trunk, and renders it busy to other selectors by grounding the signaling strip.

This trunk, as indicated in Fig. 18, leads to an office selector. The same process is repeated by the office selector, under control of the sender, to trip first the proper brush, then choose the proper group, and finally to choose an idle trunk in the group. The connection is now extended to an outgoing trunk. The sender still remains attached to the connection, since it must still control the further setting up of the connection.

The sizes of the working trunk groups on district and office selectors can vary from 5 to 90, depending upon the traffic to be handled.

Calls Between Machine Switching Offices. If the call is for a subscriber in a machine switching office it is completed as shown in Fig. 20. This figure shows a diagram of the apparatus used to connect an incoming full mechanical trunk to a subscriber's line, whether this line is in the originating machine switching office or in another which must be reached over interoffice trunks.

The incoming trunk to the machine switching office terminates on an "incoming selector," which is of the type already described. The machine switching office has a capacity for 10,000 numbers, but the incoming selector has capacity of only 500 trunks, so that the same arrangement is employed as on the district selectors; that is, the incoming selector chooses one of a number of other selectors, called "final selectors," which have access to the subscribers' lines. Since each group of final selectors has access to 500 subscribers, 20

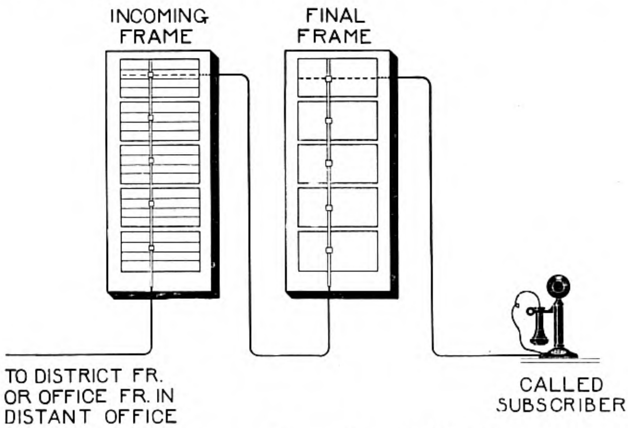

Fig. 20—Diagram of Incoming and Final Frames

groups of finals will be necessary to care for the full 10,000 numbers. On the incoming selector frames, therefore, appear 20 groups of trunks, each group leading to a different frame of final selectors.

The method of selection is the same as described for the district and office selectors; that is, first the incoming selector, under control of the sender in the originating office, trips the proper brush, chooses the proper group, and finally chooses an idle trunk leading to a final selector. The final selector then goes through the process of brush, group, and subscriber's terminal selection. The terminal selection is under the control of the sender which counts line by line in the group of ten, until the desired one is reached. If the called line is idle, it is rung, and the calling subscriber is advised of that fact by hearing the audible ringing signal. If the called line is busy it is not connected, but an intermittent buzz, recognized as the busy signal, is sent back to the calling subscriber. If the called number is that of a P. B. X. having several trunks, the final selector automatically hunts for an idle one. If the final selector, after testing all the P. B. X. trunks finds them all busy, it sends back the busy signal.

As soon as the called line is reached, the sender is dropped from the circuit to be available for another connection. It is not held during the period of ringing, during the time that the busy signal is being given, if the line is busy, or during any part of the period of conversation.

It will be noted that the method of selection is not on a decimal basis. The first selection is to choose one of five brushes on the incoming selector as already explained; that is, we choose that partucular fifth of the terminals in which the called line happens to be, and since 1–5 of 10,000 is 2000, we choose the 2000 group desired. The next selection is by groups of 500, which is again non-decimal. This "translation," as it is called, of the number from the decimal notation, as dialed by the subscriber, into the notation as needed by the selectors, is taken care of very simply in the senders.

Calls from Machine Switching to Manual Offices. Calls from machine switching to manual offices are handled at the manual office on call indicator "B" positions. Fig. 21 shows a diagram of the equipment used to connect such a call to a subscriber in the manual office.

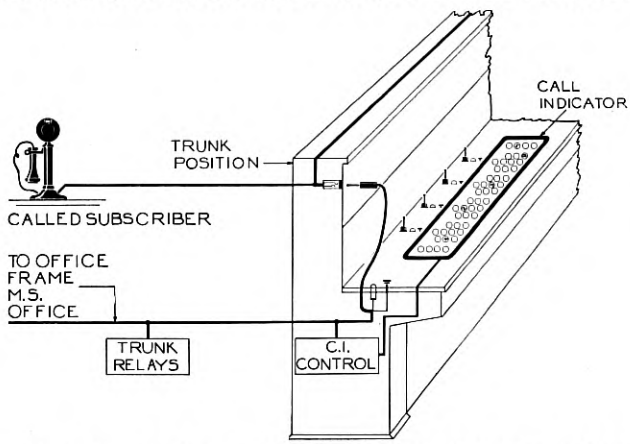

Fig. 21—Diagram of Connection from Machine Switching to Manual

The call progresses through the district and office selector in the same manner as described for the machine switching call, but the trunk which it takes up leads to a call indicator "B" position in the manual office selected. The operator is notified that a call has reached her position by the lighting of a lamp associated with the cord and plug in which the incoming trunk terminates. Upon perceiving this signal, she presses a display key associated with that trunk, and thereupon the called subscriber's number is displayed on a bank of numbered lamps located on this operator's keyboard. The operator picks up the plug, tests the called line and, if it is found idle, plugs in; or, if it is found busy, she plugs into a special jack which is arranged to send the intermittent busy tone back to the calling subscriber.

The called subscriber's number is displayed in the following manner. Associated with the operator's position, and with her call indicator, is a group of relays. When the display key is depressed, this group of relays is attached to the trunk. The sender which has meanwhile been waiting on the connection, is thereby given a signal, and sends the number called by means of code pulses which are received by the group of relays. These relays, in turn, light the set of lamps on the call indicator corresponding to the digits of the called number, as shown in Figs. 22 and 23. The code pulses employed for sending

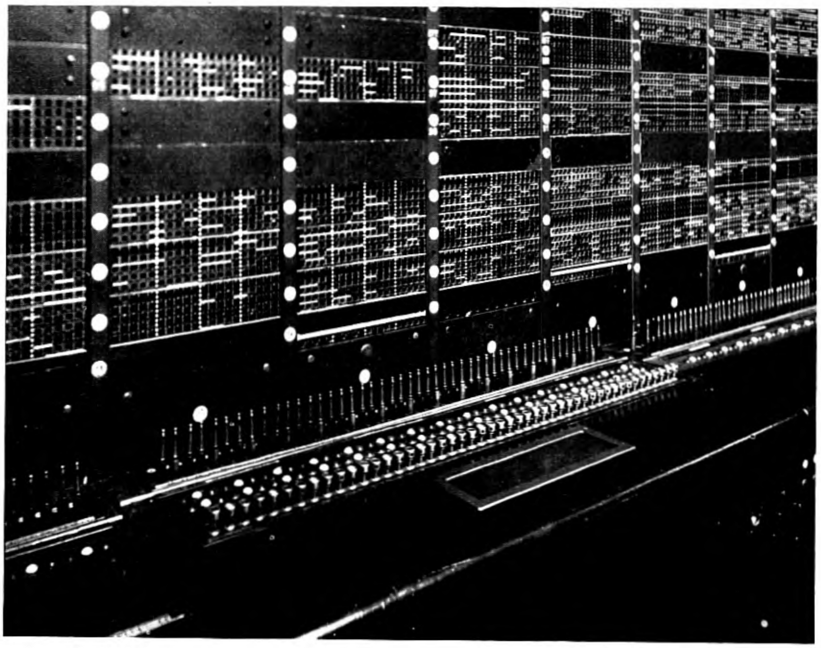

Fig. 22—Incoming Trunk Position in a Manual Office Arranged for Call Indicator Operation

this called number are positive and negative, strong and weak, and are translated by the sender from the decimal dial pulses to this type of pulse to reduce the time required and to simplify the receiving apparatus.

Incoming Calls from Manual to Machine Switching Offices. Calls from manual offices are handled at the machine switching office on the cordless "B" positions. Fig. 24 shows a diagram of the equip-

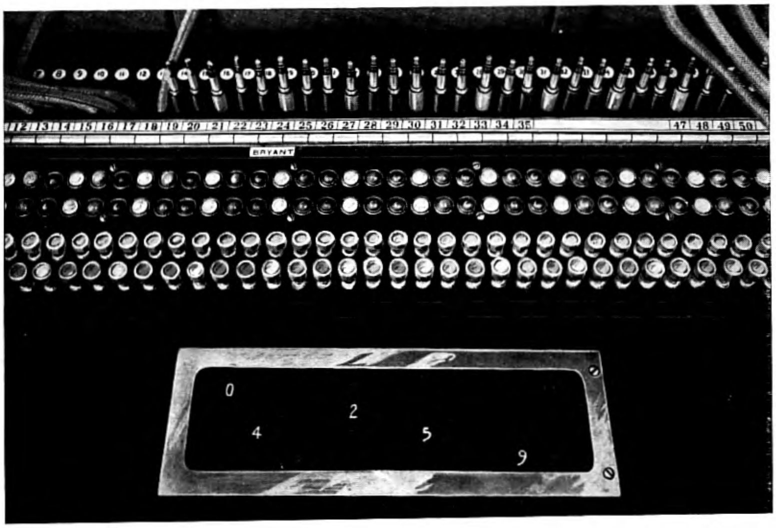

Fig. 23—Call Indicator at an Incoming Trunk Position in a Manual Office

ment used to connect a call originating in a manual office destined for a subscriber in a machine switching office. Such a call is answered by the "A" operator in the manual office in the usual manner. She takes up the call circuit by depressing her call circuit key to the

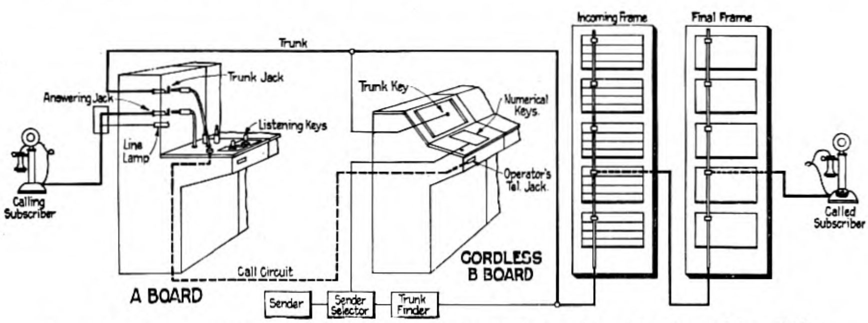

Fig. 24—Diagram of a Connection from a Manual to a Machine Switching Office

machine switching office desired, passes the called subscriber's number, and receives a trunk assignment in exactly the same manner as if the call were going to another manual office. The cordless "B" operator, upon assigning a trunk, presses the assignment key of that trunk, which temporarily attaches her keyboard to a sender and simultaneously to the incoming trunk which she has assigned. As shown in Fig. 24, the incoming trunk terminates on an incoming selector which has access to final selectors on which the called number appears, in the same manner as described before.

The operator now sets up on her numbered keys the number desired, and this information is transmitted immediately to the sender. These keys, which lock mechanically, are released after a fraction of a second by a magnet controlled by the sender and are ready for the

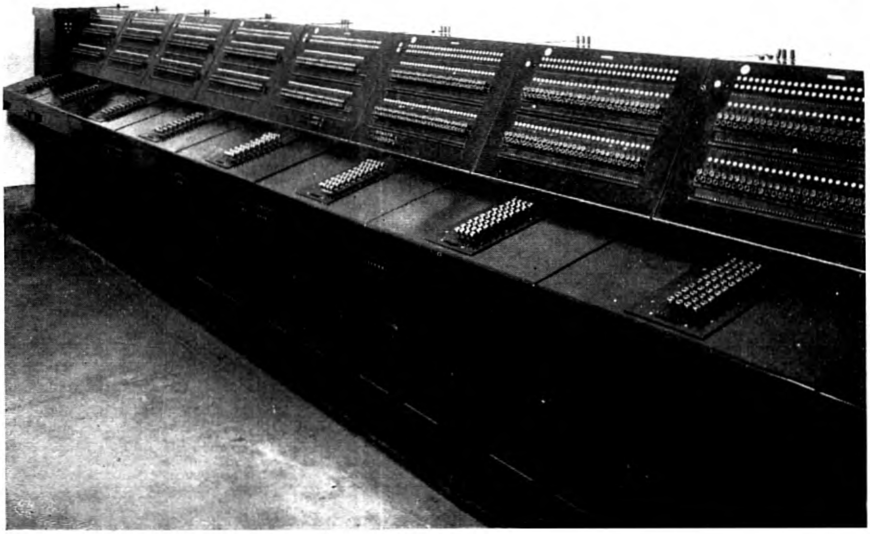

Fig. 25—Cordless "B" Positions in Machine Switching Office

next call. The "B" operator's sender now controls the incoming and final selectors in the same manner as the subscribers' senders, causing the incoming selector to choose an idle trunk to a final selector having access to the desired group of 500 numbers. The final selector reaches its destination in the manner previously described and, as soon as the line is found, the sender is released.

Fig. 25 shows a line of cordless positions. The section at the left is the cable turning section, having nothing to do with the operation of the board.

Manual Positions Required in Machine Switching Offices. While regular calls between two subscribers will be completed in this system without the aid of operators, certain classes of calls, such as toll calls to suburban points and calls for discontinued or changed numbers, etc., will require the assistance of an operator. Special manual positions are therefore provided in the machine switching office for this service. These positions also care for cases where the subscriber may need the assistance of an operator for other reasons than the above, and are in addition to the cordless "B" positions previously described.

The operators are called "Special Service Operators." The subscriber signals them by dialing "Zero," which on the dial is also marked with the word "Operator." The connection then progresses in the same general manner, through the district and office selectors, as for any originating call. An idle trunk appearing on the office selector leading to an answering jack before the special service operator is chosen and the sender released. Should a subscriber in any local service area dial a subscriber in another area, the sender will automatically route the call to a special service operator.

The special service operator in large areas has before her a number of cord circuits having one end terminating in a cord and plug. She also has upon a keyboard a set of keys similar to those described for the cordless "B" position, except that there are additional strips of keys upon which she can write up an office code. The operator answers the subscriber by inserting one of the plugs in the answering jack and, having ascertained the desires of the subscriber, directs the connection to the proper destination by setting up on her keys the proper numerical code. Senders are furnished for these positions so that, as soon as the information from the keyboard has been registered on the sender, the keys are released and are ready for another call.

The other end of the special service operators' cord circuit terminates in a district selector which, either directly or through other selectors, has access not only to trunks which the subscriber himself might call, but also to trunks leading to more distant offices which he cannot dial directly because they are toll points.

Tandem Operation. There are about 158 central offices in the area shown on the map, Fig. 3. While it is an essential requirement that any subscriber connected to any of these offices be able to reach any subscriber connected to any other office, it is obvious that to furnish trunks from each office direct to every other office would require a great number of long trunks in small groups carrying a very light load most of the time.

In order to eliminate the inefficiency that such an arrangement would entail, it has been the practise in manual operation to handle the traffic from one part of the area to another part of the area over main trunk routes. The collecting and distributing points on these trunk routes are known as "tandem centers," and the plan of operation is known as "tandem operation."

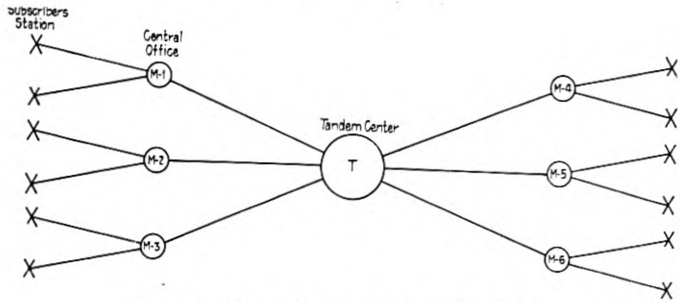

Fig. 26—Typical Tandem Trunking Plan

Fig. 26 shows an arrangement of offices in a typical tandem trunking plan. Offices marked *M* are local offices, either manual or machine switching. The office marked *T* is a tandem office. If a call is originated by a subscriber in office M-1 for a subscriber in offices M-4, M-5, or M-6, to which no direct trunks are provided, the call is routed at office M-1 to trunks terminating at tandem office T. At this point they are connected to trunks leading to the proper office, where the connection is completed to the desired subscriber in the usual manner. Likewise, calls from offices M-2 and M-3 are completed over the same groups of trunks from the tandem office T to offices M-4, M-5, or M-6.

The plan described above is typical of that followed in the New York Metropolitan area for many years, the completion of the call being controlled at the tandem office by operators.

The machine switching system is not only adapted to fit into the existing tandem plan, either when used in the local central office or at the tandem office, but also makes available possibilities for considerably extending the field of usefulness of the tandem system, due to certain advantages in handling calls at tandem points by the use of machinery.

The use of a sender at the machine switching office which is capable of routing a call in any way desired permits locating the selectors which have access to the interoffice trunks at any convenient point either at the originating office or at some distant point. In other words, the tandem office T shown on Fig. 26 may consist of a group of office selectors such as have been described previously. In this case the trunks from offices M-1, M-2 and M-3 would lead from district selectors in these offices to the office selectors at office T which would select, under control of the sender in the originating office, an idle trunk to office M-4, M-5, or M-6, as desired. At the terminating office the call would be completed through incoming and finals if it is a machine switching office, or call indicator "B" positions if it is a manual office, exactly as described previously.

If the number of points to be reached through the tandem office is greater than the capacity of a group of office selectors, a group of district selectors may be provided at the tandem office which have access to groups of office selectors located at the same office or at some distant point, as described above.

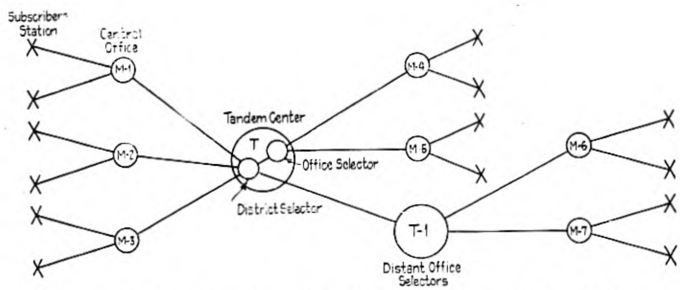

Fig. 27—Tandem Trunking Plan Showing Distant Office Selector

Fig. 27 shows schematically a tandem plan using the above method. Tandem office T is provided with district selectors on which terminate trunks from local office M-1, M-2 and M-3. These selectors have access to office selectors in the same office through which offices M-4 and M-5 are reached, and to office selectors located in the distant tandem office T-1 through which office M-6 and M-7 are reached.

To handle calls at a machine switching tandem office originating from manual offices, operators are required at the tandem office. These operators handle calls in much the same manner as cordless "B" operators in a machine switching office, as already described. The operator receives the desired office name and number from the originating operator over a call circuit and sets it up on her keyboard, which is similar to the cordless "B" board, except that it has office keys in addition to numerical keys. The number is received by a sender which then controls the operation of the selecting mechanism in the tandem office and other offices through which the call may pass, to the desired local office and subscriber's line.

Many different combinations of the above are possible and are employed when desired.

MAINTENANCE

As will have become apparent from the description already given there is, in the machine switching telephone central office, a large amount of apparatus which, in order to insure service of good quality, must be maintained in proper working condition. Consequently, the subject of maintenance has been very carefully kept in mind throughout the design of the system. For instance, all new pieces of apparatus used in this system have been subjected to the most rigid tests to insure that they will have a satisfactory life and that their margins of adjustment will be adequate.

When maintaining machine switching equipment, the main reliance is placed on preventive measures, so that incipient faults will be detected and corrected before they have got to the point of interfering with service. Ingenious automatic testing arrangements have been designed to aid in this preventive maintenance work. They subject the various circuits in the exchange to routine tests, and are arranged so that they will automatically test all of the circuits, one by one, under conditions more severe than they will ever be called upon to meet in service. In case some feature of any circuit has deteriorated from its normal standard of adjustment—which includes a wide margin—so that it will not meet this severe testing condition, the testing apparatus automatically stops and by supervisory lamps indicates the location of the trouble. An audible alarm is also sounded which notifies the maintenance man responsible that something requiring his attention has been found. The circuit in trouble may still be capable of giving service, but is below the standard set and may soon give service trouble if not corrected.

As applied to the sender, for example, the automatic routine test equipment picks up each sender in turn and puts it through its regular process of operation, under conditions more severe than are encountered in practise. If the sender under test meets the operating conditions without failure, the sender is dropped and the test equipment moves to the next sender. If any trouble develops an alarm is given, which summons the maintenance man who is able to determine by the condition of the apparatus the location of potential trouble.

The operation of the testing equipment may be varied by suitable keys, so that all the features of each sender may be tested once, or so that any one feature of the sender may be tested as many times as desired.

All the equipment in the office occurs in groups, and arrangements are made for readily taking out of service for readjustment any piece of apparatus which may have been found to have potential trouble—the other members of the group continuing to handle the calls.

Application

In the preceding pages there has been briefly described a switching system which meets the exacting and complex requirements of telephone service in the largest cities and in which, so far as is practicable, the various switching operations are performed automatically. Only such operators are required in connection with this system as are necessary for handling special classes of service and certain operations in connection with the interchange of calls between manual and machine switching central offices during the transition period.

Variations in the arrangements which have been described have been developed and are available for use whenever the conditions warrant. An illustration of this is the so-called key indicator, which permits the handling of calls from manual to machine switching offices without the aid of the cordless "B" operators. This is effected by providing the operators in the manual offices with special keys and equipment for controlling directly the selection of the subscriber's line in the machine switching office.

This machine switching system marks a very important advance in a development which began shortly after the telephone was invented, and which has been most vigorously prosecuted by the engineers of the Bell System from then to the present time. Throughout this entire development period the tendency has been to introduce automatic methods and apparatus whenever they gave a better result to the public, or whenever they were attended by an economy of any kind.

How this system works has been briefly explained. What arrangements are provided for handling regular machine switching calls, calls to and from existing manual offices, private branch exchanges, etc., has been described. How the introduction of this system into a telephone network is affected will now be discussed briefly.

Obviously, the problem of introducing machine switching equipment into such an extensive and complex structure as is the telephone plant of a big city, is a large one. It is impracticable to introduce it all at once. Its introduction must be effected gradually and this is accomplished by using it for growth and such replacements as are necessary, later extending its use as conditions warrant.

The fundamental engineering studies which have to be made and which must precede the manufacture and installation of the equipment for a machine switching office are, in all important respects, the same as those which must precede the manufacture and installation of the equipment in a new manual office. They involve a careful study of the telephone needs of the area, with a view to determining ultimately the quantities of the different kinds of arrangements necessary to give the service. This requires a study of the commercial requirements at the time when the equipment should be cut over and for several years thereafter. Data must be collected as to the probable rates of calling, the average duration of the calls and the amount of trunking to and from other offices.

With these data available, the size and arrangement of the trunk groups on the selector frames, the number, grouping and type of selectors and senders required, and the size of the power plant can be determined. From this the cabling arrangement can be worked out, and suitable floor plans prepared.

Manufacturing specifications can then be prepared in accordance with which the equipment of the office is manufactured and installed. Before the equipment is cut into service, the various arrangements are thoroughly tested individually, and when in proper condition the whole is checked up by making complete operation tests.

If time and space permitted, it would be of interest to discuss the methods of actually cutting the equipment into service, and the comprehensive program which is worked out for the training of the employees who are to handle the equipment and advising the public which is to use it. All these matters are of the utmost importance, and must be carried out systematically in order that there may be no reactions on the general service at the time of the cut-over.

Relations of Carrier and Side-Bands in Radio Transmission[1]

By R. V. L. HARTLEY

SYNOPSIS: This paper discusses generally the characteristics of carrier transmission as applied in radio and in carrier current communication over wires and analyses the factors which affect the faithfulness with which such systems reproduce the signals imparted to them. Modulation is shown to generate two side bands which, with respect to frequency, lie just above and just below the carrier frequency, the frequency width of each side band being the same as the frequency width of the original signals. Upon detection, currents of frequencies corresponding to the difference frequencies between all the possible pairs of component frequencies of the side bands and carrier are produced and, in general, are all found in the received message. It is therefore impossible to transmit messages, either telephone or telegraph, by carrier which will be absolutely free of distortion, but since the amplitude of any particular difference frequency is proportional to the product of the amplitudes of its two generating frequencies the distortion can be reduced below a troublesome value by maintaining the amplitude of the original carrier sufficiently large with respect to the amplitudes of the signal components. The distortion which arises from phase shifts between the component frequencies of the transmitted message and carrier is also considered.

The paper discusses single side-band transmission and carrier suppression with homodyne detection and their various merits are pointed out. Single side band transmission reduces the width of frequency band required for each message. Carrier suppression results in a saving of power, or a more economical expenditure of power, it having been determined that for proper freedom from distortion the power of the carrier component alone, when transmitted, should be rather larger than the peak power in a carrier suppression system. The use of local carrier in homodyne radio telephony assists in frequency selection in the same way as does the heterodyne wave in radio telegraph reception. The same applies also to static interference and, as the object of high power stations is to make the signals large compared with static, there is a gain in concentrating the power in side bands rather than in carrier.

Consideration of distortion arising from phase shifts shows that in homodyne telegraphy distortion can most readily be avoided by transmitting both side-bands, while in telephony these factors favor the transmission of only one side-band. The power of the reproduced signals is twice as great with two side-bands as with one, but there is no choice between one and two side-bands on the basis of the ratio of signals to interference.

The result of using a local detecting frequency which is not exactly equal to the original carrier frequency is discussed, and a balanced detector is described by means of which the distorting effect of the received carrier may be very much reduced. Considering a local carrier which is out of synchronism with the original carrier, it is again found that single side-band transmission is most favorable in telephony, and the transmission of both side-bands is best in telegraphy.—*Editor.*

AS indicated by the title, this paper will discuss some of the phenomena associated with radio transmission in terms of the carrier currents and side-bands into which a modulated wave may

[1] Presented before The Institute of Radio Engineers, New York, December 13, 1922. Printed in the Proceedings for February, 1923, and reprinted here by permission of the Institute.

be resolved. The use of these terms implies a point of view which perhaps is employed less commonly in radio engineering than in some of the other branches of the communication art. For this reason, I shall, at the risk of repeating much that is already in the literature,[2] review such of the fundamentals of this viewpoint as are necessary to an understanding of what is to follow.

Analysis of a Signal Wave

Briefly stated, the point of view is that any signaling wave may be resolved into sustained sinusoidal components, which may be thought of as traversing the system as individual currents and recombining at the receiving end to form the reproduced signal. The possibility of such a resolution has been demonstrated mathematically and the formulas for evaluating the amplitudes and phases of the components are well known. A periodic wave may be expressed as a Fourier series, that is, as the sum of an infinite series of components the frequencies of which may be thought of as harmonics of a fundamental frequency which is equal to the frequency of repetition of the wave. Such a resolution, however, is not directly applicable to the waves employed in communication, for by their very nature they are not periodic. A communication system must be capable of transmitting any individual symbol regardless of what precedes or follows it. We may, however, resolve such an aperiodic wave by the mathematical device of assuming it to be one cycle of a periodic wave in which the interval between successive occurrences of the disturbance in question approaches infinity. The frequency of repetition is then infinitesimal. The fundamental frequency of the Fourier series and the frequency interval between adjacent components are also infinitesimal; that is, the series of discrete lines of the Fourier series spectrum merge into a continuous spectrum. Mathematically this continuous spectrum is represented by the expression

$$F(t)=\int_{o}^{\infty} S \cos (qt+\theta)\, dq, \tag{1}$$

which is known as the Fourier integral. Physically we are to picture this infiinte series of sustained sinusoids as having such amplitudes and phases that the algebraic sum of their instantaneous values is

[2] "Carrier Current Telephony and Telegraphy," by E. H. Colpitts and O. B. Blackwell; "Transactions of the American Institute of Electrical Engineers," volume XL, page 205, 1921. "Application to Radio of Wire Transmission Engineering," by L. Espenschied; presented before The Institute of Radio Engineers, January 23, 1922.

zero for all instants before and after the disturbance in question, and equal to the instantaneous value of the wave thruout its duration. In Fig. 1, curve A represents a telegraph dot, curve B gives the rela-

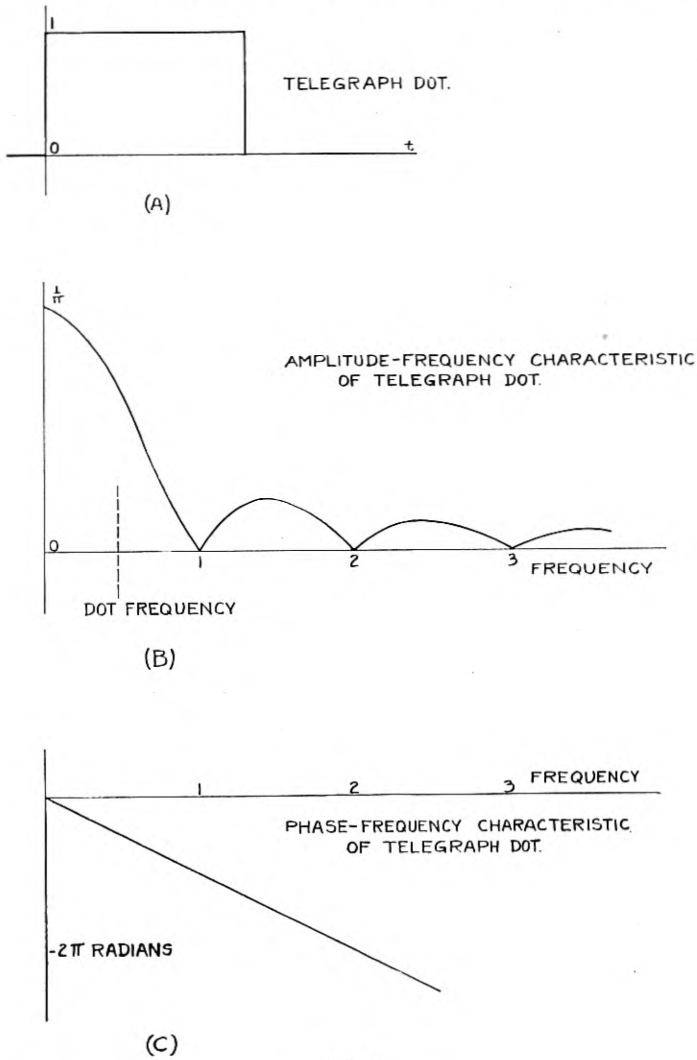

Fig. 1

tive amplitudes, S, of its components plotted against their frequencies, and curve C, their phase, Θ, also as a function of frequency. The so-called "dot frequency" corresponding to a sustained succession of such dots is indicated on curve B.

It is obvious that if either the amplitudes or the phases of the components be distorted, their instantaneous sum will be changed; that is, the wave resulting from their re-combination will be a distorted reproduction of the original wave. Also, those parts of the frequency range in which the amplitude is negligibly small can contribute little to the reproduced wave, and the elimination of all components in those ranges will have little effect on the quality of reproduction. Just what ranges it is essential to retain depends upon the nature of the signal and the standard of reproduction that is set up. What is important for present purposes is the fact that the faithfulness with which a system will reproduce any arbitrary signal disturbance is deducible, in theory at least, from a knowledge of its transmission of sustained single frequencies. By this is meant a knowledge of how the relation, both in amplitude and phase, between the input and output sinusoidal wave varies as the frequency of the wave is progressively varied thruout the frequency range.

Analysis of a Modulated Wave

Let us assume now that a radio system is called on to transmit such a signal wave, $F(t)$, which may be either a telephone or a telegraph signal. If, as is commonly assumed, the modulator causes the amplitude of the carrier wave, $C \cos p\, t$, to be varied in accordance with the signal, the resulting modulated wave may be expressed as

$$m = C\,[1 + k\, F\,(t)]\, \cos pt, \tag{2}$$

where k is a factor which measures the so-called degree of modulation. If the largest negative value of $k\, F(t)$ is just equal to unity, so that the instantaneous amplitude of the carrier wave just falls to zero, the modulation is said to be complete. The significance of complete modulation will be discussed later.

Now let us resolve the signal wave into its infinite series of components, each of the form $S \cos\,(qt + \Theta)$, where S and Θ vary with the frequency $\frac{q}{2\pi}$. Neglecting non-essential frequencies, q may be considered to cover a range from q_1 to q_2. If this value of $F(t)$ be substituted in (2) we get

$$m = C \cos pt + k\, C \cos pt \int_{q1}^{q2} S \cos\,(qt + \Theta)\, dq. \tag{3}$$

The first term, which is independent of the signal, represents a component having the carrier frequency, $\frac{p}{2\pi}$. The second term represents an infinite series of terms each derived from only one component of the signal. Hence each component of the signal is represented in the modulated wave by an expression of the form,

$$k\,C\,S\cos(qt+\theta)\,\cos pt=\tfrac{1}{2}k\,C\,S\,\{\cos[(p+q)t+\theta]+\cos[(p-q)t-\theta]\}.\quad(4)$$

This represents two sinusoidal components, the frequencies of which differ from that of the carrier by the frequency of the particular signal component. The similar expressions for the other signal components each yield a pair of components similarly placed with reference to the carrier. All of these taken together form a pair of spectra or frequency bands extending on either side from the carrier frequency in the same way that the spectrum of the signal extends from zero frequency. These bands of frequencies are spoken of as "side-bands" and the component currents of these frequencies as "side-band currents," or, more often, simply as "side-bands." The side-band which extends upward in frequency from the carrier is called the "upper side-band," and the other, which extends downward, the "lower side-band."

The form of these side-bands is shown schematically in Fig. 2, where purely arbitrary curves are used to represent the amplitudes and

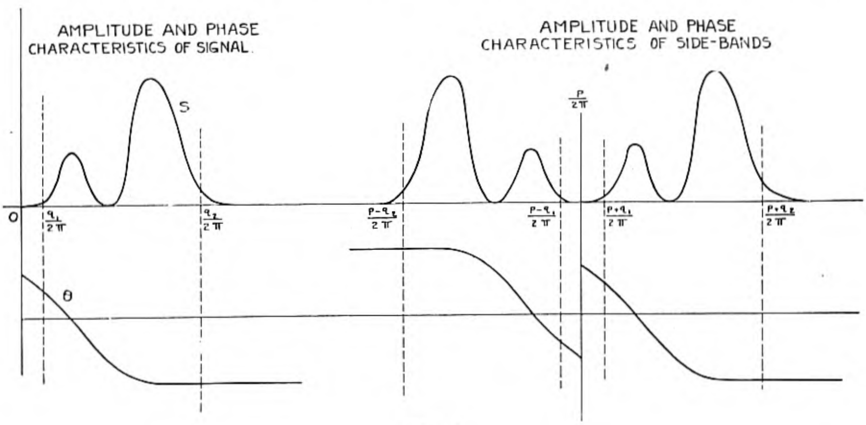

Fig. 2

phases of the signal components over a limited frequency range. It will be seen that the corresponding curves for the upper side-band are derived from these by displacing them along the frequency axis by the amount of the carrier frequency. The amplitude curve of the lower side-band is derived by inverting that of the upper with respect to the carrier frequency. For the phase curve of the lower side-band that of the upper is to be similarly inverted and also reversed in sign.

The actual magnitude of the side-band currents relative to the carrier depends on the degree of modulation, k, of equation (2). For commercial telephony the limits of the essential band may be taken roughly as 200 and 2,000 cycles. If high quality speech or music is to be transmitted, a wider band is required. For telegraphy the band width required varies widely with the speed of sending and the type of apparatus used. In general, it is desirable to preserve very low frequencies, which means that the two side-bands practically meet at the carrier frequency.

Reproduction of the Signal Wave

Having arrived at a picture of the modulated wave as given by equation (4), we shall first discuss the reproduction of the signal from this as it stands, and then consider the effect on this reproduction of various modifications to which the modulated wave may be subjected before or during the process of detection. While any device in which the current-voltage characteristic is non-linear may be used as a detector, the operation of the vacuum tube lends itself to analysis because of its approximation to a parabolic current-voltage relation. That is, we may write,

$$i=a_0+a_1v+a_2v^2, \tag{5}$$

where v is the voltage impressed on the grid, in this case the modulated wave, and i is the resulting current. As the first term is independent of v and the second represents simple amplification, detection [3] can result only from the third term, $a_2 v^2$. Since a_2 multiplies all components of v^2 alike, we may neglect it and simply consider the square of the expression for the modulated wave. This results in a series of terms which are the squares of the individual components and another which are their products taken in pairs. Since

$$\cos^2 x=\tfrac{1}{2}\,(1+\cos 2x), \tag{6}$$

the square terms will yield only direct current, and currents of approximately twice the carrier frequency. The product terms, each of which contains the product of two cosines, may, as in the case of the modulated wave above, be transformed into the sum of two cosine terms the frequencies of which are respectively the sum and difference of the component frequencies. Of these only the difference frequencies can lie in the range of the original signal. In other words, we may think of the reproduced wave as made up of the sum of all the

[3] In practice this parabolic law seldom holds strictly, and secondary contributions are made to the detected wave by terms of higher power.

heterodyne beat notes resulting from all the pairs of component sinusoids of the modulated wave.

The carrier component, $C \cos pt$, beating with a component of the upper side-band, $\frac{1}{2}\, k\, C\, S \cos [(p+q)\, t+\theta]$, equation (4), gives the beat note or reproduced component,

$$r_{+} = \tfrac{1}{2}\, k\, C^2\, S \cos (qt+\theta), \tag{7}$$

which is identical in frequency and phase with the corresponding component of the signal, and has an amplitude proportional to that of the signal component. Exactly the same expression results from beating the carrier and the corresponding component of the lower side-band. These two low frequency components, being in phase, add directly to give

$$r = k\, C^2\, S \cos (qt+\theta) \tag{8}$$

as the reproduced component. As the factor $k\, C^2$ is independent of q, all of the signal components are reproduced with the same relative amplitudes and phases, as in the original signal. Their sum is therefore $k\, C^2\, F(t)$, and the signal is accurately reproduced.

However, there are still other components of the modulated wave to be considered. Every pair of components in one side-band beat to give the difference of their frequencies, which is also the difference of the corresponding signal components. The corresponding pair of components of the other side-band yield an identical component and the two add in phase. Similarly every component of one side-band beats with every component of the other, giving in each case the sum of two component frequencies of the signal wave. Like the difference frequencies, each of these sum frequencies is produced twice. The combination of the components of the two side-bands which were derived from the same signal component yields a component of twice the frequency of the signal component. The addition of these extraneous components serves to distort the reproduced wave in a manner quite similar to that of external interference. It is of interest therefore to consider the magnitude of these distorting components relative to the reproduced signal. The product of two side-band components of amplitudes $\frac{1}{2}\, k\, C\, S$ and $\frac{1}{2}\, k\, C\, S'$, equation (4), gives as the amplitude of one of the two components of the difference frequency, $\frac{q-q'}{2\pi}$, $\frac{1}{4}\, k^2\, C^2\, S\, S'$. Comparing this with the amplitude, $\frac{1}{2}\, k\, C^2\, S$, equation (7), of one of the two reproduced signal components of frequency $\frac{q}{2\pi}$, the ratio of the undesired to desired component is found to be $\frac{1}{2}\, k\, S'$. It is evident that this type of distortion increases with the degree of modulation, k, or, as will be discussed more fully later, with the ratio of carrier to side-band.[4]

Single Side-Band Transmission

So far it has been assumed that the wave applied to the detector is identical with that produced by the modulator, a condition seldom encountered in practice. For, in addition to the undesired modifications which the modulated wave undergoes because the transmission characteristics of practical circuits are not ideal, there are other changes which when properly made yield distinct advantages. These intentional changes will be discussed first.

It will be remembered that any component of the signal can be reproduced by the combination of the carrier with either side-band. Hence it is unnecessary to transmit both side-bands. Suitably designed electrical filters make it possible to transmit one side-band and effectively suppress the other.[5] This makes possible a very great saving in the frequency range required per channel. It is of particular importance for long wave radio telephone transmission where the width of a single side-band is so large a fraction of the total frequency range available that the number of independent channels is at best very limited. The intensive development of a limited frequency range by the use of single side-band transmission has probably progressed farthest in connection with carrier telephony over wires. Here commercial service is being given over circuits on which the carrier currents of adjacent channels are separated by only 3,000 cycles. It is obvious that the transmission of both bands would nearly double this separation, thereby halving the number of channels per circuit. There is, of course, no reason why similar savings may not be effected in the field of radio transmission. In addition to this major advantage there is an incidental improvement in the quality of reproduction, for the distorted components resulting from beats between components of the two side-bands, that is, the sums of the signal frequencies, are eliminated.

Carrier Suppression and Homodyne Reception

The other important modification has to do with the so-called "unmodulated" component of carrier frequency, $C \cos pt$, in equation

[4] A similar form of distortion generally occurs in modulation, resulting in new components being produced in the frequency range of the side-band.

[5] For a description of such filters see the Colpitts and Blackwell paper referred to above.

(3). As already pointed out, good signal reproduction requires that at the detector this shall not be too small relative to the side-bands. However, it is merely a continuous alternating current, and does not itself partake of the signal variations. It is therefore immaterial whether it is transmitted from the modulator or is supplied to the detector by a local source such as an oscillator. The elimination of this component from the modulated wave at the sending station is spoken of as "carrier suppression," and its re-introduction at the receiving end as "homodyne" or "zero beat" reception. The term homodyne implies supplying the same wave as distinguished from heterodyne, meaning another. Zero beat refers to the bringing of the local carrier into synchronism with the sending carrier by reducing the beat note between them to zero frequency. While homodyne reception is essential to carrier suppression, the reverse is not true. The reception of an ordinary modulated wave may sometimes be improved by the addition of carrier at the receiving end.

The primary advantage of carrier suppression lies in the saving of sending power which it makes possible, or, what is equivalent, the increase in range made possible when all the power of a given station is utilized in the side-band. Of the various ways in which this suppression may be accomplished, the simplest is by the use of a so-called balanced modulator as shown schematically in Fig. 3. Carrier fre-

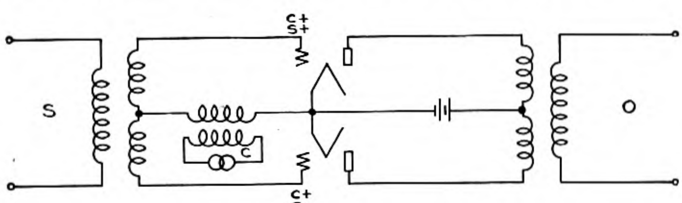

Fig. 3—Balanced modulator

quency from the source C is applied to the grids of two vacuum tubes in the same phase, while signal currents, indicated at S, are applied to the two in opposite phase. The two plate circuits are differentially connected with a common output circuit. In the absence of signaling current the amplified carrier frequency currents from the two tubes neutralize each other and nothing is transmitted. With the application of signaling current one grid is raised in potential and the other lowered, with the result that more radio frequency is developed by the first tube than by the second and the excess appears at O. The magnitude of this radio frequency current is proportional to the instantaneous value of the signaling current. Upon reversal of the direction of the signaling current the effect of the second tube predominates and radio frequency is again transmitted, this time with the phase reversed, owing to the differential connection. The wave form of a signaling current and the resulting output current are roughly as shown in Fig. 4, *A* and *B*. If this output be amplified for trans-

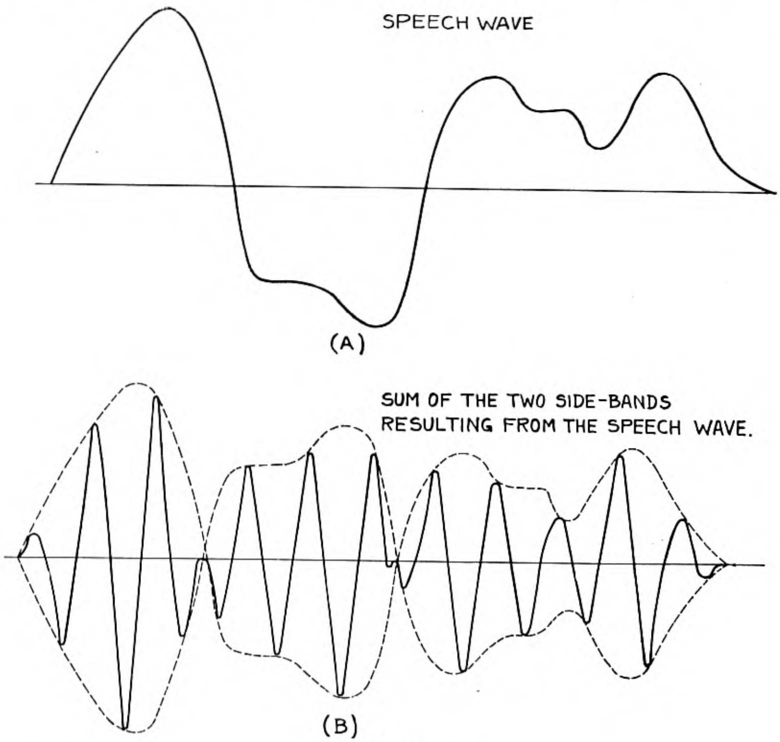

Fig. 4.

mission there will be no load on the amplifier and antenna except during actual speech, when it will be proportional to the intensity of the speech.

That these intermittent pulses of carrier frequency produced by a balanced modulator are equivalent to a modulated wave from which the carrier frequency component has been removed, may be easily shown. Consider a single sinusoidal component $S \cos (q\,t+\Theta)$, of the signaling wave which is applied to the balanced modulator. The resulting output current is a wave of carrier frequency, the amplitude of which is proportional to C and to S and varies cyclically with a frequency $\frac{q}{2\pi}$ between the values $+K\ C\ S$ and $-K\ C\ S$, where K is a constant of proportionality and the negative amplitude indicates a reversal of phase during half of the audio frequency cycle. Such a variation may be represented by the expression

$$i = K\,C\,S \cos{(q\,t + \theta)} \cos{p\,t}. \tag{9}$$

Taking the sum of these expressions for all the components of the signal gives the second term of equation (3) which was shown to represent the side-bands.

In estimating the power saved by carrier suppression the comparison should be made with a system transmitting the carrier which has been so adjusted that the power is used to the best advantage. So far as a single signal component is concerned this would call for making the carrier and side-band equal, as their product would then be a maximum. This, however, would imply that the distorting currents from the interaction of two side-band components would be as large as the signal currents themselves. That is to say, quality considerations require that the major part of the transmitted power be in the carrier component. Quantitative data on the relation between the ratio of carrier to side-band and the quality of transmission has been secured in the laboratories of the Western Electric Company, and it is hoped it will be published in the near future. Briefly, the results indicate that the good quality which is obtained when the carrier component is large falls off very rapidly as the magnitude of the carrier component is reduced so as to approach that of the side-band, the latter being measured when a sustained "ah" sound is used as the signal. Under these conditions the side-band is sustained at a value about equal to the maximum occurring in ordinary speech. That is to say, even the peak power in a carrier suppression system is less than the carrier component alone in an ordinary system adjusted to give the same side-band. From these considerations it appears that there has been a tendency to attach undue significance to "complete modulation," as a more or less unique and ideal condition of operation. For nothing revolutionary occurs as the carrier is decreased thru the value corresponding to that condition. The distortion due to interaction between the side-bands is present for larger values of carrier and continues to increase progressively for smaller values. The exact degree of modulation to be permitted therefore depends upon the standard of quality to be met. In a carrier suppression system the degree of modulation, k, approaches infinity more or less closely depending on the completeness of the suppression.

In addition to making possible the use of carrier suppression, homodyne reception presents other advantages. It furnishes a ready means of increasing the intensity of the reproduced signal, since this is proportional to the carrier component at the receiver as well as to the side-band. Also, by making the carrier large, k is made very small and the distorting currents due to interaction of the side-bands become negligible. The use of a large local carrier in homodyne radio telephony assists in frequency selection in the same way as does the hetrodyne wave in radio telegraph reception. Suppose an interfering message is separated from the desired one by only a few thousand cycles and so is not entirely suppressed by the receiving selective circuits. Currents of voice frequency can be reproduced from its side-bands only by interaction with its own carrier, and hence they will be small compared with those of the desired message, which are proportional to the local carrier. On the other hand, the large currents due to the interfering message and local carrier will all have frequencies above the voice range, and so can be suppressed by selective circuits in the output of the detector.

The same general reasoning applies also to static interference. Appreciable interfering currents of signal frequency can result only from those components of the static wave which lie in the frequency range of the side-bands. Moreover, they will bear the same ratio to the signal currents as do the static components to the side-band components. We may conclude, then, that when means are provided for eliminating all of the static except that which is inherently inseparable from the signal, the disturbing effect of the residue is determined solely by the relative magnitude of the *side-band* components and the static components which lie in the same frequency range. As the object of high power stations is to make the signals large compared with the static, the importance of concentrating the power in the side-bands rather than in the carrier is obvious.

Effect of Radio Distortion

Let us pass now from the intentional modifications of a modulated wave and consider the effects of unintentional distortions. Limiting our attention first to systems in which the carrier is transmitted, we have to consider the effect of distortion such as might be introduced by the sending and receiving circuits and the transmitting medium. Assuming the characteristics of these to be known in terms of their transmission of sinusoidal components of various radio frequencies, we wish to determine their effect on the amplitudes and phases of the components of the reproduced wave. We shall assume the current-voltage relations in the transmission system to be linear, so that no new frequencies are introduced. Then any possible distortion in the modulated wave may be represented by assigning the proper amplitudes and phases to all of the components. Corresponding to a single component of the signal we may write for the received wave

$$m = B \cos (pt - \phi) + B_{+} \cos [(p+q) t + \theta - \phi_{+}] + B_{-} \cos [(p-q) t - \theta - \phi_{-}] \tag{10}$$

where the amplitude, B, and phase lag, ϕ, may vary in any arbitrary manner for the different components of the modulated wave. We shall assume that B is always large enough compared with B_{+} and B_{-} that the interaction between the side-band components may be neglected. It will be seen that the single frequency components reproduced from the two side-bands are not in general equal nor in phase and may either aid or tend to neutralize each other. They will be of the form,

$$r = B \{ B_{+} \cos [q\,t + \theta - (\phi_{+} - \phi)] + B_{-} \cos [q\,t + \theta - (\phi - \phi_{-})] \}. \tag{11}$$

Taking the resultant of these two gives as the component of the reproduced wave,

$$r = R \cos (qt + \theta - \Psi) \tag{12}$$

where

$$R = B \sqrt{B_{+}^2 + B_{-}^2 + 2\, B_{+} B_{-} \cos [(\phi_{+} - \phi) - (\phi - \phi_{-})]} \tag{13}$$

$$\tan \Psi = \frac{B_{+} \sin (\phi_{+} - \phi) + B_{-} \sin (\phi - \phi_{-})}{B_{+} \cos (\phi_{+} - \phi) + B_{-} \cos (\phi - \phi_{-})}. \tag{14}$$

It is evident that both the amplitude, R, and the phase shift, Ψ, of the reproduced component depend upon both the amplitudes and phases of the corresponding components of both side-bands and on the phase of the carrier. The amplitude depends also on the amplitude B of the carrier, but as variations in this affect all components alike, they do not alter the wave form of the reproduced signal, but only its magnitude.

The expressions for the reproduced wave become much simpler for a system in which one side-band, say the lower, is suppressed. Then

$$B_{-} = 0 \tag{15}$$

and equations (13) and (14) reduce to

$$R = B\, B_{+} \tag{16}$$

$$\Psi = \phi_{+} - \phi. \tag{17}$$

The amplitude of the reproduced component is independent of the phases in the modulated wave, and is proportional to the amplitude of the side-band component. Hence amplitude distortion of the reproduced wave can result only from unequal transmission of the different component frequencies of the side-band. The change in

AMPLITUDE-FREQUENCY AND PHASE-FREQUENCY CHARACTERISTICS FOR BAND-PASS FILTER.

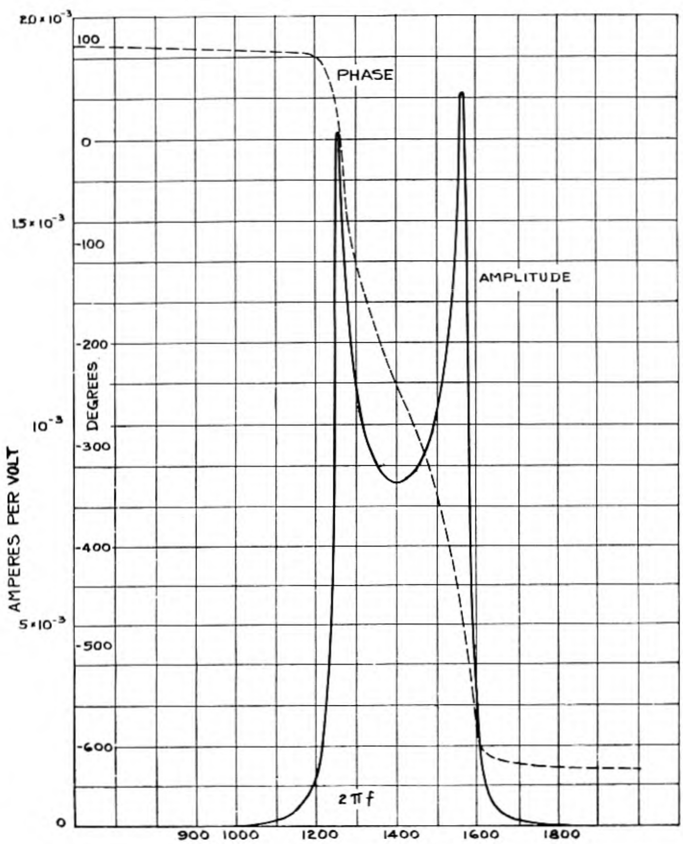

Fig. 5

the amplitude curve for the signal will be identical with that of the side-band. The phase shift, Ψ is independent of amplitude distortion of the modulated wave. It is equal to the difference between the phase lags of the side-band component and the carrier. Fortunately the quality of telephone reproduction is not seriously impaired by shifting the phases of the various components by even as much as several cycles. In telegraphy, however, the shape of the signal current which operates the relay depends very much on the preservation of the proper phase relations of the components, and the entire nature of the signal may be changed by phase shifts of even a fraction of a cycle.

It is worth while then to examine some of the phase shifts which are likely to occur in practice. Transmission of a sinusoidal wave thru the free ether involves a phase lag proportional to the distance and to the frequency. Hence the phase lags, ϕ_+ and ϕ, due to this cause, will be proportional to $p+q$ and p respectively, and their difference, Ψ, will be proportional to q. Replacing Ψ by $h\,q$ in equation (12) and regrouping terms gives

$$r = R\,cos\,[q(t-h)+\theta]. \tag{18}$$

By displacing the origin of time by h this becomes identical with the original signal component. Also, since h is independent of q, the same time shift brings all the components into agreement; that is, a phase shift proportional to the frequency does not distort the wave, but merely delays it by the corresponding time of transmission.[6] In considering the terminal circuits then it is only the departure of their phase lag versus frequency curve from a straight line that need be considered as a source of distortion. It is of interest to note here that for most filters this relation is approximately linear thruout the range of free transmission. The actual curves for a particular band filter are shown in Fig. 5, where there is plotted against frequency the relation of the amplitude and phase of the current at the third section of an infinite filter to those of the voltage applied to the first section. It will be noticed how the phase curve departs abruptly from a straight line at the edges of the band where the sudden drop in the amplitude curve occurs. Similarly Fig. 6 shows how in the current-voltage relation of a simple resonant circuit, the distortion of phase and of amplitude occur together.

In case both side-bands are transmitted, a simple relation is found if the distortion is symmetrical with respect to the carrier frequency. By this is meant that, however, the different components are distorted relative to each other, for every signal component the two corresponding side-band components are equal in amplitude and are

[6] For a fuller discussion of this point see a paper by T. C. Fry on "Theorie des binauralen Hörens nebst einer Erklärung der empirischen Hornbostel-Wertheimerschen Konstanten," "Physikalische Zeitschrift," 23, page 273, 1922.

shifted in phase relative to the carrier by the same amount; that is to say, for every value of q considered separately,

$$B_+ = B_- = B_\pm \tag{19}$$

$$\phi_+ - \phi = \phi - \phi_- = \delta. \tag{20}$$

Then

$$R = 2\, B\, B_\pm \tag{21}$$

$$\Psi = \delta. \tag{22}$$

The same considerations as to distortion of the side-band apply here as for the single side-band. There is one point, however, of some practical significance. As is evident from Fig. 6, the charac-

AMPLITUDE-FREQUENCY AND PHASE FREQUENCY
CHARACTERISTICS OF SIMPLE RESONANT CIRCUIT.

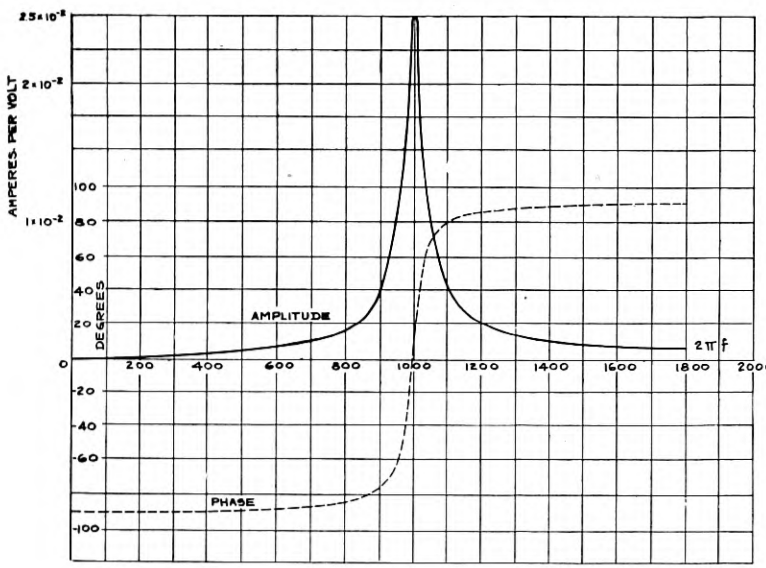

Fig. 6

teristics of a resonant circuit come very close to satisfying these symmetrical conditions if the carrier coincides with its resonance frequency. Its effect on the amplitude and phase curves of the reproduced signal may therefore be derived independently from the amplitude and phase curves of the tuned circuit. If, however, the circuit be detuned, this symmetry is upset and we are forced to the complicated relations of equations (13) and (14), from which it is difficult to draw general conclusions.

An interesting case of unsymmetrical transmission is that in which one side-band is only partially suppressed owing to insufficient selectivity. Let us assume that the upper side-band is transmitted without distortion. Then for a given amplitude of the lower side-band its effect on the amplitude curve of the reproduced signal will be worst when the phase relations are such that for some frequencies it aids the upper side-band and for others it opposes. The greatest fractional change in the amplitude of any one signal component due to the presence of the lower side-band occurs when the two oppose. It is then reduced in the ratio

$$\frac{B_+ - B_-}{B_+} = 1 - \frac{B_-}{B_+}. \tag{23}$$

Thus, if the lower side-band component were a tenth of the upper, the most it could do would be to change the amplitude of the signal component by a tenth. Such a change would have little effect on telephone quality, particularly as it would have this maximum value at only a few frequencies. The case of telegraphy is rather different. Here the two side-bands lie so close together that it is practically impossible to separate them by radio selective circuits, and even when, as in wire transmission, so low a carrier frequency is used that the two may be separated fairly well by filters, the side-bands corresponding to the lower signal components differ so little in frequency that even a sharp filter does not produce very great discrimination between them. This, coupled with the fact that the phase shift of a filter ceases to be linear near the edge of the transmitted band, leads to very considerable amplitude distortion.

The effect of the unsuppressed side-band on the phases of the reproduced components is also rather complicated. Equation (14) shows that it is a maximum when

$$\begin{aligned} \phi_+ - \phi &= 0 \\ \phi - \phi_- &= 90^\circ, \end{aligned} \tag{24}$$

in which case the presence of the lower side-band changes *tan* Ψ from 0 to $\frac{B_-}{B_+}$. As in the case of amplitude, this effect is unimportant in telephony, but would need to be considered in telegraphy.

Phase of the Local Carrier

Coming now to homodyne reception, the important new factor to be considered is the fact that the carrier component is now perfectly arbitrary in amplitude and phase. This is true even tho the sending carrier is not suppressed, for, by suitably choosing the local carrier, the resultant of the two may be given any desired value. Since the amplitude of the carrier affects only the magnitude of the reproduced signal as a whole, we need consider here only the effect of arbitrary values of its phase, ϕ. For simplicity we shall assume that the modulated wave reaches the receiver unchanged except for the phase lags involved in undistorted transmission. Let us designate by ϕ_1 the phase lag of the carrier which is received from the transmitting station or would be received if it were not suppressed. Then

$$\phi=\phi_1+\eta, \tag{25}$$

where η may be regarded as the phase displacement of the local carrier.

Consider first a system in which one side-band is suppressed. From equation (16), the amplitudes of the reproduced signal componants are independent of the phase of the carrier. From equation (17), the phase,

$$\Psi=\phi_+ -\phi_1-\eta. \tag{26}$$

But $\phi_+ -\phi_1$ represents only the phase shifts of undistorted transmission; that is, the delay suffered by the signal as a whole. Hence the net result is that all components have their phases shifted by the same amount; namely, the phase displacement of the carrier, which can never be more than a single cycle. For telephony this is of no practical importance, but it is evident that in a telegraph system using side-band suppression and homodyne reception the phase of the local carrier would have to be very carefully controlled.

Consider now the case of homodyne reception of both side-bands received without distortion; that is,

$$B_+ =B_-=B_\pm \tag{27}$$

and

$$\phi_+ -\phi_1=\phi_1-\phi_-=h\,q. \tag{28}$$

From these relations and equations (13) and (14) we get

$$R=2\,B\,B_\pm cos\ \eta. \tag{29}$$

$$\Psi=h\,q. \tag{30}$$

This shows that the amplitude of every component varies as *cos* η; that is, when the local carrier is in phase or 180° out of phase with the received carrier the reproduced components are maximum; for intermediate values they decrease, becoming zero when the two carriers are in phase quadrature. The phase lag, $h\ q$, is that due to transmission alone; that is, the phases of the reproduced components are independent of the phase of the local carrier. Since the phase of the local carrier affects only the amplitudes and affects these the same for all components, it does not alter the wave form of the reproduced signal, but does affect its magnitude very materially.

Thus in a carrier telephone system fluctuations in the phase of the local carrier are much more serious when both side-bands are transmitted than when one is suppressed, the only effect then being an unimportant phase distortion. In a carrier telegraph system, however, the amplitude fluctuations which occur when both side-bands are transmitted may not be particularly troublesome since telegraph receiving apparatus is designed to operate over quite a range of signal intensity. The phase distortion occurring in single side-band transmission is however serious. It may perhaps be considered fortunate that the requirements as to phase regulation are least severe in telephony with a single side-band and in telegraphy with both side-bands, since these modes of operation appear on other grounds to be the most practical for the two cases.

In comparing single and double side-band transmission it is interesting to note that for equal sending power, the power of the reproduced signal component is twice as great with two side-bands as with one. However, the power of the same frequency resulting from static is also twice as great, so that the ratio of signal to interference is the same in both cases. To show this, let B_1 be the amplitude of a component of the single side-band and B_2 that of each of the corresponding components of the double side-band. Then equality of power gives

$$B_1^2 = 2\ B_2^2. \tag{31}$$

For the single side-band the amplitude of the reproduced component is

$$R_1 = g\ B_1, \tag{32}$$

where g is a constant of proportionality. The power,

$$P_1 = \tfrac{1}{2}\ g^2\ B_1^2 = g^2\ B_2^2. \tag{33}$$

(The resistance is here omitted as it is assumed constant thruout.) For the double side-band, since the two components are in phase, the resultant amplitude,

$$R_2 = 2\ g\ B_2, \tag{34}$$

and the power,

$$P_2 = 2\ g^2\ B_2^2 = 2\ P_1. \tag{35}$$

If the static be assumed to approximate an impulse, the amplitudes of all its components will be sensibly the same. If we call this amplitude S, then, in the case where the receiving circuit admits only one side-band, the amplitude of the reproduced interfering current of the frequency of the signal component is

$$I_1 = g\ S, \tag{36}$$

and its power,

$$W_1 = \tfrac{1}{2}\ g^2\ S^2. \tag{37}$$

With both side-bands this interfering current is made up of two equal components derived from the static components of frequencies $\frac{p+q}{2\pi}$ and $\frac{p-q}{2\pi}$ respectively. The phase difference ϵ between these two will be accidental, so for any one case the resultant amplitude,

$$I_2 = 2\ g\ S\ cos\ \epsilon, \tag{38}$$

and the power,

$$W_2 = 2\ g^2\ S^2\ cos^2\ \epsilon. \tag{39}$$

As all values of ϵ are equally probable, we may average W_2 with respect to ϵ, whence

$$\overline{W}_2 = g^2\ S^2 = 2\ W_1. \tag{40}$$

There is then no choice between one and two side-bands on the basis of the ratio of signal to interference. With a single side-band, the major advantage of economy in frequency range is secured at the expense of the minor disadvantage that to give the same response the amplification of the receiving set must be greater by a factor of two in power, or about three miles of standard cable.

Use of Non-synchronous Local Carrier

In practice, however, unless the receiving carrier frequency is controlled by the same source as the sending carrier, it is rather difficult to maintain even the frequencies alike, to say nothing of the phases. Let us suppose that the local carrier is out of synchronism by a small amount, n. Consider first the simplest case where the carrier is suppressed and one side-band only is transmitted. The local carrier beating with each component of this side-band gives a component of normal amplitude, but of a frequency differing from that of the original signal component by n. That is, all the frequencies of the speech are raised or lowered by the same amount, n. This must alter the wave form very decidedly, but the surprising thing is that in telephony the intelligibility is not seriously affected when the difference is made as much as fifty cycles or so. The apparent pitch of the voice changes, of course, as n is varied.

If the carrier is transmitted, either intentionally or thru incomplete suppression, the situation is less favorable to asynchronous reception. The two carriers then beat together, giving a component of frequency n which may be troublesome if the received carrier is large. However, its frequency is generally below the voice range, and so it can be suppressed by a filter in the detector output. In addition the received carrier beating with the side-bands gives the components of the original signal. These are superposed on the displaced speech from the local carrier, the corresponding components of the two differing in frequency by n. As a result, the two sounds beat together just as two tuning forks would. For very little differences in frequency a periodic rise and fall in intensity is heard. When the difference is increased so that the individual beats can no longer be distinguished, a sensation of roughness results. And when the difference is made still greater the two waves may be heard as separate sounds of noticeably different pitch. The prominence of this beating effect depends, of course, upon the relative magnitude of the two carriers, since the two sets of speech currents are in the same ratio as the two carriers.

This effect of the received carrier may be very much reduced, and in the ideal case entirely eliminated, by the use of a balanced detector similar in structure to the balanced modulator of Fig. 3. It can be shown that with such a circuit the combination frequencies resulting from any two components applied at S are neutralized in the output circuit, while the combination of each with the carrier applied at C is transmitted. Thus if the side-band and received carrier enter together at S, the components having the original signal frequencies are eliminated and only the displaced components remain.

When the other side-band is added, the situation is still further complicated. In the absence of received carrier, the local carrier and one side-band give a set of components the frequencies of which are greater than those of the signal by n, while the carrier and other side-band give a set less by the same amount. These two sets combine in much the same way as do the displaced and normal speech obtained with a single side-band and received carrier. Here, however, the beat frequency is $2n$. Also, as the two sets are equal in amplitude, the beats will be much more pronounced, the intensity falling to zero each time the two waves are in opposition. For slow beats the apparent pitch of the sound is half way between the frequencies of the two equal components, and so the normal voice frequency will be heard. With large frequency displacements of the carrier the two displaced speech waves, being of equal intensity, will be more easily distinguished than in the case of the single side-band.

It is interesting to note that this result, as well as the frequency shift that occurs with a single side-band, follows directly from the relations arrived at above for the phase displacement of a synchronous carrier. The non-synchronous carrier may be thought of as a synchronous one the phase of which is varied with the frequency of the departure from synchronism. With a single side-band it was shown that a phase displacement of the carrier affects only the phase of the reproduced component and that it changes this by an amount equal to its own displacement. This progressive phase displacement in all the components of the reproduced wave is, of course, equivalent to a change in their frequencies equal to the frequency displacement of the carrier. With both side-bands present, a phase displacement was shown to have no effect on the phases but to change the amplitudes of the reproduced components by the factor $\cos \eta$. Thus a progressive change in η will cause a cyclic variation in amplitude having two minima for each cycle of η; that is, a frequency of $2n$.

If the two side-bands are accompanied by the carrier there are added the beat note of the two carriers and the components of the original signal. The addition of a small amount of this speech of uniform amplitude to that of varying amplitude already present merely tends to make the variation slightly less pronounced. From the foregoing it appears that for telephony the most favorable condition for using a local carrier which is out of synchronism is that in which only one side-band is transmitted. Fairly considerable frequency variations are then permissible and asynchronous operation appears to have practical possibilities.

For telegraphy the case is quite different. In the first place the important components of telegraph signals are much lower in frequency, so that the side-band lies closer to the carrier, and a much smaller absolute displacement of the carrier frequency is needed to give the same effect as in the telephone case. Considering only such small displacements, it appears that the general addition or subtraction of frequencies which occurs with a single side-band will alter the shape of the signals quite seriously. The slow fluctuations in signal intensity which occur with both side-bands are probably less serious over most of the cycle. However, they might well cause some signals to be lost entirely each time the intensity passed thru zero.

For asynchronous reception, then, just as for the case of a local carrier displaced in phase, single side-band transmission is preferable for telephony and double side-band for telegraphy. The difficulties are of the same general nature in the two cases, but with the asynchronous carrier they are considerably greater. This is in agreement with the idea expressed above, that lack of synchronism may be looked upon as an aggravated case of phase displacement.

Public Address Systems[1]

By I. W. GREEN and J. P. MAXFIELD

Synopsis: A public address system comprises electrical equipment to greatly amplify a speaker's voice so it will reach a much larger assemblage than he could speak to unaided. Beginning with the presidential conventions of the two major parties in 1920 and the inaugural address of President Harding in March 1921, when a special address system installed by the telephone engineers enabled him to address an audience estimated at 125,000, there followed in rapid succession, many public events demonstrating the value of such systems. One of the most notable of these occurred on Armistice Day 1921, when the speeches, prayers and music at Arlington, Virginia, were heard, not only by 100,000 persons gathered there at the National Cemetery, but by some 35,000 in New York City and 20,000 in San Francisco. On this occasion the three public address systems, one for each of these cities, were joined by long distance telephone circuits.

The fundamental requirements of a satisfactory public address system are naturalness of reproduction and wide range of output volume. The meeting of these two requirements for music proves more difficult than for speech.

The public address system here described is most readily considered in three sections—"pick-up" apparatus which is placed in the neighborhood of the speaker and converts his words into undulatory electric currents; a vacuum tube amplifier for amplifying these currents; and a "receiver-projector" for reconverting the current into sound waves and distributing the sound over all of the audience. In the present system each of these three parts of the equipment has been designed with the intention of making it as nearly distortionless as possible, so that the various parts might be adaptable for audiences ranging in size from possibly one thousand to several hundred thousand, and might also be used in connection with the long distance telephone lines and with either radio broadcasting or receiving stations. One of the larger public address systems is easily capable of magnifying a speaker's voice as many as 10,000 times.

The pick-up device whether of the carbon microphone variety or a condenser transmitter need not be placed close to the speaker's lips but will operate satisfactorily when four or five feet away. The loud-speaking receiver mechanism is so designed that it will carry a power of several watts with small distortion. Under normal conditions, 40 watts distributed among a number of receiver-projectors arranged in a circle is ample to reach an audience of 700,000 persons.—*Editor.*

THIS paper aims to present the problems encountered in the development of electrical systems for amplifying the voices of public speakers and music; and to describe the equipment as brought to a commercial state and now in use in the United States and various other countries.

The two main requirements of a successful public address or loud speaking system are, first, that it shall reproduce the sounds, such as speech or music, faithfully; and second, that this faithful reproduction shall be loud enough and sufficiently well distributed for all of the audience to hear it comfortably. Most of the development work

[1] Presented at the Midwinter Convention of the A. I. E. E., New York, N. Y., February 14–17, 1923. Published in the Journal of the A. I. E. E. for April, 1923.

has been directed toward obtaining these two results under the various conditions which surround the operation of these systems.

The faithful and natural reproduction of sound depends upon many factors, of which the following are some of the more important: The acoustics of the space in which the sound originates, the characteristic of the loud speaking system itself and the acoustics of the space in which the sound is reproduced. Where the sound is picked up and reproduced in the same space, as is the case when the speaker is using one of these systems to address a large audience locally, there is a reaction between the horns and the transmitter or pick-up mechanism which is controlled by the acoustic conditions under which the system is operated.

Acoustics of the Space

In connection with the acoustics of the space in which the sound originates, or in which it is reproduced, four factors stand out. These concern the effects of reverberation, of echo, of resonance, and of diffraction. In the specific cases where the sound is reproduced in the same space or room in which it originates, another effect is encountered, which has generally been termed "singing," and is evidenced if sufficiently great by the emission of a continuous note from the equipment.

Reverberation is caused by reflection and is evidenced by the persistence of the sound after its source has ceased emitting. When the reverberation in the space in which the initial sound is being picked up is sufficient to cause one sound to hang over and become mingled with succeeding sounds, in other words, so that the sound from one syllable interferes with that of the succeeding syllable, it is practically impossible to improve the acoustic conditions solely by the use of the public address system. In such a case, the first procedure is to place material which absorbs sound in the space. The purpose of this absorbing material is to lower the time required for the sound to die away after the source ceases to emit. The amount which any given material lowers the time of reverberation depends not only upon the amount of material introduced, but also upon its disposition within the space.

The term "echo" applies to a similar phenomenon, but is generally used where there is sufficient time lag between the reflected sound and that originally emitted, so that two distinct impressions reach the ear.[2]

[2]Collected Papers on Acoustics, Wallace Clement Sabine, Harvard University Press, 1922.

The troubles encountered from echoes usually occur only in large buildings or large open spaces surrounded by buildings, trees, or other obstacles and are generally associated with interferences with the reproduced sound rather than with the original sound. There are cases, however, particularly in auditoriums, where some of the walls or ceiling are large curved surfaces, in which case localized echoes may result. The speaker's voice or extraneous sounds from the audience may be reflected from one or more of these surfaces to focus spots where the volume of sound is consequently abnormally great. It is important, therefore, that the transmitter which is picking up the sound shall not be located at one of these spots. These points of localized echo are particularly troublesome also when they occur in the space occupied by the audience. Under these conditions not only is the sound intensity too great, but the character of the sound is altered and very often badly confused. The avoidance of such difficulties is a matter of test and the proper arrangement of the reproducing mechanism, as will be seen later in some detail.

The effect of resonance seldom occurs in connection with the amplified and reproduced sound, inasmuch as the spaces dealt with are large and their natural frequencies are too low to be troublesome. Resonance usually becomes of importance in connection with mounting the pick-up apparatus or transmitter. It generally results from attempts to conceal the transmitter by placing it in some form of small enclosure. The best form of housing from an acoustic standpoint consists of a screen cover which protects the instrument from being struck or injured but in no way affects the sound reaching it.

Resonance produces a distortion which it has been customary to consider as of two varieties. First, there is an unequal amplification of sounds of various frequencies and second, there is the introduction of transients. These transients occur whenever the sound changes but are most easily recognized audibly by their continuation after the source has ceased emitting. They also have frequency characteristics which depend not only on the sound which started them but also upon the character of the resonant portion of the system.

The troubles introduced by diffraction are seldom of very great importance except where the sound is reflected from regularly spaced reflectors or passed through regularly spaced openings. Quite serious diffraction troubles have been encountered when operating a loud speaker in a large field, surrounded by an open work board fence, the trouble being evidenced by very distinct areas, particularly at the outskirts of the audience, where the sounds were badly distorted.

The difficulties encountered as a result of "singing" form one of the most troublesome problems connected with the actual operation of these systems. When a portion of the sound emitted by the projectors reaches the transmitter with sufficient intensity, that its reproduction is as great as the originally emitted sound from the projectors, and with such phase relation that it tends to aid the original sound, the system will emit a continuous note. Moreover, when the portion of the sound from the projectors which reaches the transmitter is not sufficient to cause a continuous note, it may be sufficient to cause considerable distortion of the speech or music. In excessively reverberant halls these conditions are often fulfilled when the actual amplification is so small that the people at the distant points are scarcely able to hear the speaker. In all cases in our experience the difficulty has been sufficiently overcome by properly placing the transmitter with respect to the projectors. The situation is very much helped by the presence of the audience, which adds considerably to the acoustic damping of the room.

It will be seen, therefore, that the acoustic conditions of the space in which loud speakers are used are of considerable importance.

Characteristics of the System

The first requirement of the system itself is that it shall reproduce speech or music faithfully. A system is said to do this, or in other words, its quality is called perfect, when the reproduced sound contains all of the frequencies, but no others, contained in the original sound striking the "pick-up" mechanism, and when these frequencies have the same relative intensities that they had in the original.

An imperfect or distorting system is one which fails to fulfill this requirement. There are two main types of distortion which had to be considered; the first being the unequal amplification of the system for the various frequencies constituting the sound and the second being the introduction of frequencies not present in the original sound. For simplicity of discussion, this last class will be divided in three parts, namely: the effect of transients, the effect of asymmetric distortion and the effect of disturbing noises.

The effect of transients has already been mentioned in connection with acoustics and they, of course, produce the same type of distortion whether they occur in the acoustic or the electrical system. Transients occur whenever the sound changes either in pitch or intensity, and are introduced at the beginning and ending of each speech sound. This modification of the characteristics of the speech sounds acts to lower the intelligibility. It probably causes more trouble in speech transmission than the fact that the sound continues after the source ceases.

Asymmetric distortion affects one half of the wave differently from its other half. This causes the introduction of frequencies which, in some cases, produce very serious disturbances in the transmission of music and speech. The most noticeable troubles are from the formation of sum and difference tones.[3] Such tones are likely to give rise to dissonances with the other sounds occurring in the music. In the case of speech asymmetric distortion manifests itself by a lower intelligibility.

The effect of foreign noises sometimes encountered is twofold. First, they influence the ability of the listener to hear the characteristics of the speech sounds and hence tend to lower the intelligibility. Secondly, the constant attempt of the hearer to sort out the speech sounds or music through the disturbing noises tires him appreciably. In order that this strain shall be inappreciable, it is desirable that the sound delivered by the system shall be at a power level approximately 10,000 times that of the noise.

The second general requirement which is placed on a successful system is that it shall deliver its faithful reproduction loud enough for all the audience to hear it comfortably and enough above noise for good intelligibility. In this connection there have arisen one or two interesting points bearing on the psychology of hearing. One of the most striking of these is concerned with the coordination between hearing and seeing. Although the projectors are usually mounted twenty or more feet above the speaker's head, and in some exceptional cases, slightly to one side of him, the majority of the audience is conscious of only one source of sound, and that appears to be the speaker himself.

This phenomenon is so marked that in several cases the question has been rasied in the minds of the listeners as to whether the system was functioning. They could only be convinced that it was by having it shut down for a few seconds when their inability to hear made them realize how successfully the system could operate.

Another of these psychological phenomena deals with the apparent distortion of the voice when its intensity at the ears of the listener is too great or too small. If the speaker is talking in a normal conversational tone, his voice contains a larger percentage of low frequencies than is the case when he is raising his voice to a considerable

[3] Origin of Combination Tones in Microphone-Telephone Circuits. E. Waetzmann, Annalen der Physik, Vol. 42, 1913.

volume. If the loud speaker so amplifies this voice that it reaches the audience with such volume that their instinct tells them that the speaker should be shouting, the system appears to make his voice sound quite heavy and somewhat unnatural. It has been found necessary, therefore, to so regulate the amount of amplification that the people at the furthest portion of the hall can hear comfortably and the volume of sound shall not be permitted to become any louder than necessary to meet this condition. On the other hand, if the volume is insufficiently loud, certain of the weaker speech sounds are entirely lost, and it becomes difficult to understand.[4]

Solution of the Problem

With these considerations in mind it may be interesting to take a brief survey of the whole problem and the method by which the solution was reached. Two general methods of attack were considered. The first was to attempt to make each unit of the system faithfully reproduce its input, while the second was to make any distortions of one part of the system, cancel those of another portion, so that the complete system would operate satisfactorily. In either case, it was desirable to keep each unit free from asymmetric distortion, as this type of distortion cannot be easily compensated for.

While it would probably have been simpler to follow the second line of attack, the greatly increased flexibility of a system in which each part is correct in itself was of sufficient value to cause the attempt to be made that way. When it is realized that these systems, to be commercially successful, must be capable of operating for various sized audiences, ranging possibly from one thousand to several hundred thousand, that they must be used in connection with long distance telephone lines, as well as with either radio broadcasting or receiving stations, the desire for flexibility can be understood.[5]

As a result of attempting the development in the manner already described, there has resulted a system which involves four functional units; a "pick-up" mechanism or transmitter unit, a preliminary amplifier unit, commonly called the speech input equipment, a second amplifier unit commonly called the power amplifier, and a receiver-projector unit for transforming the amplified currents back into sound, and properly distributing it throughout the space to be covered.

[4] Physical Examination of Hearing, R. L. Wegel, *Proceedings of the National Academy of Sciences*, Volume 8, Number 7, July, 1922.

[5] Use of Public Address Systems with Telephone Lines, W. H. Martin and A. B. Clark. Presented before A. I. E. E., Feb. 14, 1923.

It may be interesting at this place to determine how successfully these various units and the system as a whole fulfill the requirements of equal sensitivity to all frequencies within the important speech or music range. Fig. 1 shows the relative sensitiveness of the trans-

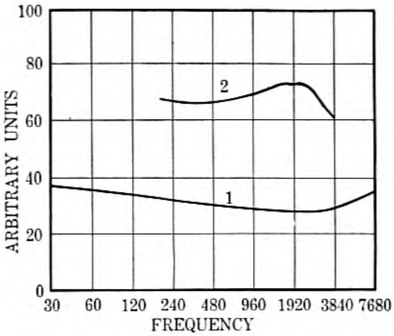

Fig. 1—1-Condenser Transmitter with Associated Amplifier.
2-Carbon Transmitter without Amplifier.

mitter as a function of frequency. The ordinates are proportional to the logarithm of the power delivered for constant sound pressure at the diaphragm and the abscissae to the logarithm of the frequencies employed. The lower of the two figures refers to the condenser transmitter with its associated input amplifier.[6] The upper refers to the push-pull carbon-type transmitter. These transmitters will be described in detail later.

Fig. 2 shows a similar curve for the complete amplifier system, comprising a three-stage speech input amplifier, and a power stage capable of delivering approximately 40 watts of speech frequency

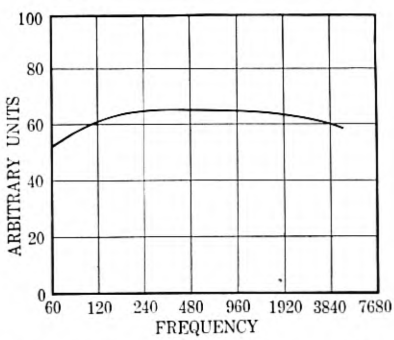

Fig. 2—Public Address System Amplifiers.

[6] The Sensitivity and Precision of the Electrostatic Transmitter for Measurement of Sound Intensities. E. C. Wente, *Physical Review, N. S.* Vol. 19, No. 5, May, 1922.

electrical power without distortion. In connection with these amplifiers a sharp distinction should be made between their gain rating, or amplification, and their overload or power rating. Gain measures the power amplification which can be obtained provided the input is small enough so that the equipment at the output end is not overloaded. Overload or power rating refers to the maximum power which can be supplied by the amplifier without causing distortion of the currents being amplified. Although the power rating of power equipment is usually determined by the heat which can be dissipated, a marked distortion of wave form takes place when the iron in any of the apparatus is worked beyond the straight line portion of the magnetization curve. In the case of amplifiers, the maximum power obtainable is limited by the power output at which distortion occurs rather than by the heat which can be dissipated.

Fig. 3 shows a chart for the characteristics of the complete system,

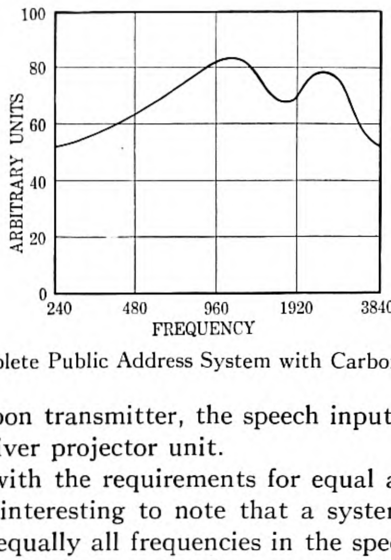

Fig. 3—Complete Public Address System with Carbon Transmitter.

including the carbon transmitter, the speech input and power amplifiers and the receiver projector unit.

In connection with the requirements for equal amplification of all frequencies, it is interesting to note that a system, which does not fail to reproduce equally all frequencies in the speech range by more than a ratio of 10 to 1 in reproduced power, is indistinguishable from a perfect system or from the speaker, himself. It seems probable that this effect is, in some way, connected with variations in the frequency sensitiveness curve of normal ears. Normal ears show a sensitiveness variation with frequency as great as 10 to 1 and the frequencies of maximum sensitiveness vary materially from one individual to another.[7]

[7] Frequency Sensitiveness of Normal Ears, by H. Fletcher and R. L. Wegel, *Physical Review*, July, 1922.

It has been found that in order to transmit speech with entire satisfaction for loud speaker purposes, that is, sufficiently well so that the audience is not aware of the contribution of the mechanical equipment, it is necessary for the system to operate with essentially uniform amplification over a range of frequencies from 200 to 4000 cycles. While there are, in speech, frequencies slightly outside of this range, the loss in naturalness and intelligibility by the system's failure to reproduce them, is slight.[8]

While no such frequency range is required for intelligibility only, it has been found that systems not covering substantially this frequency range, sound unnatural. When the lower frequencies are missing, the reproduction sounds "tinny." When the higher frequencies are missing it sounds heavy and muffled. The requirements for thoroughly natural reproduction of music are probably more severe, particularly in the low-frequency region, than are the similar requirements for speech, but, at the present time, complete data are not available to indicate the contribution of these frequencies to naturalness.

In connection with the flexibility of the system, it is interesting to note that the speech input equipment has been designed to raise the power delivered by the transmitter to such an extent that it is sufficient for long distance telephone transmission or for the operation of a radio transmitting set. The power amplifier is designed to receive power at approximately this level and deliver it to the projector units sufficiently amplified to operate them satisfactorily.

Future Development

In viewing the loud speaker field from the point of view of future development there are two lines of attack along which work is being done, and which give promise of success. These are the improvements in frequency characteristics and increase in the range of loudness which the system can accommodate satisfactorily.

The improvement to be expected from a more uniform frequency characteristic is mainly an increase in naturalness, especially where music is being reproduced. A slight increase in intelligibility may be hoped for, although this factor is of little importance, as the present system is satisfactory in this respect.

The other improvement mentioned, namely, the volume range, is probably the more difficult, but is necessary before music can be re-

[8] The Nature of Speech and Its Interpretation. Harvey Fletcher, *Journal of the Franklin Institute*, Vol. 193, No. 6, June, 1922.

produced in a perfect manner. Rough experimental data indicate that the loudness in an orchestra selection may vary from one part of the selection to another by a ratio as great as 50,000 to 1. While the present equipment does not operate with entire satisfaction over this range of loudness, it has been found relatively easy to obtain good results by manual adjustment of the amplification during the rendering of the selection. If the gain is varied in small enough steps, the change is not noticeable to the listeners.

An increase in the loudness range would render the manual adjustment unnecessary and would make the reproduction a faithful duplicate of the music as actually played.

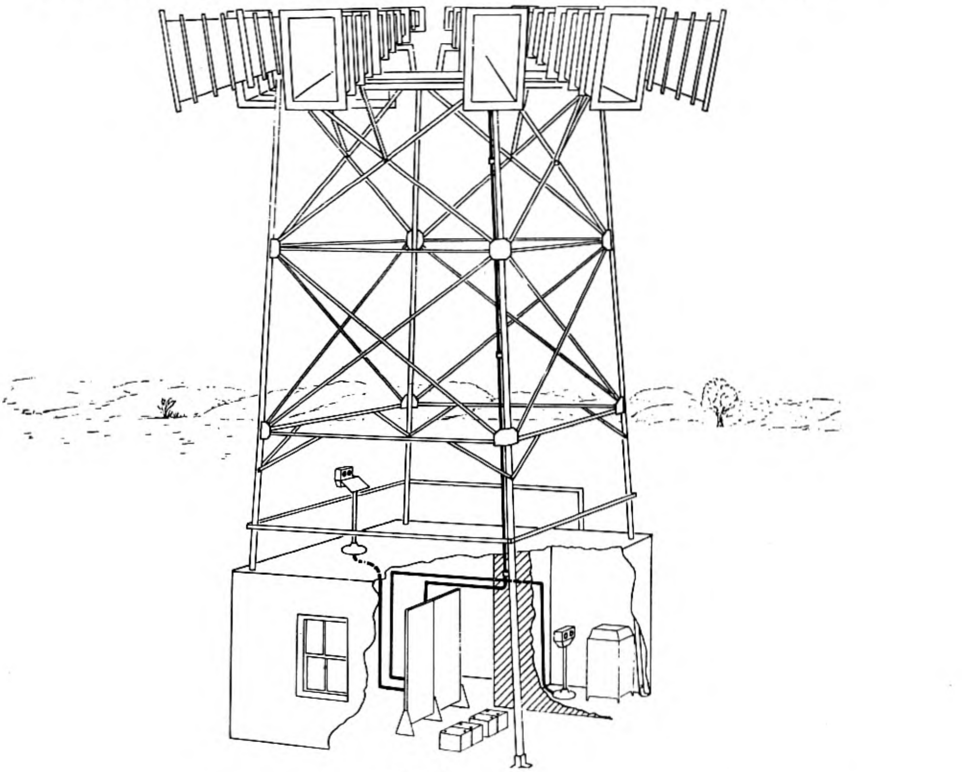

Fig. 4.

Technical Description of the System

The foregoing discussion having described the requirements which must be met in order that the public address system shall successfully transmit speech and music, the system in its commercial form will now be described. In order to make clear the arrangement of the equipment, a typical installation is shown in Fig. 4, this being an installation where the audience and speaker are in the open air, and where no connection is made with the long distance lines. It might be well to state here that with the equipment shown an audience of 700,000 can be adequately covered.

Some of the sound leaving the speaker's mouth is picked up by the transmitter, on a reading-desk type of pedestal, which is normally mounted at the front of the platform.

The feeble currents from the transmitter are led by carefully shielded leads to the amplifiers in the control room, which is usually

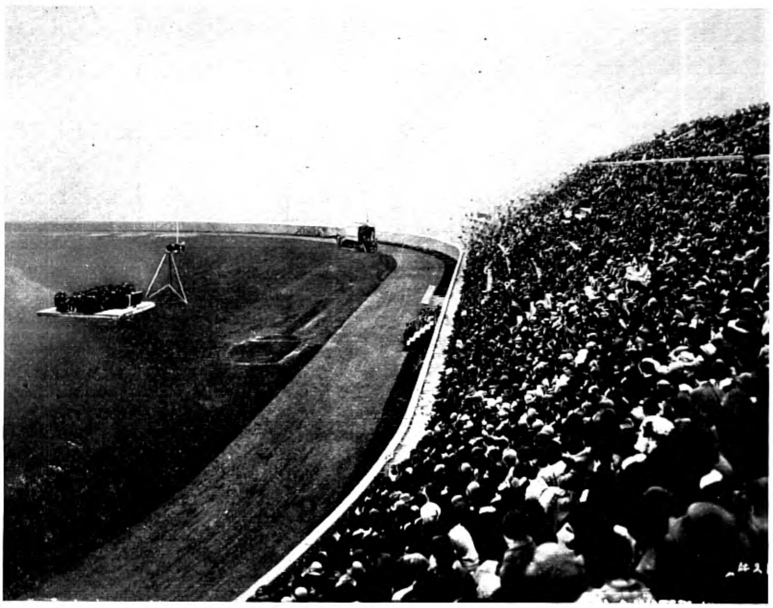

Fig. 5.

located directly beneath or to one side of the speaker's stand. A floor space of not more than 125 square feet is required for this room, even in the case where it is desirable to transmit phonograph music to the audience between speeches.

The amplifier and power supply equipment is shown on the two panels in the center of the control room. The amplified speech currents are led from these amplifiers to the receiver projector units, which, in this case, are arranged on the super-structure above the speaker's platform. This position is most desirable, as the illusion produced is such that the voice appears to come from the speaker rather than from the projectors, a factor, the importance of which has already been mentioned. Moreover in this position the acoustic coupling between the transmitter and the projectors is a minimum, permitting the operation of the system at a satisfactory degree of amplification with an ample margin below the point where singing troubles are encountered.

A public address equipment, similar to that just described, but with a somewhat lower power output, has been developed for use at the smaller open air meetings, and in all but the largest indoor auditoriums. Fig. No. 5 shows one of these equipments, mounted on an automobile truck, which has been employed at a number of points in the eastern part of the United States. This smaller system has characteristics as good as the larger system in regard to faithful reproduction of speech and music, with a power output in the order of one-tenth as great. An audience of 50,000 can be adequately covered at an outdoor meeting with this system.

Fig. No. 6 is a schematic arrangement of the equipment at an installation of the type shown in Fig. 4. At the extreme left are the

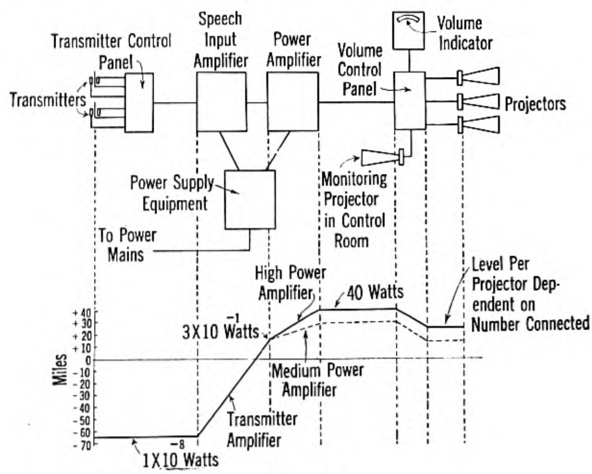

Fig. 6.

transmitters where the sound waves are picked up. The output from these transmitters is taken to a switching panel where means are provided for cutting in the various transmitters. From this panel the transmitter currents are taken to the transmitter amplifier, which is capable of amplifying them to a power level suitable for input to the power amplifier, or for connection to the long distance lines, in those cases where the speeches are transmitted to distant audiences. It is also suitable where connection is to be made to a radio station for broadcasting the speeches. The power amplifier is shown just to the right of the transmitter amplifier. Below it is indicated the power supply equipment by which the commercial power is converted to a form suitable for the vacuum tubes in both amplifiers. The output from the power amplifier is taken through a panel where switches and a multi-step auto-transformer are provided for the regulation of several projector circuits. Just above this panel is an indicating instrument, known as the volume indicator, provided in order that the operator may know what volume output is being delivered to the projectors.

The projectors, at the extreme right of the figure, consist of the motor or receiver unit transforming the speech currents into sound waves, and a horn to provide the proper distribution of the sound.

It is interesting to note the power amplification which is obtained in the larger of the two systems from the transmitter to the projectors. Referring to Fig. No. 6, a chart will be seen which indicates the power levels through the system drawn to a scale based on miles of standard telephone cable, our usual reference unit. The output of the high quality transmitter is of the order of 65 miles below zero level, this latter being the output from a standard telephone set connected to a common battery central office by a line of zero resistance. Expressed in watts the output of this transmitter under average conditions of use with the public address system is of the order of 10^{-8} watts. Incidentally, this is of the same order as the speech power picked up by the transmitter, or in other words, the transmitter does not amplify the speech power received by it as is the case with the transmitter used for regular telephone service.

This very minute amount of power in passing through the transmitter amplifier may be amplified about 120,000,000 times. Expressed in terms of telephone power levels, this is 17 miles above the zero level previously mentioned, or a few tenths of a watt.

The power amplifier serves to increase this power from a level of 17 miles to about 40 miles, the latter corresponding to about 40 watts. This power is then distributed to the projectors, the amount consumed by each projector, of course, depending upon the number connected.

An idea of what this amount of power at speech frequencies means may be given by the statement that it is sufficient to operate at about the level considered commercial all of the 14,000,000 telephone receivers in use in the Bell system if these were directly connected to the amplifier.

In describing the various pieces of equipment which together make up the system, we will follow the order in which the power is carried through the system from the transmitter to the receiver-projector units where the amplified sound waves are propagated.

Transmitters

In the early work on the public address system, an air-damped, stretched diaphragm condenser transmitter was employed, having a thin steel diaphragm about 2 inches in diameter, constituting one plate of the condenser. The other plate was a rigid disk, the dielectric being an air film 1/1000 of an inch in thickness. Due to the stretching of the diaphragm and the stiffness of the air film, the diaphragm of this transmitter had a natural period of approximately 8000 cycles per second which is well above the important frequencies in the voice range. This high natural period, in conjunction with the damping due to the thin film of air, resulted in a transmitter of very high quality of reproduction. However, its extremely small capacity (in the order of 400 micro-microfarads) made it necessary to use leads of very low capacity between the transmitter and the first amplifier, and due to the high impedance of the transmitter and its associated input circuit to voice frequency currents, these leads were very susceptible to electrostatic and electromagnetic induction. It was necessary to limit them to a length of 25 feet, and to provide complete shielding. Moreover the output of this transmitter was less than one five-thousandth of that of the transmitter now used, and for the early installations of the system, it was necessary to provide a preliminary amplifier beneath or to one side of the speaker's stand in order to keep the transmitter leads short and to provide sufficient power to properly operate the main amplifiers. Work was therefore undertaken to provide a transmitter having quality practically as good as the condenser transmitter, volume output sufficient to operate the main amplifiers, and not requiring the elaborate precautions as to shielding the leads.

The high quality transmitter which was the result of this development work is of the granular carbon type with two variable resistance elements, one on each side of the diaphragm and is commonly known as a push-pull transmitter. It has nearly the same high quality reproduction characteristics as the condenser transmitter, due to the use of the same stretched diaphragm and air damping structure. It introduces no appreciable distortion over the range of frequencies required for good reproduction of speech, but it must be understood, that this quality was obtained only at the sacrifice of sensitiveness, the latter being in the order of 1–1000th that of the transmitter used at telephone stations in the Bell system. With the multi-stage vacuum tube amplifiers available this low volume efficiency is not serious, and in fact we are using this transmitter for what is known as distant talking, *i.e.*, the speaker may be at a distance of five or six feet from the transmitter. This is, of course, necessary in any transmitter suitable for public address work as it is not possible to greatly limit the movement of the speakers, nor can they be required to use a hand transmitter. It might be well to point out that this sacrifice in volume efficiency in order to gain high quality is possible at the transmitting end of the system, but not at the opposite end where the electrical power is transformed into sound waves and propagated, as the device at this point must be capable of handling large amounts of power with minimum distortion.

Referring to Fig. No. 7 which is a cut-away view of this push-pull high quality carbon transmitter, the granular carbon chambers will be seen. The electrical path through each of these variable resistance elements is from the rear carbon electrode through the carbon granules

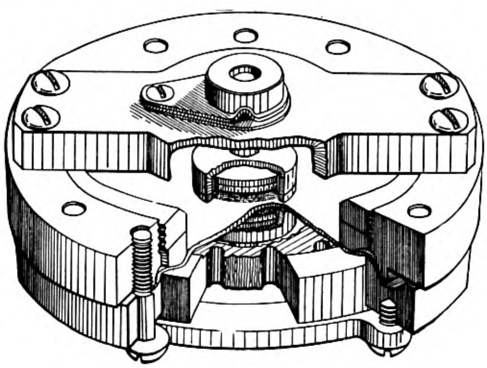

Fig. 7.

to a gold-plated area on the diaphragm itself. The resistance of this path is about 100 ohms and as the two buttons are in series for the telephone currents, the transmitter is designed to work into an impedance of 200 ohms. The double button construction almost completely eliminates the distortion caused by the non-linear nature of the pressure-resistance characteristics of granular carbon.

As this instrument has a practically flat frequency characteristic no collecting horn or mouth piece is used with it as resonance is introduced by such chambers, with accompanying distortion. To insure the insulation of the transmitter from building vibrations, a simple spring suspension has been provided. To protect the transmitter from injury, two types of transmitter mountings have been used, both arranged for the suspension of the transmitter in a screen-enclosed space—the first adapted to take a single transmitter for indoor use only, while the second for outdoor use, mounts two transmitters within a double screen enclosure to prevent any noise effects due to winds. This second type is arranged to attach to a simple pedestal-type of reading desk, which it has been found desirable to provide as there is a slight tendency for the speaker to remain fairly close to the desk. In this connection it is interesting to note that we have found a small rug, so placed as to cover the area which the speaker should occupy during the delivery of his speech, is of great assistance in this regard, as he unconsciously confines himself to the area of this rug. Both of these measures to insure the speaker remaining in proper relation to the transmitter, are supplemented, wherever possible, by an explanation of the system to all the speakers previous to the actual performance.

Transmitter Switching Panel

Resuming the path of the speech currents through the system, the output from the transmitters is taken to a panel designed to enable the operator to switch quickly from one transmitter to another, as with some public functions, the speeches are made at different points during the ceremonies. This switch is arranged to short-circuit the output of the power amplifier when passing from one transmitter to another, to prevent clicks in the projectors. In certain cases, the equipment is arranged to permit two or more transmitters to be connected to the amplifiers at one time, as is desirable when solo singers and an orchestra are to be picked up in a theatre, with proper adjustment of their respective volumes.

The amplifier equipment has been built in four units which may be grouped as necessary under the various conditions encountered in commercial installations. The proper amplifiers are determined, first, by the source of the voice frequency current to be amplified, that is whether a distance talking or a close talking transmitter is to be used, or whether the speeches are brought in over a telephone line, and secondly, the size of the space in which the amplified sounds are to be delivered to the audience. It was found that four units would provide for all the conditions occurring in practise, two of these being speech input or transmitter amplifiers with different gains and two being power amplifiers of different power ratings. These units and other equipment used with the system, are made up in panels, of uniform width, in order that the proper equipment for any installation may be assembled on two vertical angle iron racks arranged to be fastened to the control room floor.

Speech Input Amplifier—First Type

The first of the speech input amplifiers is shown schematically in the upper part of Fig. 8. It is a three-stage amplifier. Two po-

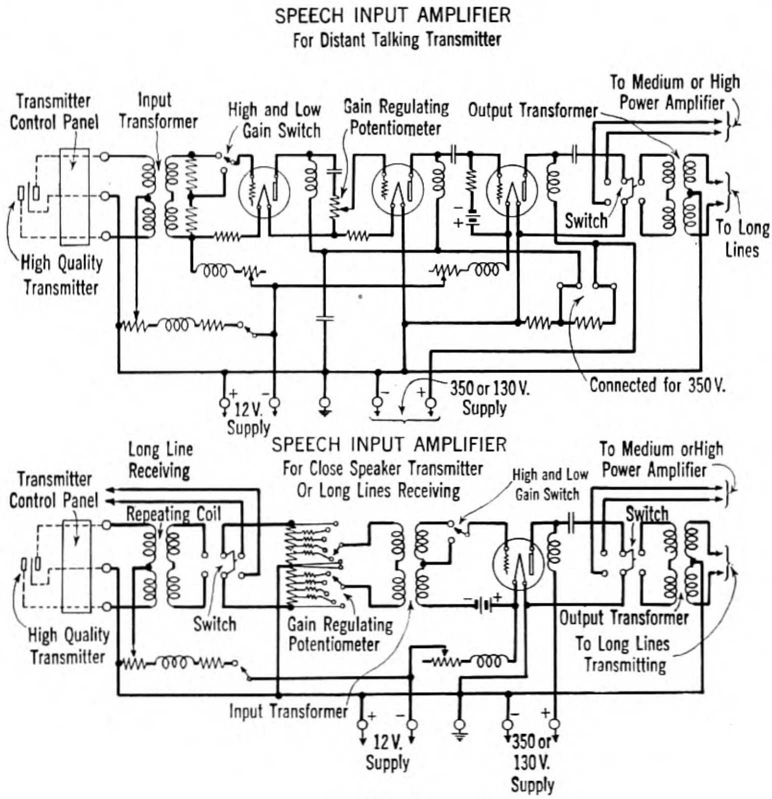

Fig. 8.

tentiometers provide adjustment of the gain over a large range, and switching arrangements allow the output to be connected directly to the input of the power amplifier, when the program is to be transmitted to a local audience; or to be connected, through a transformer of proper impedance, to the long distance lines when the program is to be transmitted to a distant audience, or to a radio-broadcasting station. The filaments of the tubes are supplied from a 12-volt storage battery, while the plate circuits obtain direct current at 350 volts from the power supply equipment mentioned later. Arrangements are also provided for using 130 volts instead of 350 volts under certain conditions. The proper grid potentials are obtained by utilizing the drop over a resistance in the filament circuits of the first two tubes, and for the third tube small dry cells furnish the grid potential. The maximum gain with this amplifier is 85 miles, which expressed as a power ratio is 1.2×10^8. Under this condition the output is approximately 3/10 of a watt. The front and rear views of this amplifier, mounted on the supporting rack, as shown in Fig. 13, where the gain regulating potentiometer, the rheostats for controlling the filament and transmitter currents, the three tube mountings with protective gratings and the jacks which permit the connection of instruments for determining the current flow in the filament, plate and transmitter circuits, will be noted. Great care was taken in the design of this amplifier to obtain as nearly as possible equal amplification of all the important frequencies in the voice range. The transformers, and the retardation coils in the plate circuits were chosen with this consideration in mind.

Power Amplifiers

For practically all of the larger installations the maximum power possible with the system is required and the output from the transmitter-amplifier is taken directly to the high power amplifier. Referring to Fig. 9 it will be seen that this is a four-tube amplifier so connected that but one stage of amplification is obtained. Usually alternating current at 12 to 14 volts is used for heating the filaments of these tubes, the latter being connected in what we know as a push-pull arrangement. It will be seen that each side of the push-pull arrangement consists of two power tubes in multiple. It is interesting to note that this push-pull arrangement of the tubes will deliver somewhat more power for equal quality than the same number of tubes connected in the ordinary multiple arrangement, since the tubes may be worked beyond the straight part of their characteristic. The grid potential is chosen to permit the largest variation of current without distortion and is obtained from a group of small flashlight batteries.

The output transformer at the right of the figure is designed to match accurately the impedance of the tubes to that of the number of receiver-projector units which has been found to give the greatest flexibility under the varying conditions of commercial operation. This amplifier, speaking in telephone terms, is worked at a gain of 23 miles, a power amplification ratio of about 200, the

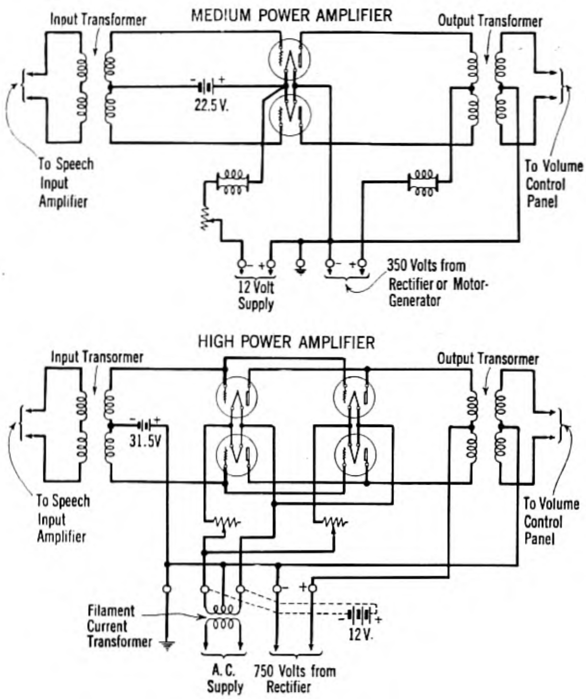

Fig. 9.

maximum output being about 40 watts. The plate circuits of the tubes are supplied at a d-c. potential of 750 volts. As has been pointed out previously, this amplifier gives a practically uniform gain for all the important frequencies in the voice range. This high-power amplifier is shown mounted on the supporting rack, in Fig. 13. The apparatus on the rear of the panel is protected with a sheet metal cover and integral with this cover is a disconnecting switch, which, when the cover is removed, cuts off the high potential from all the exposed parts on the set.

For indoor installations where the audience is small the power output given by the high-power amplifier is not required and a medium-power amplifier has been developed for this use. It is arranged to connect directly to the transmitter amplifier and the output is taken to the projectors through the volume control panel. It has a gain of 17 miles or a power amplification ratio of about 33. The maximum output is about 4 watts, or about one-tenth of the power obtainable from the high-power amplifier.

The schematic of this amplifier, is shown in Fig. 9. The input coil is the same as is used in the high-power amplifier. The push-pull connection of the tubes is also used in this amplifier, although but two power tubes are used. The filaments of these tubes are supplied from a 12-volt storage battery while the plate circuits are supplied at 350 volts direct current from a motor generator set which will be described later.

Speech Input Amplifier—Second Type

A speaker using the system may read his speech from his home or office and in such cases it is unnecessary to use the push-pull carbon transmitter in the distant-talking manner. For use when this transmitter is spoken into from a distance of a few inches, a second form of speech input amplifier has been made available having a gain of the proper value to supply either of the power amplifiers, or a long distance line if desired. This gain is relatively small as the output of the transmitter when used for close talking is about 10,000 times that when it is used for distant talking.

Fig. 8 shows the schematic of this amplifier which is a single-stage one, employing one tube and having the same over-load characteristic as the first form of speech-input amplifier. A two-way switch permits the connection of the transmitter or an incoming long distance line to the amplifier. To the right of this switch is a potentiometer for regulation of the gain. To the right of the tube is a second two-way switch for connecting the output either to the power amplifier or through an output transformer to an outgoing long distance line. The power supply for the tubes and transmitters, is the same as was described under the first form of speech input amplifier.

The switching means provided on this amplifier allow it to be used in a number of ways. Announcements from a close talking transmitter may be made from the projectors through a power amplifier or may be sent out on the telephone lines to a distant public address system installation or a radio-broadcasting station. In addition to these uses, incoming speech over the long distance lines may be put out on the projectors through the power amplifier or may be sent out on the long distance lines to a distant installation.

Volume Control

As discussed heretofore, it is necessary to give the operator control of the volume put out by each projector or group of projectors. The equipment provided for this purpose is mounted on a panel uniform with the others and consists essentially of an auto-transformer connected across the output of the power amplifier with 11 taps multipled to the contacts of eight dial switches, the arrangement being shown schematically in Fig. 10. Seven of the dials control projector circuits on each of which one or more projectors may be grouped, the

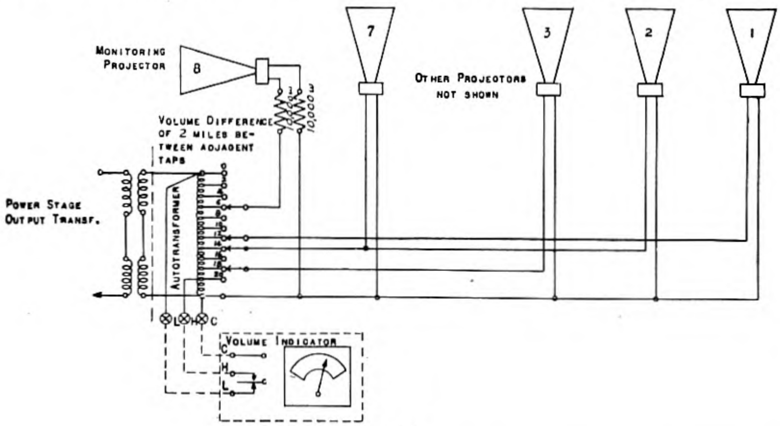

Fig. 10.

eighth dial being reserved for controlling the volume of the operator's monitoring projector in the control room. A key is associated with each dial for opening the circuit and a master key is provided for cutting off all of the projectors simultaneously.

The device shown as "Volume Indicator" in this figure consists of a vacuum tube detector bridged across the output terminals of the power amplifier. The rectified current is taken to a sensitive direct-current meter of the moving coil type, the degree of deflection of this meter measuring the output from the power amplifier when connected at a proper place in the circuit. The deflections of the meter therefore serve as a basis for determining the adjustment required on the transmitter-amplifier to give the required output when switching from one transmitter to another or for different speakers.

Receiver—Projectors

From the control panel the power is taken to the projectors, each of these consisting of a loud-speaking receiver mechanism to transform the speech-currents into sound waves, and a horn to distribute the sound. The receiver is so designed that it will carry several watts

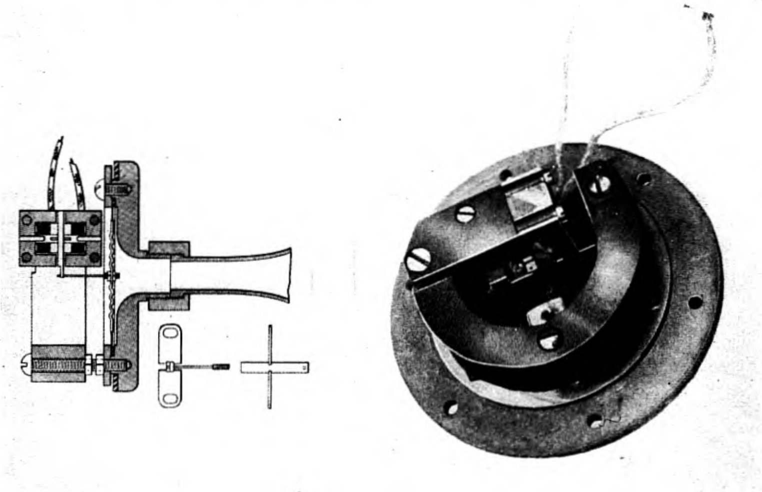

Fig 11.

with small distortion. It is shown in Fig. 11 where it will be seen that a light spring-supported iron armature is mounted between the poles of a permanent magnet and passes through the center of the

Fig. 12.

coils carrying the voice currents. A light connecting link ties one end of this armature to the diaphragm which is of impregnated cloth, corrugated to permit vibrations of large amplitude. A stamped metal cover protects the parts from mechanical injury, and a cast iron case, in which the whole assembly mounts, is provided for protection against moisture.

One of these receivers equipped with the largest projector provided, will carry without serious distortion or overheating, power which is

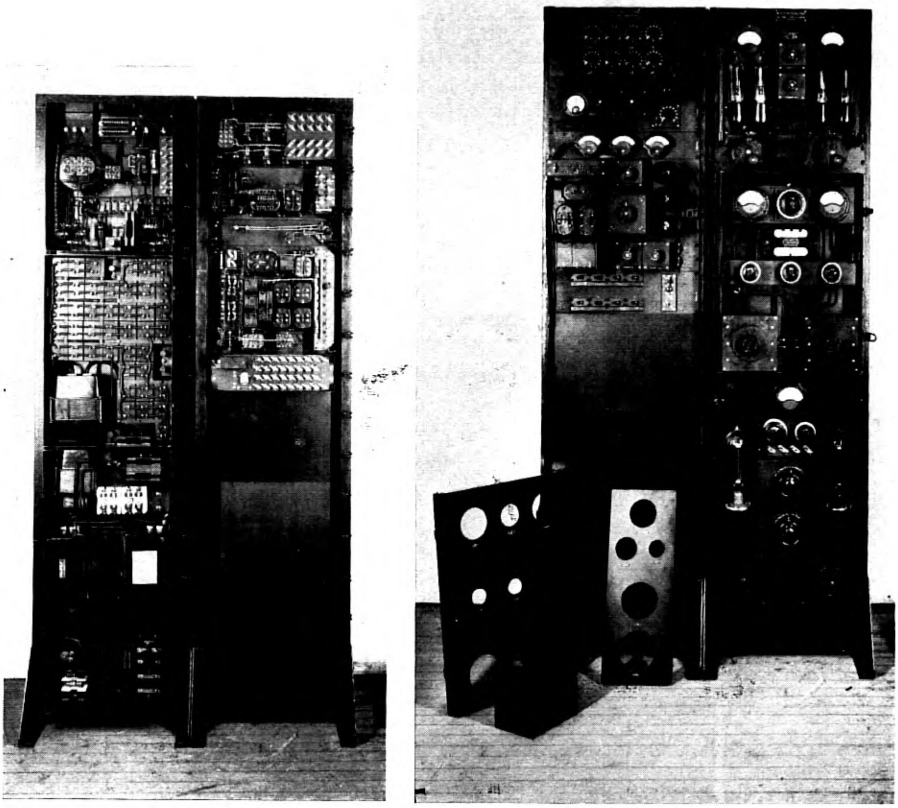

Fig. 13.

about 27 miles above the zero level. With this output, it is possible to project speech a distance of 1000 feet under ordinary weather conditions and this has been done at several installations.

On account of the different conditions encountered in installations three types of horns have been used, shown in Fig. 12. Where it is necessary to project the sound to great distances, a tapering wooden horn is used, of rectangular cross section, 10½ feet long, the walls being stiffened to prevent lateral vibration. For most installations these large horns are not required, and two types of fibre horns are used. One of these is straight in the body, with a flaring open end, while the other used in the control room, is bent.

The grouping of projector units on the volume control switches differs with the type of installation. In outdoor performances, the necessity of correcting the volume in certain directions due to varying winds makes it advisable to group adjacent projectors on a single switch. This is not the case with indoor performances, as no wind effects are possible. Instead, symmetrically placed projectors which will always require equal volume are grouped on a single switch.

Power Supply Equipment

In order to convert the commercial electric power supply to forms suitable for supplying the filament and plate current for the vacuum

Fig. 14a.

tubes in the amplifiers, two types of power equipment have been made available. When the installation is of a size requiring the high-power amplifier, a vacuum tube rectifier taking its supply at 110 or 220 volts, 60 cycles, and delivering 750 volts direct current for the plate circuits is employed. A potentiometer arrangement provides a direct-current supply at 350 volts for the speech-input amplifier tubes. Full wave rectification is obtained and a filter consisting of a large series reactance coil and bridged condensers is used to render the direct-current output suitable for this use. Included in the

Fig. 14b.

power equipment is a step-down transformer for supplying the filaments of the power amplifier. For the larger installations, employing the rectifier, the total power drawn from the commercial supply is 1500 watts.

For installations of a size not requiring the use of the high-power amplifier, a compact motor generator set is provided consisting of a 350-volt d-c. generator driven by a suitable motor, the total power drawn from the supply mains being about 500 watts. A low-voltage generator for supplying direct current at 12 volts for the operation of the amplifier tubes is incorporated in this motor generator set. A filter is necessary and a reactance coil and a 12-volt storage battery is floated across its output. This supplies the transmitters and the tube filaments. The necessary indicating meters are provided on a meter panel for observing the voltages and currents of all the items of equipment which do not have individual meters associated with them.

Observing System

In addition to the monitoring projector provided in the control room for the guidance of the operator, it has been found necessary in all but the simplest installations to provide observing stations at

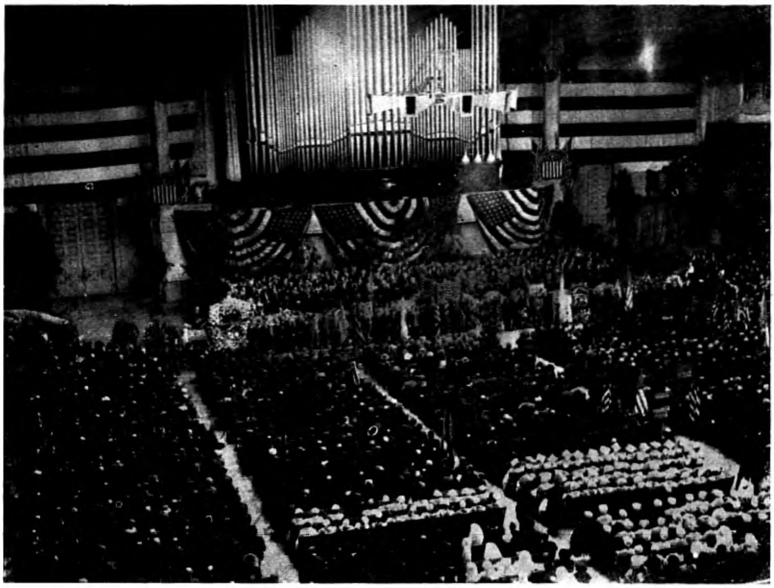

Fig. 15.

various points in the audience. The observers stationed at these points are equipped with portable telephone sets, by which they may immediately communicate with the operator, who is provided with a telephone set consisting of a head receiver and a breast transmitter. The value of these observation stations for regulation of output volume during a program will be apparent.

In the case of an open air performance a variable wind may make it necessary to increase the volume of certain projectors and decrease the volume of others in order to cover the audience uniformly. Without the observers, the control operator would be unable to take care of these changes.

Considerable preparation is required where the equipment is being used for the first time, in order that the performance of the public address system installation will be of the highest order. Where the acoustic conditions are unfavorable it is necessary to make tests with various arrangements of the projectors, in order to determine the

Fig. 16a.

most satisfactory one. It has been found advisable to carry out the entire program previous to the performance in order that the operating force may become familiar with the sequence.

Conclusion

The usefulness of such systems is very well illustrated by a few of the results which have actually been obtained. Fig. 14 shows a crowd of approximately 125,000 people, every one of whom was able to hear clearly and distinctly all of the words spoken in President Harding's inaugural address in March, 1921. This crowd was relatively small, compared with the crowd which could be accommodated by one of the larger type systems. Some insight into the number of people which could be accommodated can be gained from the fact that such a system will cover comfortably a complete circle whose diameter is 2000 feet when the projector units are placed at the center.

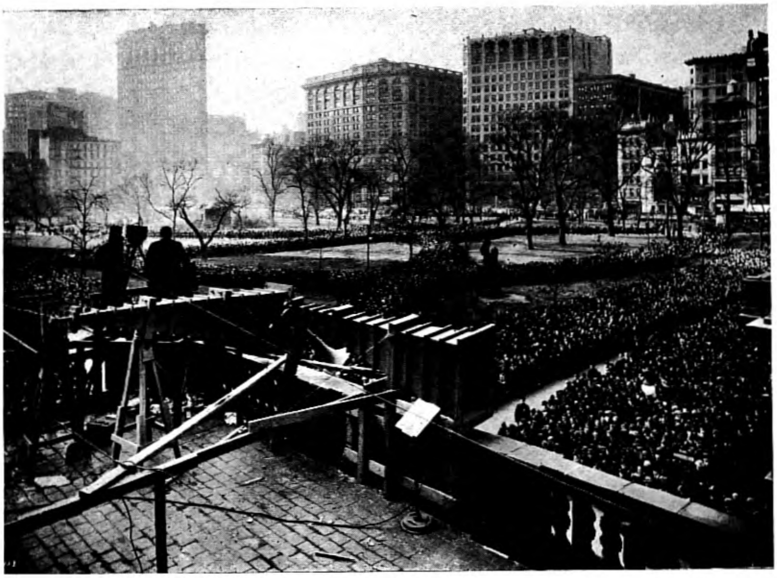

Fig. 16b

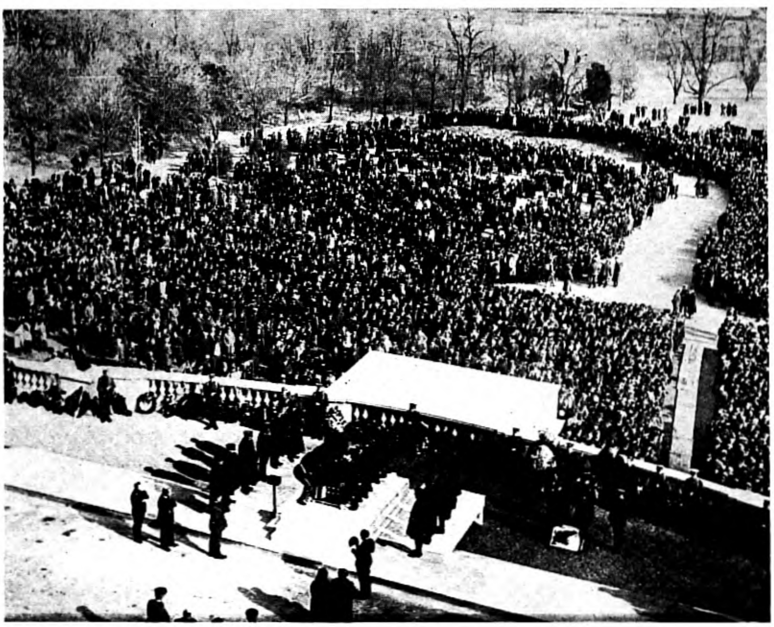

Fig. 17a.

One of the largest and most successful uses to which this equipment has been put took place on Armistice Day in 1921 when 20,000 people in San Francisco, 35,000 people at Madison Square Garden, New York City, and approximately 100,000 people at Arlington Cemetery near Washington joined in the impressive ceremonies which took place at the burial of the Unknown Soldier. Figs. 15, 16 and 17 are views at the three cities, during the ceremonies.

Some of the other uses which have been made of the public address system are the Republican and Democratic Conventions prior to the last presidential election, after-dinner speaking in large ballrooms and in halls where speakers have to address large audiences. There

Fig. 17b.

is one more application of this type of equipment which is gaining rapidly in its use. This last is the application of the speech input equipment to radio broadcasting. The broadcasting of the opera, "Aida," from the Kingsbridge Armory, and of the Philharmonic

Concerts from the Great Hall of the College of the City of New York are two of the successful uses where music and speech were concerned, while broadcasting of the results of the football games from the various distant cities indicates possibilities for the dissemination of interesting information.[9]

The social and economic possibilities of the system are scarcely realized by the public as a whole at the present time, when the method resorted to for reaching large numbers of people is usually the printed word. While this method is effective, it leaves much to be desired in that the personal touch between the man with ideas and the people to receive them is entirely lost. The difficulty for any but those possessing the strongest voices to reach an appreciable number of people at one time has led to a decline in oratory as a means of conveying public messages to large numbers, for it is not always the man with the best ideas or the best ability of presenting them, who is blessed with a powerful voice. A system such as the one which has just been described enables the speaker, even though his voice be relatively weak, to address at one time and in one gathering, several hundred thousand persons, and if the system be used in connection with long distance telephone lines or radio broadcasting, the number which may be reached is increased almost indefinitely. The value of such a situation can hardly be overrated in times of national emergency or stress, when it is necessary for those in responsible positions in the Government to get their message to the people directly.

The development of the apparatus just described has been the result of the efforts of such a large number of investigators working cooperatively that no attempt has been made to acknowledge the individual contributions.

[9] Use of Public Address Systems with Telephone Lines. W. H. Martin and A. B. Clark.

Use of Public Address System with Telephone Lines[1]

By W. H. MARTIN and A. B. CLARK

SYNOPSIS: The combination of the public address system and the telephone lines makes it possible for a speaker to address, simultaneously, audiences located at a number of different places. Such a combination has been used in connection with several public events and a description is given of the system as used on Armistice Day, 1921, when large audiences at Arlington, New York and San Francisco joined in the ceremonies attending the burial of the Unknown Soldier, at the National Cemetery, Arlington, Virginia.

More recently the public address system has been used in conjunction with telephone lines to attain two-way loud-speaker service. This arrangement permits the holding of joint meetings between audiences in two or more locations, separated by perhaps thousands of miles, in such a manner that speakers before each of the audiences can be heard simultaneously by the other audiences. A demonstration of two-way operation was given at the mid-winter convention of the American Institute of Electrical Engineers in February, 1923, and took the form of a joint meeting between 1,000 members in New York and 500 in Chicago.

The electrical characteristics of any telephone line which is to be used in conjunction with loud-speaker equipment must receive special attention. In commercial telephone service the main requirement is understandability, while with the loud-speaker naturalness of reproduced speech is very important. People are accustomed to hearing through the air with very little distortion and naturally expect the same result with loud speakers. A satisfactory line for this purpose must show freedom from transients, echo effects, etc., as well as good uniformity of transmission over the proper frequency range.

The public address system, apparatus and methods has also been applied to radio broadcasting. The combination of the public address system with lines and radio makes it possible for one speaker to address enormous numbers of people located all over the country.—*Editor.*

THE public address system which is described in the preceding paper by I. W. Green and J. P. Maxfield, was developed and first used for the purpose of extending the range of the voice of a speaker addressing an audience. With the aid of this system enormous crowds extending from the speaker's stand to points a thousand feet and more distant have in reality become an audience and have easily understood the speaker whose unaided voice covered only that portion of the crowd within a hundred feet or so from him.

When this system, consisting of a high quality telephone transmitter, distortionless multi-stage vacuum tube amplifiers, powerful loud speaking receivers and projectors, had so shown its capabilities in reproducing speech sounds, a logical extension of its application was to use it with telephone lines. By connecting the transmitting and receiving elements of the public address system through a suitable

[1] Presented at the Midwinter Convention of the A. I. E. E., New York, N. Y., February 14–17, 1923. Published in the *Journal of the A. I. E. E.* for April, 1923.

telephone line a system is provided whereby a speaker can address an audience at a distant point. Also with a complete public address system at the point where the speaker is located, connected by lines to receiving elements of the public address system located at one or more distant points, the speaker is enabled to address a large local audience and to be heard simultaneously by audiences at one or more remote points. This last arrangement was first used on Armistice Day, 1921, when audiences at Arlington, New York and San Francisco joined together in the ceremonies attending the burial of the Unknown Soldier at the National Cemetery at Arlington, Virginia.

By means of the public address system, the meeting of this Institute at New York, at which this paper is presented, is attended and participated in by Institute members at a meeting in Chicago. This is the first occasion on which complete public address systems installed at meetings in two cities have been connected together by telephone lines so that speakers at each meeting address the local and distant audiences simultaneously.

With the transmitting element of the public address system working into the radio transmitter of a broadcasting station and with the receiving elements of the system connected to the output of radio receiving sets, a system is provided whereby a number of people can be reached by each radio receiver.

The combination of these wire and radio communication channels with the elements of the public address system is, therefore, without limit in the number of persons who may be reached simultaneously by one speaker. Such combinations may prove extremely serviceable for occasions of nation-wide interest and importance.

The public address system apparatus has been used not only for transmitting speech sounds but also for music, both vocal and instrumental. The paper[2] describing the public address system has pointed out that the requirements for such a system are that for a wide frequency range it be practically distortionless, that is, transmit and reproduce with equal efficiency all frequencies in that range. This requirement must apply likewise to lines which are used with the loud speaker system. It has been found that a circuit which transmits without material distortion the frequency range from about 400 to 2000 cycles, can be used with the public address system to reproduce speech sounds which are fairly understandable under favorable conditions, although sounding unnatural. In general it is important to extend this range at both ends in order to improve the intelligibility of the sounds and increase the naturalness. For vocal and for some

[2] Green and Maxfield, "Public Address System."

types of instrumental music the melody can be reproduced with the above frequency range, but these tones also are lacking in naturalness. Since some of the musical instruments are used to produce tones three and even four octaves below middle C, it is evident that the proper reproduction of music requires a further extension of the lower limit of the transmitted band than does speech. While the fundamentals of the higher musical tones lie in general in the range mentioned above, it is the harmonics in musical tones which distinguish those produced by different instruments and which give what musicians term "brilliance." The true reproduction of many musical selections requires the distortionless transmission of a frequency band of from about 16 cycles to above 5000 cycles. Many musical selections, however, employ only a part of this range and accordingly can be satisfactorily reproduced by systems not transmitting the whole range. Also, even with slight distortion obtained with somewhat narrower ranges, reproductions may be given which are agreeable to many popular audiences.

Line Requirements

In general the same line requirements which make for satisfactory transmission of speech over commercial telephone circuits also make for satisfactory transmission when telephone circuits are associated with loud speakers. There is this difference however. The loud speakers tend to make the line distortion much more noticeable and serious. Speech transmitted over a particular telephone line is, in general, more difficult to understand when listening to loud speakers than when listening to telephone receivers.

In commercial telephone service the main requirement is intelligibility while, with the loud speaker, the naturalness of the reproduced speech sounds is very important. People are accustomed to hearing transmission through the air with very little distortion and naturally expect the same result with loud speakers.

The above constitute the reasons why, for transmitting voice currents over telephone lines with loud speakers, it is necessary to pay unusual attention to the electrical characteristics of the lines. Evidently when music is to be transmitted, particularly music of a fairly high grade, it is necessary to place even more severe electrical requirements on the lines.

An analysis of what constitutes the electrical requirements of a telephone line which make for good transmission, particularly when loud speakers are employed, will now be given.

In the first place, as explained above, it is essential that a sufficiently broad frequency range be transmitted. As explained in another paper[3] it is not sufficient that a telephone circuit transmit sustained alternating currents within a given frequency range. It must also transmit short pulses of alternating currents within the proper frequency range without introducing oscillations of its own or "transient effects." This requires that loaded circuits for loud speaker use have a high cut-off frequency and hence have the frequencies of the predominant natural oscillations high. It has been found that when the cut-off frequency of loaded circuits is about 5000 cycles, good results are secured with loud speakers.

The two types of telephone circuit which best meet the requirements of transmitting a broad band of frequencies, both when sustained and when applied in short pulses, are non-loaded open-wire lines and extra-light loaded cable circuits. These are suitable for transmission over very long distances. For transmission over short

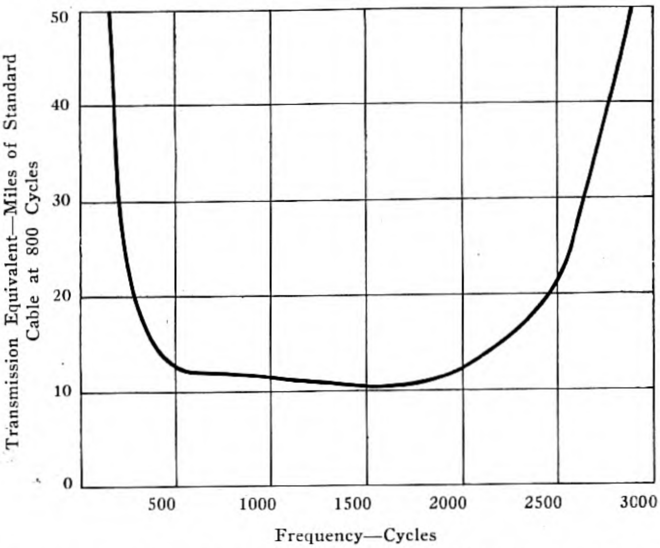

Fig. 1—Transmission Characteristic of Transcontinental Circuit—New York to San Francisco.

distances, say from one point in a city to another point in the same city, non-loaded cable circuits equipped with distortion networks or attenuation equalizers for equalizing the attenuation, give good results.

A good idea of the range of frequencies which can be transmitted

[3] Clark, Telephone Transmission Over Long Cable Circuits, *Journal of A. I. E. E.*, January, 1923. Also Bell System *Technical Journal* for January, 1923.

over high grade telephone circuits can be secured from Fig. 1, which shows the transmission efficiency at different frequencies for the New York-San Francisco circuit. This circuit is a non-loaded No. 8 B. W. G. open wire line equipped with twelve telephone repeaters and is 3400 miles long. Its frequency characteristic meets very well the requirements for easy understanding of voice transmission although it causes some loss of naturalness.

The frequency range which can be transmitted with approximately constant efficiency is limited at the lower end by the fact that composite sets are employed in order to make it possible to superpose direct current telegraph circuits. The elimination of these composite sets would make it possible to improve the transmission of low frequencies and thus improve the operation of the circuit in connection with loud speakers. The resulting improvement, however, would not

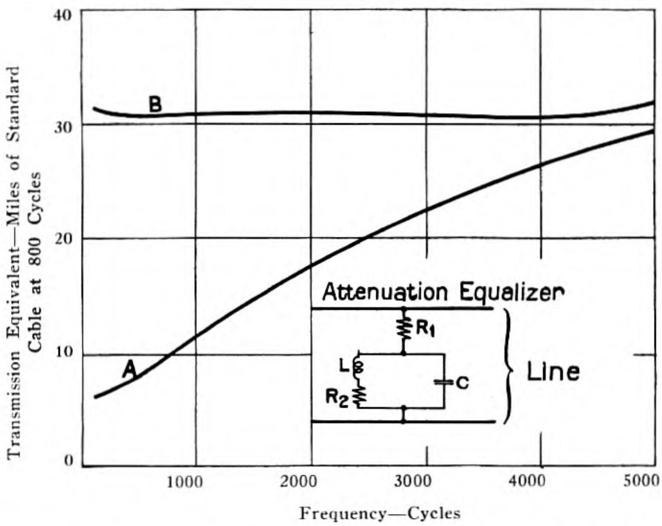

Fig. 2—Transmission Characteristic of No. 19 Gage Non-Loaded Cable Circuit.

A—Without Attenuation Equalizer.
B—With Attenuation Equalizer.

be of importance for commercial telephone service and would render it more difficult to avoid noise on circuits exposed to induction from paralleling power or telegraph circuits.

At high frequencies the range is limited because these same wires are equipped with apparatus to permit super-position of multiplex carrier telegraph circuits above the voice range. This limitation also is not important for commercial telephone service although it is of importance for loud speaker use. To raise the upper limit of the voice transmission range would require giving up some of these facilities.

Fig. 2 will give an idea of how the distortion introduced by a length of non-loaded cable can be corrected by employing distortion networks or attenuation equalizers. This figure shows the transmission frequency characteristic of about 10 miles of non-loaded No. 19 A. W. G. cable. Curve A, in the figure, shows the characteristic when uncorrected, while Curve B shows the characteristic for the circuit when equipped with an attenuation equalizer.

After choosing the proper types of telephone circuits for use in connection with loud speakers, there remains to be considered a number of other important matters.

The maintaining of the telephone power within proper limits at different points in the circuit is very important. The power must not be allowed to become too weak, otherwise the extraneous power induced from paralleling circuits would tend to obliterate the telephone transmission. On the other hand, the telephone power must not be amplified to such an extent that the telephone repeaters will be overloaded or severe cross talk be induced into paralleling circuits.

To keep the telephone power throughout the circuit between the above limits, requires careful study and adjustment. For handling regular telephone connections, the circuits are laid out and equipped with repeaters at proper points so that each circuit will be able to handle the varying volumes applied at the terminals when different subscribers are connected without getting into serious difficulties. When loud speakers are employed it is necessary to maintain the volume at the terminals of the toll lines at least within these limits and it is preferable to do somewhat better than this.

With the public address system, the high quality transmitter which picks up the sound at the sending end is usually associated with an amplifier whose adjustment is varied, depending on the output of voice currents from the transmitter. In order to obtain the proper adjustment of this amplifier, it is necessary to have some means for quickly indicating the volume of transmission. For this purpose, there has been developed a device which is called a "volume indicator." This consists of an amplifier detector working into a direct-current meter. With this volume indicator connected across the output of the transmitter amplifier, the volume of transmission delivered to the line is indicated by the deflections on the meter. By adjusting the amplifier, therefore, to keep the deflections of this meter reasonably constant at some deflection determined by previous calibration, it is practicable to keep the telephone power within the required limits. Obviously, this same device may also be employed to keep the telephone power constant at any other point in the system.

While the necessity for keeping the power applied to the toll lines within proper limits cannot be over-emphasized, it should also be noted that this is not sufficient. It is also essential that all parts of the toll circuit, including the repeaters, be maintained at prescribed efficiency so that the power levels at all intermediate points in the circuit will also be kept within proper limits. Long telephone lines are designed with special emphasis on this matter of constant efficiency so that, in general, no special precautions are required when using these circuits in connection with loud speakers.

In another paper, [4]the "echo" effects which may occur on long telephone circuits are explained. When setting up two-way circuits for loud speaker use, it is necessary to pay particular attention to effects of this sort. Furthermore, there is another source tending to produce echoes in circuits arranged for two-way use with loud speakers. This is the tendency for the sound delivered from the loud speaker projectors to enter the sensitive transmitter and be returned to the distant end of the circuit as an echo. Owing to the relatively slow velocity of transmission of sound through air the lag in such an echo may be great enough to be serious, although the line is a short one with high transmission velocity. It is, therefore, evident that this coupling through the air between the loud speaker projector and the transmitter must be kept small. If a very sensitive transmitter arranged so that a speaker may stand several feet away from it is employed, this problem becomes even more difficult.

There is one thing more that remains to be considered: the necessity for special operation. When a large number of people are assembled at some point to hear an address delivered at a distant point, it is evident that delay in establishing the connections cannot be tolerated. It is, therefore, necessary to establish such connections ahead of time and it is usually also necessary to set up spare circuits for use in case of failure of the regular circuits. A special operating force is required for checking up the circuits, establishing the connections when required, and making the necessary adjustments. Rehearsals are necessary on important occasions to insure proper functioning of the circuits and proper co-ordination of the handling of the circuits with the programs at different points.

[4] Clark, *loc. cit.*

Typical Circuit Combinations of Public Address System and Lines

Following are a number of typical combinations of the public address system and telephone lines. The combinations by means of which one-way service may be rendered, are given first, following which certain combinations for giving two-way service are discussed.

By one-way service is meant service in which no provision is made for anyone in the distant audience to talk to the place where the speaker is located. Two-way service provides for speakers at either of two or more points addressing all of the other points. This is similar to the two-way service rendered by regular telephone circuits.

Fig. 3 shows the circuit arrangement which would be used when a speaker at one point in a city, for example, at his office, is to address

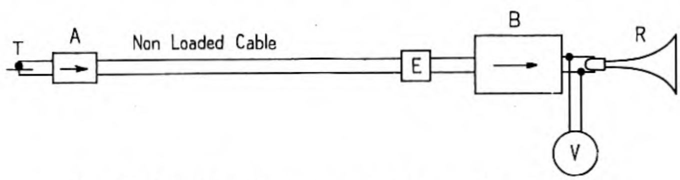

Fig. 3—One-Way Connection to Point in Same City.

an audience at another point in the same city. A high quality close talking transmitter T, together with a fixed gain single-stage amplifier A, are provided at the point where the speaker is located. This combination is designed to deliver to the line the same amount of power as a commercial type substation set. Connecting this point with the point at which the audience is gathered is a non-loaded cable circuit. To correct for the distortion in this cable circuit, an attenuation equalizer E is provided. The apparatus at the point where the audience is located is the equipment of the public address system without the transmitter and its associated amplifier. In Fig. 3, B is the amplifier for delivering sufficient power to the group of loud speaker projectors indicated by R. A volume indicator V associated with the amplifier B is used in maintaining constant the volume of sound delivered from the projectors.

Fig. 4 shows the circuit combination required when a connection is to be established to a distant city where the loud speaking receivers are located. In the city where the speaker is located, connection is made to the toll office by means of a non-loaded cable circuit equipped with an equalizer similar to Fig. 3. A volume indicator V_1 is associated with the amplifier C_1 at the toll office to enable proper adjustment of amplifier C_1 to be made so that the power delivered to the toll line will be within the proper limits. As explained above if the volume at the toll office is allowed to become too great, the telephone repeaters on the toll line will be over-loaded and serious distortion will result, while if the volume is allowed to become too weak, extraneous noise

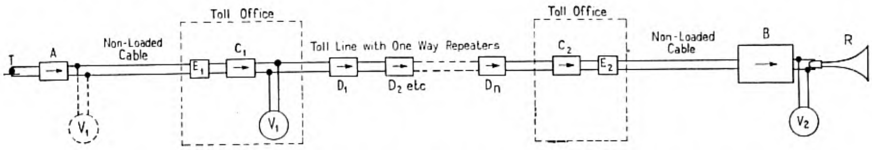

Fig. 4—One-Way Connection to Point in Distant City.

and crosstalk will tend to obliterate the direct transmission. If a distant talking transmitter is used for the speaker, a multi-stage adjustable amplifier is associated with it. In this case the volume indicator is located at the output of this amplifier as shown by the dotted lines in Fig. 4. When the volume indicator is employed at this point it is necessary to take into account the loss introduced by the non-loaded cable and the equalizer E_1, together with the gain of the repeater C_1, in order to deliver volume within proper limits to the toll line. The toll line, shown equipped with repeaters D_1, D_2, etc.,

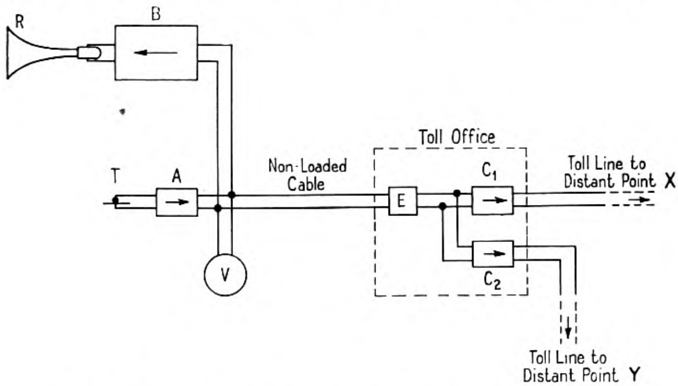

Fig. 5—One-Way Connection for Addressing Local and Distant Audiences Simultaneously.

extends to the toll office in the distant city. At this point the amplifier C_2 is located, together with another equalizer E_2, for correcting the distortion in the local non-loaded cable circuit. The apparatus at the point where the audience is located is similar to that shown in Fig. 3.

Fig. 5 shows the circuit combination employed when a local address is to be given, while at the same time the same address is delivered to one or more distant points. In order to allow the local audience to hear the address by means of the loud speakers, the power amplifier B supplying energy to these is bridged across the output of the amplifier A associated with the transmitter T. A volume indicator V, connected across the circuit at the point where the bridge is made, makes it possible to maintain constant volume both for the local loud speakers and for the transmission applied to the toll lines by suitable adjustment of amplifier A. At the toll office means are indicated for connection to two distant points X and Y. Owing to the fact that amplifiers C_1 and C_2 are one-way devices, no inter-actions can occur between lines X and Y or between these lines and the local loud speaking system. The arrangements for reaching the distant points X and Y are similar to the one illustrated in Fig. 4.

All of the circuit arrangements which have so far been described are arranged simply so that a speaker may address one or more local or distant points. When it is desired that the speaker and the audience at the sending end also be able to hear a speaker at the distant point, more complicated arrangements are required.

Fig. 6 shows a circuit arranged for such two-way service, the line being operated on the four-wire principle, *i. e.*, two separate transmis-

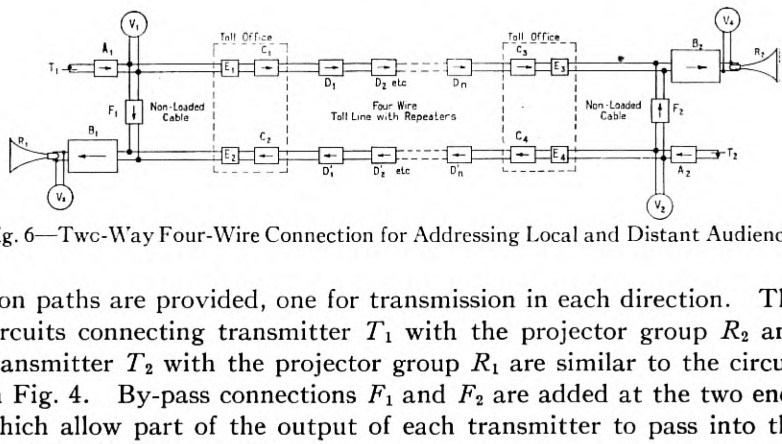

Fig. 6—Twc-Way Four-Wire Connection for Addressing Local and Distant Audiences

sion paths are provided, one for transmission in each direction. The circuits connecting transmitter T_1 with the projector group R_2 and transmitter T_2 with the projector group R_1 are similar to the circuit in Fig. 4. By-pass connections F_1 and F_2 are added at the two ends which allow part of the output of each transmitter to pass into the local loud speakers. These by-pass connections are so arranged that transmission can pass only in the proper direction. Two volume indicators are provided at each end. Referring to the left-hand terminal, volume indicator V_1 is provided to insure that power is supplied to the toll line within the proper limits of volume, as explained above.

V_3 is provided to facilitate adjustment of the by-pass circuit F_1 and of amplifier B_1 so as to deliver proper volume from R_1 both for the local talking and for the reception of the addresses from the distant end of the circuit. The volume indicators V_2 and V_4 at the right-

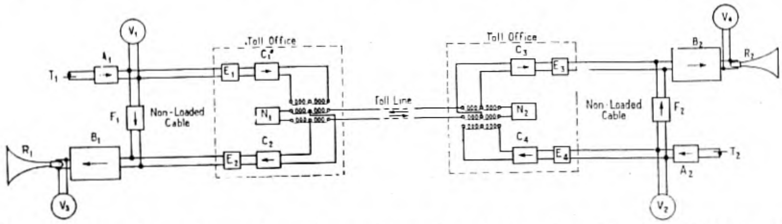

Fig. 7—Two-Way Two-Wire Connection for Addressing Local and Distant Audiences.

hand end of the circuit have functions similar to those of V_1 and V_3 respectively.

Fig. 7 is similar to Fig. 6 with the exception that the toll line is of the two-wire type. At each end of the toll line, which may, or may

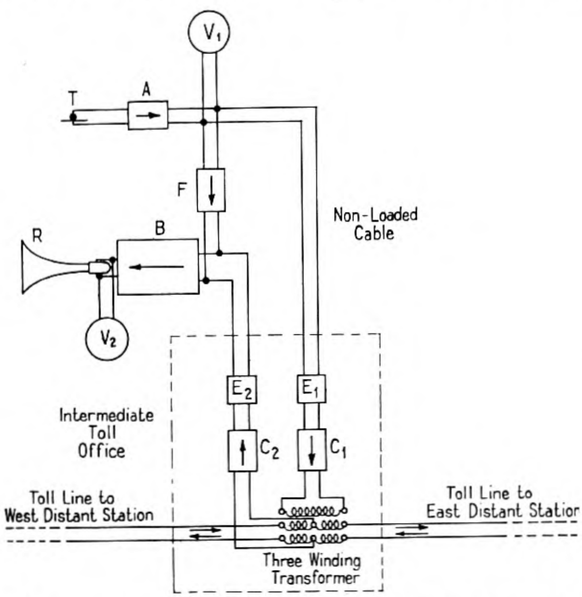

Fig. 8—Arrangement for Connecting Third Point to Circuit of Fig. 7.

not, contain two-way repeaters, transformers and networks N_1 and N_2 are placed for converting the two-wire circuit into a four-wire circuit. The equalized cable circuits at the two ends thus form two sides of short four-wire circuits. The conditions of balance between the networks and the toll lines prevent more than a very small amount of the direct transmission from each local transmitter from entering the local loud speading receiver circuit at the points where the local circuits connect to the toll line. Practically all of the transmission from transmitter T_1 to projector group R_1 and from transmitter T_2 to projector group R_2 is delivered through the adjustable by-pass circuits F_1 and F_2, respectively.

For connections requiring to and fro conversations between three or more points, all of which may be equipped with loud speakers, intermediate points may be connected to a two-wire telephone circuit by employing the arrangement shown in Fig. 8. A three-winding transformer is inserted in the toll line which is so constructed that the impedance which it introduces into the circuit is small enough to avoid a serious irregularity. Talking currents are put out on the toll line through this transformer. The received transmission is obtained from a high impedance bridge across the midpoints of two of the windings of the three-winding transformer. Amplifiers C_1 and C_2 introduce sufficient gain to overcome the losses due to the inefficient coupling with the telephone line. The rest of the circuit at the intermediate point is the same as Figs. 6 and 7, the local speaker being heard by his own audience by means of transmission delivered through by-pass F. A modification of the arrangement of Fig. 8 can, of course, be used with a four-wire toll circuit.

Arrangements for Armistice Day, 1921

Fig. 9 shows the circuit which was employed on Armistice Day, 1921, when audiences of 100,000 people at Arlington, 35,000 people at New York and 20,000 people at San Francisco, joined in the services at the burial of the Unknown Soldier. This was the first time that audiences at more than one distant point were simultaneously addressed from one point by means of the public address system.

At Arlington three different transmitters T_2, T_3 and T_4 were used for the different parts of the ceremonies. T_2 was used for the musical selections, T_3 for the speeches made in the amphitheatre, and T_4 for the speeches at the grave of the Unknown Soldier. Another transmitter T_1 was provided for the use of an announcer who kept the audiences at New York and San Francisco advised of the proceedings. The speech currents leaving these transmitters were brought up to moderate volume by means of amplifiers A_2 and A_1, the former taking care in turn of the three different transmitters employed during the ceremonies.

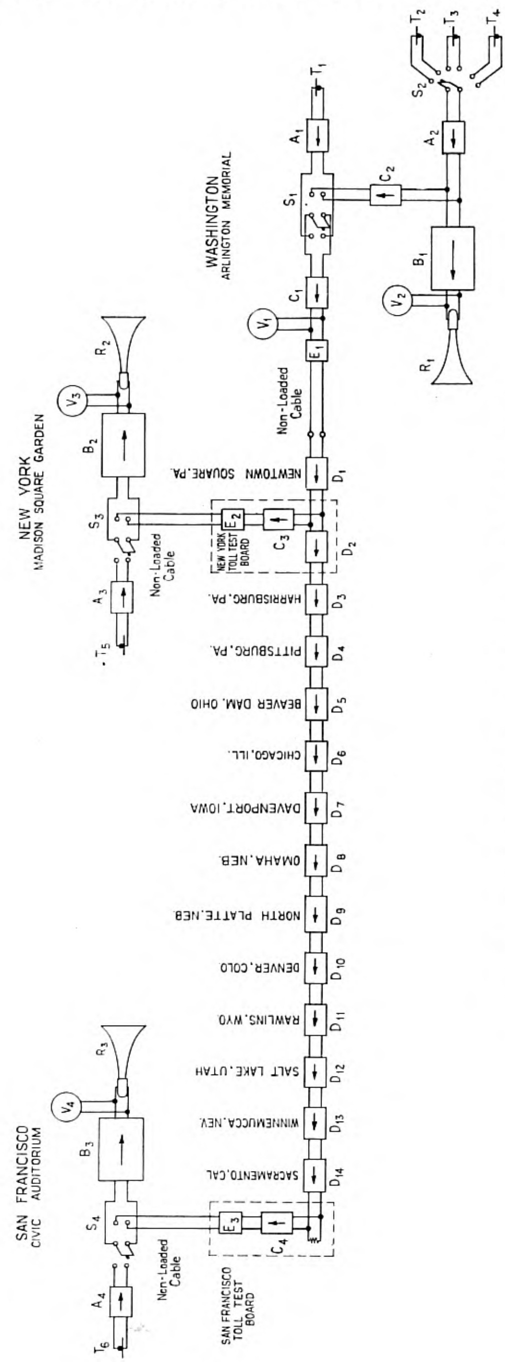

Fig. 9—Circuit Used for Ceremonies on Armistice Day, 1921.

The voice currents from the transmitters which were employed for the ceremonies, after passing through amplifier A_2, separated into two branches, one branch going to the local amplifier B_1, which supplied the local loud speakers R_1, the other going to the telephone circuit through amplifier C_2, switch S_1 and amplifier C_1. The switch S_1 was provided for connecting either the announcing transmitter T_1 or one of the transmitters for picking up the ceremonies to the end of the toll line. V_1 and V_2 are volume indicators, V_1 being employed to indicate that the proper power was being put into the toll line, while V_2 furnished an indication of the volume which was being delivered by the projector group R_1. During the ceremonies the amplifier C_2 was continuously adjusted so as to deliver proper volume to the long distance telephone circuit, the volume indicator V_1 making it possible to keep the volume applied to the toll line within close limits. At the same time independent adjustments were made of the amplifier B_1 to take care of the varying conditions introduced by the different talking conditions as well as the varying conditions introduced by shifting of the crowds listening to the ceremonies.

After leaving the amplifier C_1 at Arlington, the voice currents first passed through a non-loaded section of cable whose distortion was corrected by equalizer E_1. A non-loaded 8-gauge open-wire circuit carried the voice currents to New York City. At this point, the circuit again branched, one branch delivering a part of the voice currents to the apparatus at Madison Square Garden, the other branch going to San Francisco over one of the non-loaded No. 8-gauge transcontinental circuits. The arrangements employed at Madison Square Garden and at the Civic Auditorium in San Francisco were similar, switches being provided at each point to connect to the projector groups the circuit from Arlington or from the local transmitter.

The difficulties involved in transmitting voice currents for the first time to loud speaker installations at distant points, as well as the great importance of the occasion, made it necessary to take elaborate precautions in order to insure the success of the undertaking. The long distance telephone circuits were carefully inspected ahead of time and all of the amplifiers and other apparatus employed were subjected to numerous careful tests. For checking the complete circuit, alternating currents of different frequency were applied at Arlington and measured simultaneously at New York and San Francisco. The curve on Fig. 1 was obtained from the results of one of the measurements made on this occasion.

To guard against possibility of failure of the circuits, emergency circuits were provided, these emergency circuits taking different routes wherever possible. Fig. 10 shows the network of long distance circuits which was set up for this occasion. The solid lines in this figure indicate telephone circuits while the broken lines indicate telegraph circuits. The latter were for the purpose of transmitting orders

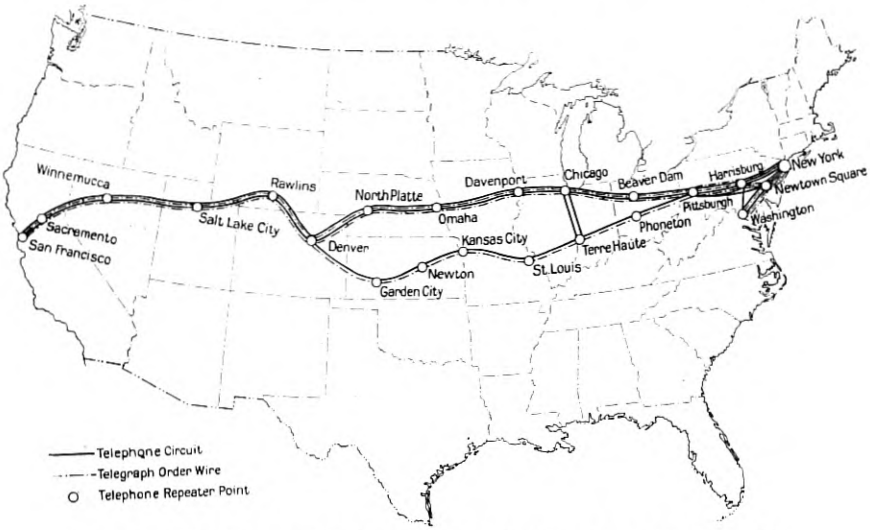

Fig. 10—Telephone and Telegraph Lines Used on Armistice Day, 1921

between different units of the operating organization at different points.

At Arlington the nature of the ceremonies and the place in which they were held presented many difficulties from the acoustic standpoint. The main addresses were made in an open amphitheatre sursounded by a double colonnade of marble. The platform on which the speakers were located was partially covered by a marble arch. The floor of the amphitheatre is of cement on which are arranged marble benches. Temporary seats also were placed on top of the colonnade. During the ceremonies large crowds surrounded the amphitheatre on all sides. The arrangement of the amphitheatre and the surroundings is shown by Fig. 11.

In order that the crowds outside of the amphitheatre might hear the speakers, loud speaking receivers and their associated projectors were placed on top of the colonnade. They were arranged in four groups as shown on Fig. 11, the projectors referred to, being numbered from 1 to 21 inclusive. Those in the east group were on top of the structure forming the main entrance to the amphitheatre. The projectors were carefully directed to cover uniformly the area around the amphitheatre and were supplied with sufficient power so that the speaker could be heard for at least a thousand feet from the outside of the amphitheatre. It was found, however, that while these projectors are highly directive, some of the sound from them could be heard inside the amphitheatre. This sound leakage at the western side was particularly serious because of the fact that it reached the rear seats inside of the amphitheatre sufficiently far enough ahead of the corresponding sounds directly from the speaker to be noticeable.

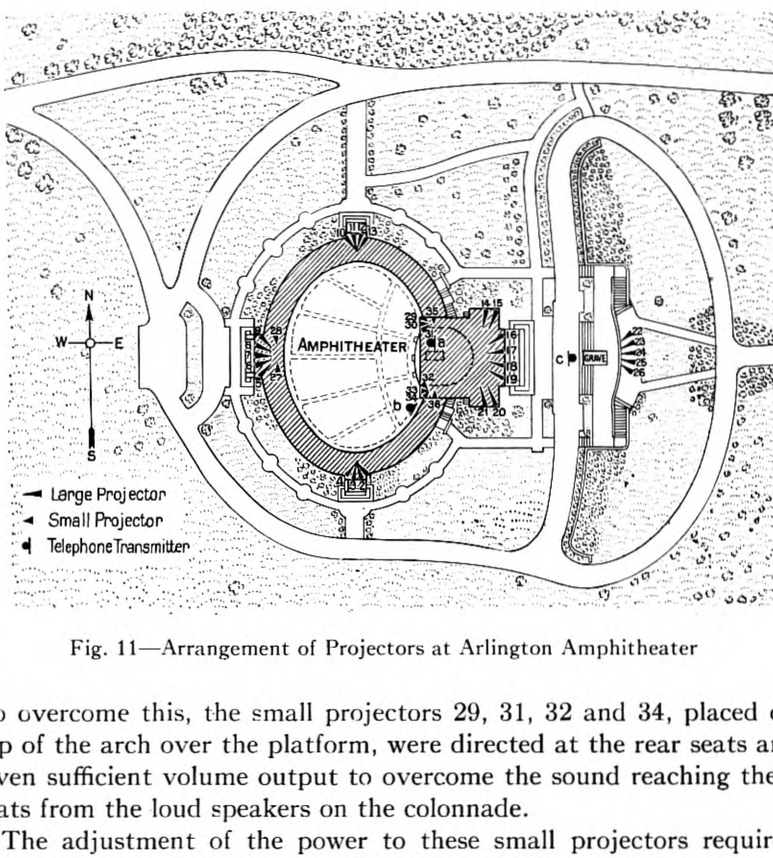

Fig. 11—Arrangement of Projectors at Arlington Amphitheater

To overcome this, the small projectors 29, 31, 32 and 34, placed on top of the arch over the platform, were directed at the rear seats and given sufficient volume output to overcome the sound reaching these seats from the loud speakers on the colonnade.

The adjustment of the power to these small projectors required great care because if given too great volume, bad reflections would be set up in the amphitheatre. On the other hand if this volume were not great enough, the outside projectors would cause serious interference. The small projectors 27 and 28 were used to overcome the sound leakage effects on the top of the west side of the colonnade.

The projectors 35 and 36 covered the top of the colonnade on the east side.

Fig. 11 shows also the location of the three transmitters used during the ceremonies, *a*, on the platform for the speakers, *b*, in front of one of the boxes in which were placed the singers and behind which was located the band, and *c*, at the grave. When the transmitter at the grave was tested it was found that serious interference was obtained between the speaker's voice and the sound from the projectors 16 to 19 inclusive. For the ceremonies at the grave, therefore, these loud speakers were disconnected and those numbered 22 to 26 used instead. Also in order to properly cover the inside of the amphitheatre during the ceremonies at the grave, the small projectors 30 and 33 were used. These were located on the arch over the platform and were directed at the front seats in the amphitheatre.

The projectors were divided up into a number of small groups and so connected that the volume of sound delivered by each group could be varied without affecting the other groups. This was necessary in arriving at the power to be delivered by each projector to give uniform distribution and to avoid interference between different groups.

By means of these arrangements all parts of the ceremonies were carried to all parts of the audience at the National Cemetery and were also delivered by means of the lines to the audiences in the distant cities.

At New York, a group of fifteen loud speakers was used in Madison Square Garden to satisfactorily reach all parts of the audience and a group of twenty-one loud speakers was suspended outside the building for the outside audience. At San Francisco, ten loud speakers were used in the Civic Auditorium and seven outside.

Use of Public Address System Apparatus with Radio

When radio broadcasting came into general use, the apparatus and methods which had been developed for the public address system were applied to this new field as it also demands high quality reproduction for speech and music. The transmitters and amplifiers associated with them in the public address system are used in radio broadcasting studios for delivering speech frequency electrical power to the radio transmitter. Loud speaking receivers and amplifiers for delivering sufficient power to operate them are used with many of the radio receiving sets.

The methods which have been employed to connect public address system transmitters with toll lines are being used for the broadcasting by radio of speeches and music given at points remote from the radio station. In such cases the transmitter and its associated amplifier are operated and controlled in the same way as described above for toll lines. In some cases the radio station is in the same city as the place where the speech or music is given and in other cases the two have been in different cities. In the first case the output of the transmitter amplifier is carried to the radio station over non-loaded cable circuits which are equalized by means of distortion correction networks to have uniform efficiency over a wide frequency range, in some cases up to 5000 cycles. Where the two points are in different cities, the non-loaded cable circuit goes to the toll office and there is connected to the toll lines which are operated in the same manner as described above for loud speaker use.

For some of the higher grade music, such as that given by symphony orchestras, the less efficient, but slightly higher quality condenser type transmitter has been used instead of the double button carbon type. This requires the use of an additional two stage amplifier in front of the regular three stage transmitter amplifier.

The output of the transmitter amplifiers is controlled with the aid of a volume indicator bridged across the output terminals of the amplifier. For best results, particularly in reproducing music, it is necessary to adjust the gain of these amplifiers to compensate partially for the large range in the volume of the music. If the amplifiers are set high enough in gain to send through the low passages of the music with sufficient volume so that it will override the static and the interference from other sending stations, the loud parts of the music will seriously overload the radio transmitter system, unless it is of very large capacity, and will in general overload the receiving sets. Furthermore putting out these loud parts at the same relative level with respect to the low passages as they are given by the orchestra, makes the interference between radio stations more serious. In some orchestral concerts the power amplification of the transmitter amplifier has been adjusted over a range of more than a hundred to one, these changes being made, however, so that they were not noticed by those listening to the concert by radio.

Proper volume control is very important in picking up such music for radio broadcasting. The lack of such control is responsible for many of the poor results that are being obtained. In this connection, the location of the transmitter with respect to the various instruments in the orchestra or smaller combination of instruments, so as to maintain in the reproduced music the proper balance between the several parts is, of course, of great importance.

An interesting illustration of the combination of the public address system, telephone lines and radio broadcasting was used in connection with reporting a football game played in Chicago in the fall of 1922. By means of high quality transmitters and amplifiers located at the football field, announcements of the plays and the applause of the spectators were delivered to a circuit extending to the toll office in Chicago. This circuit was connected there to a toll line to New York where it delivered the telephonic currents to a radio broadcasting transmitter. In Park Row, in New York City, was located a truck on which was mounted a radio receiving set arranged to operate a public address system. By this means the reports of the plays of the football game in Chicago were delivered to a large crowd in the streets of New York.

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