The Principles of Electric Circuits Applied to Communication[1]

By H. S. OSBORNE

Synopsis: This paper discusses the method of presenting in the curricula of engineering schools the fundamental electrical principles, emphasizing the desirability of presenting them as far as practical in a general way and of making clear the relations of specific applications, such as the relation between circuit theory equations as applied to power systems and to telephone systems, and the relation between ordinary circuit theory and the generalized electromagnetic equations. An outline is given of some interesting problems arising and results obtained in the application of electric principles to telephone systems.

ENGINEERING education shares with other forms of education the general movement toward greater emphasis on the unity of subject matter which plays such an important part in the development of modern educational methods. By the unity of subject matter I refer to the aim to reduce as far as practicable the number of separate compartments in which the educational subject matter is kept, and to present this subject matter under a smaller number of broader headings. Whereas the curriculum must be divided into a certain number of different courses for administrative and practical reasons, I take it the modern educational method is opposed to the presentation of these courses as individual entities, separated from other subjects, but insists rather that the curricular partitions be kept as low as possible so that the student may appreciate as fully as possible the continuity of each subject with its neighbors, and may obtain a good perspective of the close mutual relations of the different parts of the educational material and realize their mutual dependence and the large areas in which they are jointly applicable.

The wisdom of this move is evident to men in the industries as well as to educators. The tremendously rapid growth of fundamental electrical science and of the electrical industries have both worked rapidly in this direction. The time has long passed when it was at all possible to cover both fundamental electrical science and its applications in a four year engineering course. I judge that the old question "Is it more important to teach the fundamentals of electrical science

---

[1] Presented at Pittsburgh July 18, 1928, at the Summer School for Electrical Engineering Teachers under the auspices of the Society for the Promotion of Engineering Education.

The author expresses his appreciation of the assistance given him by Mr. C. O. Gibbon, American Telephone and Telegraph Company, in the preparation of this paper.

or their application?" is no longer even discussible, as far as the engineering school is concerned. Applications must indeed be learned by the student, but this can best be done after graduation, with the help of the industry employing him, and under the stimulus of the necessity of learning his job and preparing himself for greater usefulness in the organization. The question before the colleges is not "Shall we teach fundamentals?" but "What fundamentals shall we teach, and how can these most effectively be presented? How much of the fundamentals of our present far flung electrical science can we convey to the students in a four year course?"

The same question naturally presents itself in this discussion. The communication field, from the nature of the problems which it presents, has a great wealth of material relating to the principles of electric circuits, both as regards the practical application of these principles and research extending our fundamental knowledge of these principles. What phases of this subject matter should be presented here? In this Mr. Hammond's circular to the members of the summer school staffs is a guide. He points out that among the various purposes of the summer schools the principal aim is to produce tangible results for improving methods of teaching. I do not understand that I am expected, in talking with a group of educators, to discuss teaching methods directly, and will not presume to do so. However, in response to your invitation to discuss "The Principles of Electric Circuits Applied to Communication" I shall refer to the use in the communication field of those principles within the scope of student work which appear to have the broadest general application, including all fields of electrical engineering. Also, it will no doubt be of interest for us to give some consideration to the relative conditions, including similarities and differences, of application of these principles to communication problems and to other branches of the electrical industries.

Limiting the discussion in this way necessarily results in leaving untouched many phases of the application of electrical principles to communication which are of great interest but of less application in other fields, and so I have left out such important matters as, for example, modulation and demodulation, the balancing of line impedance characteristics by artificial lines, inductive effects between different circuits, and the performance characteristics of various types of apparatus.

Also, of course, this will in no sense be a general discussion of the work of the transmission engineers of the telephone companies. While their work is based on the application of electrical principles, and requires that they understand those principles, the theoretical work which they do on electric circuits is, with the exception of a few men, relatively small, and their work is also very largely based on the use of economic principles, knowledge of the telephone system, general business principles and common sense.

GENERAL PRINCIPLES

Communication circuits in general are very complicated networks and the application of electric principles to these networks involves the solution of numerous new problems and the development of a great many practical approximations. To be effective in this work it is of prime importance that the young engineer have a good grounding in the general fundamental principles of direct and alternating current theory. By a good grounding we mean an appreciation of the generality of these principles so that they can be applied by the student to the problems of his particular work, no matter in what branch of electrical engineering that work may be. He needs also to have a facility in their application to new problems. The relations of resistance, reactance, conductance and susceptance, the use of Kirchhoff's laws, the relations of resonance and conditions for maximum transfer of energy between two branches of a network—all these we would list as a matter of course. We should include also in the list of basic fundamentals some simple but extremely useful practical theorems, including the reciprocity theorem and Pollard's or Thevenin's theorem.

Along with these fundamental principles we believe it helpful to a man in any branch of electrical work to have absorbed the idea of the equivalence of networks of different types; for example, the expression, in terms of equivalent T or Pi circuits or other convenient form of the characteristics of any 4 pole network (that is, a network with two input and two output terminals) from the measurements which can be made at its terminals. Fundamental training of this sort gives the man a mastery in the solution of electrical problems, not only through ability to place a given problem in its most convenient form, but by assisting the engineer in the formation of correct and simple physical ideas regarding the processes which are taking place.

A very good illustration of this point is given by the transformer. Most young men graduating from engineering schools, I believe, think of the operation of the transformer in terms of its vector diagram. This is a valuable way of getting a physical picture of the effect of a transformer which is useful in certain types of problems but less convenient in others. If in addition to the vector diagram the student is taught the equivalent network of a transformer, as is done in some texts, he can more easily apply it to other types of problems, and the equivalent T network of the transformer is so simple that it is very helpful in showing the variation in the performance of the circuit with changes in the constants of any part of the circuit.

Familiarity with the fundamental principles of networks and equivalent circuits is particularly helpful in case of a man who comes in contact with problems associated with networks made up of a number of similar sections, as for example, electric filters, which already play such an important part in certain branches of the communication art.

In the study of fundamental principles it would appear to be very helpful in enabling the student to get an appreciation of their generality if the specific problems and illustrations used in his work are drawn from the various fields of electric work rather than from a single field. The communication field is replete with specific problems illustrating these principles which are very suitable for the use of the student.

TRANSMISSION LINE THEORY

In discussing the application of the principles of electric circuits to communication it is natural to give particular attention to transmission line theory because of its importance in connection with the transmission of electrical energy for any purpose whatever, including both power and communication services, and because of the interest of the problems it involves. Transmission line theory in one sense dates back to Lord Kelvin who in 1855 applied laws of diffusion of heat to the determination of the flow of electricity through long submarine cables. This solution ignored the effect of line inductance which was unimportant in the particular problem to which Lord Kelvin applied this solution, but which is very important in any general transmission line theory. Through the work of Heaviside and others the general transmission line theory was at an early date applied to telephony. It is, of course, in relatively recent years that the great development of long distance power transmission lines has made the general theory of value in power transmission work, the performance of early alternating current systems being adequately represented by approximate formulas, entirely neglecting the effect of the capacity of the line. It is indeed not long ago that the effect of line capacity, assumed lumped at one or two points, became important and still more recently that it became necessary in power problems to take more accurate account of the distribution of the capacity.

It is no doubt partly as a result of the historical development of the application of transmission line theory to telephony and to power transmission problems, and partly the result of differences in conditions which the solution must meet in the two fields of application that it seems in the past not always to have been made clear to students that the power line equations and the telephone line equations are simply special solutions of the same general line formula.

To illustrate this point it is desirable to refer to a few well-known equations. The differential equations for what may be called the classical transmission line theory are given in equation 1. Equation 2 is a solution of these differential equations for the steady state, for the circuit indicated in Fig. 1.

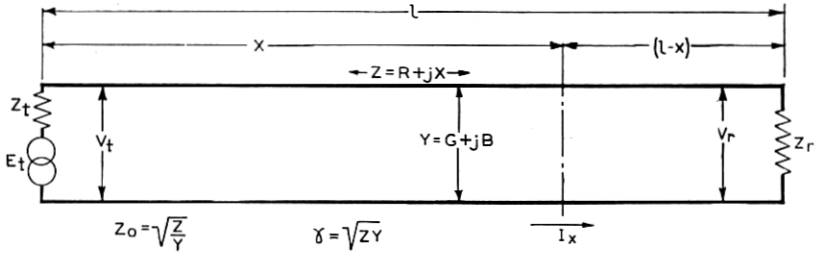


Fig. 1

$$\left.\begin{aligned} \left(L\frac{d}{dt}+R\right) I &= -\frac{\partial}{\partial x} V, \\ \left(C\frac{d}{dt}+G\right) V &= -\frac{\partial}{\partial x} I, \end{aligned}\right\} \tag{1}$$

$$\begin{aligned} I_x = \frac{E_t}{Z_0+Z_t}\Bigg\{ & \epsilon^{-\gamma x}\left[1+\left(\frac{Z_0-Z_t}{Z_0+Z_t}\cdot\frac{Z_0-Z_r}{Z_0+Z_r}\right)\epsilon^{-2\gamma l}\right. \\ & \left.+\left(\frac{Z_0-Z_t}{Z_0+Z_t}\cdot\frac{Z_0-Z_r}{Z_0+Z_r}\right)^2\epsilon^{-4\gamma l}+\cdots\right] \\ & +\epsilon^{-\gamma(l-x)}\left[\frac{Z_0-Z_r}{Z_0+Z_r}\epsilon^{-\gamma l}+\frac{Z_0-Z_t}{Z_0+Z_t}\left(\frac{Z_0-Z_r}{Z_0+Z_r}\right)^2\epsilon^{-3\gamma l}\right. \\ & \left.+\left(\frac{Z_0-Z_t}{Z_0+Z_t}\right)^2\left(\frac{Z_0-Z_r}{Z_0+Z_r}\right)^3\epsilon^{-5\gamma l}+\cdots\right]\Bigg\}. \end{aligned} \tag{2}$$

This equation indicates the current flowing at any point in the circuit for a given impressed voltage. The solution in this form seems to have special educational value because it gives a very clear physical picture of what is taking place in the transmission line. As was early pointed out by Heaviside, the current flowing in any simple circuit such as indicated can be considered to be built up from a directly transmitted wave which at the transmitting end has the magnitude of $\frac{E_t}{Z_t+Z_0}\cdot$ This direct wave is attenuated as it is propagated along the line, and at the receiving end is reflected in the ratio of the difference between the receiving impedance and characteristic line impedance to the sum of these impedances; propagated back toward the transmitting end with continued attenuation; reflected there if the transmitting end impedance is not equal to the characteristic line impedance, the doubly reflected wave propagated toward the receiving end, and so on in an infinite series of propagations and reflections.

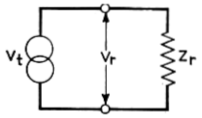
In both power and communication work one quantity which is of great importance in considering the characteristics of the transmission line is the ratio of the voltage at the transmitting end to that at the receiving end. This is, of course, readily derived from equation 2, and is presented in equation 3 in the beautifully compact form offered by the use of hyperbolic functions of the propagation constant of the line.

$$\frac{V_t}{V_r} = \cosh \gamma l + \frac{Z_0}{Z_r} \sinh \gamma l. \tag{3}$$

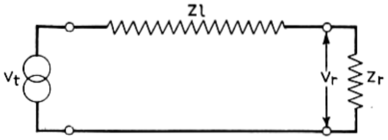
Considering first the application of this general transmission line theory to power transmission circuits, it would appear to be of great value for the student to appreciate the relationship between the general formula and the approximations used for short lines. This is brought out clearly by equation 4 and the diagrams and equations presented under 5.

$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} + \frac{YZl^2}{2!} + \frac{YZ^2l^3}{3!Z_r} + \frac{Y^2Z^2l^4}{4!} + \frac{Y^2Z^3l^5}{5!Z_r} + \dots \tag{4}$$

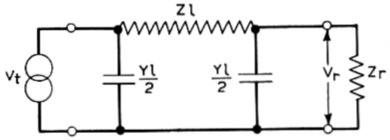
Equation 4 is simply the development of the general formula of equation 3 into a series of terms of ascending powers of Zl, the total resistance and reactance of the line, and of Yl the total shunt admittance of the line. The comparison of this series expansion with the results indicated by various approximate methods is of considerable interest. The first term, unity, is naturally the ratio of transmitting and receiving voltages with no transmission line, as indicated in 5*a*. With the addition of the second term $\left(\frac{Zl}{Z_r}\right)$ one has the result obtained by entirely ignoring the capacity of the line as indicated in 5*b*. The first three terms of the series give the result obtained by assuming that one half of the capacity of the line is concentrated at each end of the line as indicated in 5*c*, namely, a simple Pi network. The simple T network, assuming the capacity all concentrated at the middle as indicated in 5*d*, gives 4 terms, but you will note that the fourth term



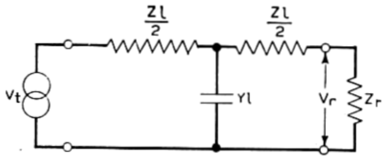
$$\frac{V_t}{V_r} = 1 \tag{5a}$$



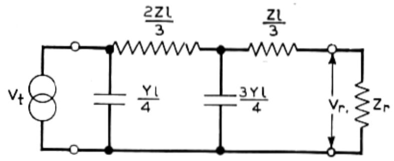
$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} \tag{5b}$$



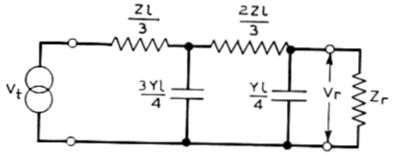
$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} + \frac{YZl^2}{2!} \tag{5c}$$



$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} + \frac{YZl^2}{2!} + \frac{YZ^2l^3}{4Z_r} \tag{5d}$$



$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} + \frac{YZl^2}{2!} + \frac{YZ^2l^3}{3!Z_r} \tag{5e}$$



$$\frac{V_t}{V_r} = 1 + \frac{Zl}{Z_r} + \frac{YZl^2}{2!} + \frac{YZ^2l^3}{3!Z_r} + \frac{Y^2Z^2l^4}{4!} \tag{5f}$$

is 50 per cent. greater in magnitude than the fourth term of the series, and this approximation, therefore, does not commend itself for determining the voltage ratio, since if one wishes a precision requiring four terms of the series it is naturally better to use the correct fourth term. In order to correctly represent four terms of the series by an equivalent network it is necessary, as indicated in 5*e*, to assume one fourth of the capacity concentrated at the sending end of the line and the other three fourths concentrated at a point two thirds distant from the sending end. Finally, if this unsymmetrical network be reversed in direction, as indicated in 5*f*, the first five terms of the series are accurately reproduced.

The degree of approximation represented by dropping off various terms of this series is indicated for three typical cases in Figures 2, 3, and 4. Fig. 2 represents a typical 11,000 volt distribution line. It is to be noted that even neglecting the third term, which is the first in which the capacity of the line appears, results in an error of only 0.4 per cent. as indicated by consulting the values of ratios between successive terms of the series which are given with the diagram. The first ratio shown is that between the second and first term, and the second ratio when divided by two is that between the third and second term. The ratios between successive terms in the series are equal alternately to these two values divided by coefficients increasing in simple arithmetical progression as indicated. This fact would seem to make the series very convenient for computations.

Fig. 2

20 Miles, 11 Kv., Three Phase Distribution Line
200 Kw. at 90% Power Factor, 60 ~
Ratio of Terms:

$$\frac{Zl}{Z_r} = .0540\underline{/2°}[1\ \tfrac{1}{3}\ \cdots]$$

$$YlZ_r = .0668\underline{/116°}[\tfrac{1}{2}\ \tfrac{1}{4}\ \cdots]$$

To take the opposite extreme of power transmission, Fig. 3 has been prepared showing the degree of approximation resulting from the use of different numbers of terms of the series for a 220 kv. line, 250 miles long, transmitting 100,000 kilowatts. Here it is seen that in order to get a precision of a fraction of one per cent. four terms are necessary. The results obtained by a simple Pi network are indicated by the results of the first three terms. It is seen that even for this somewhat extreme case the computation by the series expansion is not at all laborious. This is, of course, due to the fact that even for 250 miles at 60 cycles the power line represents only about one-fifteenth of a wave-length.

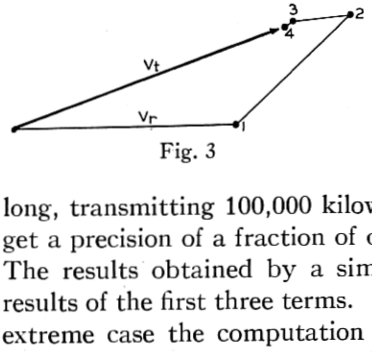


Fig. 3

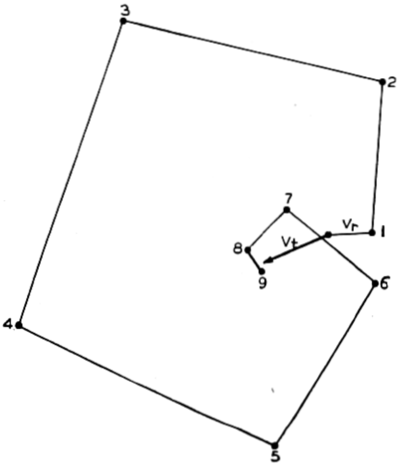
250 Mile, 220 Kv., Three Phase Power Line
100,000 Kw. at 90% Power Factor, 60 ~
Ratio of Terms:

$$\frac{Zl}{Z_r} = .464\underline{/60°}[1\ \tfrac{1}{3}\ \cdots]$$

$$YlZ_r = .588\underline{/116°}[\tfrac{1}{2}\ \tfrac{1}{4}\ \cdots]$$

Series expansions of the type discussed are, of course, not novel. I have dwelt on these somewhat, however, because of the value which they appear to have in clarifying the students' ideas about electric transmission, and because few students appear to be familiar with this method of treatment.

It is no doubt true that in many cases the student can best start transmission line theory with a simple approximation. It would seem, however, that before he gets through his study of the principles of electric circuits he should have a clear picture of the physical processes involved in the propagation of electric power over transmission lines, such as is given by equation 2, and of the assumptions involved in the various approximations which may be presented to him. If the scope of the course is not such as to permit the derivation of the general equations from the differential equations, it is possible to get equation 4 by a method of successive approximations as is shown in at least one textbook, and from 4 to derive the general equation 2.



100 Mile, 8BWG Copper Telephone
Circuit, 1000 ~
Terminating Impedance Equals
Characteristic Impedance

Ratio of Terms:

$$\frac{Zl}{Z_r} = YlZ_r$$
$$= 3.5\underline{/83^\circ}[1 \ \tfrac{1}{2} \ \tfrac{1}{3} \ \tfrac{1}{4} \ \tfrac{1}{5} \ \tfrac{1}{6} \ \tfrac{1}{7} \ \tfrac{1}{8} \cdots]$$

Fig. 4

In contrast with the power line cases, Fig. 4 indicates the results obtained by the series computation of a relatively short telephone toll line, an open wire circuit 100 miles long, and using 1,000 cycles as one typical telephone frequency. Although this line is only a little more than half a wave-length, the solution by the series for this case is quite laborious and indeed impracticable, and of course, would be even more so with the longer lengths or the higher attenuations ordinarily involved in telephone circuits.

The form of the general equation under discussion which is found most convenient for telephone use is given in equation 6.

$$\frac{E_t}{V_r} = \frac{Z_t + Z_r}{Z_r} \cdot \epsilon^{\gamma l} \cdot \frac{\dfrac{Z_0 + Z_t}{2\sqrt{Z_0 Z_t}} \cdot \dfrac{Z_0 + Z_r}{2\sqrt{Z_0 Z_r}}}{\dfrac{Z_t + Z_r}{2\sqrt{Z_t Z_r}}} \cdot \left[1 - \frac{Z_0 - Z_t}{Z_0 + Z_t} \cdot \frac{Z_0 - Z_r}{Z_0 + Z_r} \cdot \epsilon^{-2\gamma l} \right]. \quad (6)$$

This applies to the same circuit as equations 3 and 4, the only difference being that for telephone purposes the ratio E_t/V_r is used rather than V_t/V_r since in the telephone case the internal voltage of the generating apparatus rather than the terminal voltage is the more convenient reference voltage. Otherwise the two equations are identical consisting simply of a rearrangement of terms. The outstanding feature of the arrangement shown in equation 6 is that it consists of the product of a number of terms rather than the sum of a series of terms as in equation 4. The first term represents the ratio of voltages which would be obtained if there were no line present, namely $\frac{Z_t + Z_r}{Z_r}$. The second term illustrates the effect of propagation over the line itself without allowance for reflection at the terminals. The next three terms, two in the numerator and one in the denominator are the factors which make allowance for this reflection. Each is dependent upon simply the magnitude of two impedances, and their inclusion in the equation represents the fact that inserting the line between the two impedances inserts the reflection factors between the line and the transmitting impedance at one end, and the line and receiving impedance at the other end, and takes out the reflection factor directly between the transmitting and receiving impedances. The reflection factor becomes unity in any case in which the two impedances are equal. The last term of the equation is called the interaction factor because it represents the effect of multiple reflection back and forth between the two terminals of the line. This factor necessarily is complicated as it depends upon the characteristics of the line and on both transmitting and receiving impedances. It will be noted that this factor becomes substantially equal to unity in case either the transmitting impedance and the line impedance are approximately equal, the receiving impedance and the line impedance are approximately equal, or the attenuation of the circuit is considerable. In most practical telephone circuits these conditions are approximated sufficiently closely so that the departure of this factor from unity can usually be neglected.

In general, practical telephone circuits are, of course, a good deal more complicated in form than the simple circuit indicated above. It is, however, necessary to have for practical telephone purposes, means for readily determining to a good degree of approximation the overall efficiency of these complicated circuits as a part of the everyday work of certain departments of the telephone companies. The process of expressing the efficiency in terms of the product of a number of factors provides a convenient means for doing this. Under these conditions the large factors such as line attenuation and certain other factors are determined for the individual circuits, whereas factors which are close to unity can be treated approximately by tables representing various types of cases rather than individual circuits.

The convenience of treatment of circuit equations in this way for telephone use has led to the use of a logarithmic measure for expressing the efficiencies of telephone circuits. Although the computations can often be made in terms of currents or voltages, where changes of impedance are involved, such as inequality ratio transformers, we are, of course, concerned with variations in power rather than variations in either the current or voltage. The losses in a telephone circuit are therefore expressed in terms of the logarithm of the ratio of input power to output power. The unit is so defined that 10 transmission units correspond to a ratio of 10, 20 transmission units correspond to a ratio of 100, etc. The overall efficiency of practical telephone circuits from transmitter to receiver is in many cases in the order of 20 transmission units, that is, the circuit delivers at the receiving end one per cent. of the power delivered to it at the transmitting end.

LINE EFFICIENCY

A problem of great importance in electric transmission in all fields is that of obtaining the maximum transmission line efficiency practicable within economic limits. Certain comparisons between power transmission and telephone transmission would seem to be of interest.

The losses in a unit length of transmission circuit include both resistance losses and leakage losses, and may be represented by the formula $I^2r + V^2g$. If both r and g are constant with variations in voltage and current, it is easy to show that the maximum efficiency of transmission takes place when the voltage and current are so adjusted that these two parts of the line losses are equal in magnitude.

Actually in a well designed power transmission circuit without Corona losses V^2g is very small. Hence the solution of the problem of increasing line efficiency is to raise the transmission voltage, thus decreasing the transmission current. This is accomplished in the shorter power transmission lines by using step-up and step-down transformers at the ends of the line, the line itself having a relatively small effect on the impedances thus obtained. For the longer lines, however, the line characteristics play a very important part in this process, and this is best illustrated by consideration of the telephone case.

In the ordinary telephone line the leakage losses are also small compared with the resistance losses, and the voltage can be raised by a factor of 2 or 3 before these losses become equal. The solution of the problem here as in the case of the power line is therefore to raise the transmission voltage and decrease the current, that is, to increase the impedance of the line. In a telephone case, however, this cannot be done by changing the impedance of the terminal apparatus since, as has been pointed out, practically all of the power is absorbed in line losses, and therefore the impedance at the transmitting end of the line is not appreciably affected by the impedance of the receiving apparatus. In order to raise the ratio of voltage to current on the telephone line, it is therefore necessary to operate on the line itself.

The impedance of an electrically long transmission circuit is very approximately equal to $\sqrt{L/C}$. In telephone lines the most practical way to increase this impedance is to increase the inductance. This may be done, as you know, either by uniformly distributed inductance or by lumped inductance, providing certain essential conditions are met, and the result is what is called a "loaded" telephone circuit. It is particularly to be noted that this is not a resonance phenomenon. On the contrary, loading in this way tends to decrease the variations with frequency of the efficiency of transmission of the circuit, and when so proportioned as to give maximum power efficiency, results in distortionless transmission.

In the very long power lines on the other hand, it is desired to transmit efficiently only one frequency, the fundamental. The use of methods depending upon resonance is therefore permissible, and in fact the method which will undoubtedly have increasing use in the future as with increasing length of power transmission lines the effects of line capacity become more important, will be the partial neutralization of the effects of this capacity by shunt inductances distributed along the line, that is, induction machines, or synchronous machines underexcited. This reduces the equivalent capacity of the lines by supplying at least a part of the charging current at the intermediate points. Thus is a similar end obtained in the two cases by different means.

LONG LINE PHENOMENA

The notable success of the vacuum tube amplifier has made a great change in the character of the problems encountered in the design of very long telephone circuits, and our discussion would not be complete without a brief consideration of the nature of these problems. A detailed discussion of these problems is given in numerous papers in recent technical literature.

With the amplifier it is possible in a very large measure to overcome at a relatively small cost the effects of power losses in the telephone circuit. Whereas before the general use of the amplifier it was necessary to make every possible effort to further improve the efficiency of the long circuits in order to increase the distance over which satisfactory telephone transmission could be given, with the amplifier of today there is a limit to the amount of money which can properly be spent merely for the improvement of the volume efficiency of the line as the line losses can always be made up if desirable by the use of amplifiers. As a result, in general, very long telephone circuits have become electrically so long that factors other than power efficiency determine the limits of their effectiveness. While a quantitative theoretical discussion of these problems is necessarily in large measure beyond the scope of undergraduate work at the present time, this may not long be the case, and in any event a general appreciation of these phenomena is of a good deal of interest.

Although these effects are common to all long circuits in principle, they are most prominent in very long telephone cable circuits as these are electrically the longest circuits in use. For example, the propagation constant of a toll circuit in cable between New York and Chicago is at 1,000 cycles approximately $50 + j300$. This is approximately the same as the propagation constant of a high voltage power line transmitting power at 60 cycles of 25,000 to 50,000 miles in length. If there were no intermediate amplification in the circuit the ratio of input to output power would be ten to the 45th power so that with our usual telephone input of about one milli-watt the circuit would deliver only one electron in each two months, and even if all the power available in New York City or Chicago could be used at the input without burning up the circuit, the received current would be utterly inappreciable. However, there are far more practical reasons than this for frequent intermediate amplification. The lower limit to which the power level can be permitted to fall in the circuit is limited by the disturbances picked up from other telephone circuits in the same cable or from other electric circuits outside the cable, and the maximum power level is, of course, limited by considerations of economy in the design of the amplifiers. These limits result in the use of amplification in these circuits at approximately 50 mile intervals, there being 17 intermediate points of amplification between New York and Chicago on the shortest route.

With such a circuit the variation of efficiency with temperature is very rapid and the emergence of the sun from under the clouds could make as much as 1,000 fold-difference in the amount of power delivered. It is therefore necessary for practical operation to control the power gain introduced by the amplifiers by means of pilot wires in the cable subject to the same temperature variations as the talking circuit, and in this way to compensate automatically for the effect on the propagation constant of varying temperature.

In order to obtain for these cable circuits as far as possible the benefits of high voltage transmission, the circuits are loaded. This loading also in large measure equalizes the efficiency of transmission over the frequency range required for the transmission of speech.

The velocity of wave propagation over conductors loaded with inductance is, of course, relatively slow compared with the velocity of light. In the case of loaded telephone circuits in cable the velocity for the two types of circuit in general use is respectively 10,000 miles a second and 20,000 miles a second. The low velocity circuits are loaded with more inductance and are of higher efficiency and therefore preferable from the standpoint of volume. It is necessary, however, for the long circuits to use facilities of higher velocity and lower efficiency because of several very interesting phenomena.

For one thing, with circuits of high efficiency conforming to present day standards, the currents reflected from the distant end because of irregularity of impedance between the line and the terminal apparatus are by no means inappreciable. When the time for the propagation of these currents over the line and back to the transmitting end is very short, the reflected currents can be large without interference with service as they are indistinguishable from the sound directly heard by the speaker. If a circuit from New York to Chicago were used on the lower speed of the two types of circuit mentioned above, however, the reflected currents would arrive about one fifth of a second late. An interval of this magnitude would result in serious confusion to the speaker due to hearing his words twice, by direct transmission and after reflection from the distant end of the circuit. With the high speed facilities the time interval is reduced to one tenth of a second, and the interfering effect is very much smaller. Even with the high speed facilities, however, the effect is sufficient so that on circuits of over a few hundred miles in length special devices known as echo suppressors are used to intercept the echo currents and prevent their interference with the speaker.

Another important effect is the imperfect equalization of the transmission of different frequencies within the range of important telephone frequencies. This imperfection can be offset by the use at intervals of correcting networks which introduce a distortion opposite to that produced by the line, and the design of such networks is one of the interesting problems which has been worked out in connection with these very long circuits. The distortion is not only one of magnitude but also one of phase due to the difference in the velocity of wave propagation of component currents of different frequencies. This may be extremely important on long circuits of the heavier type of loading in which any minor disturbance at the transmitting end of the line is transmitted in such a way that the low frequency components appear first at the receiving end, followed by progressively higher frequency components and causing disturbing transient noises somewhat similar to the chirrupping of a bird. Phase distortion is less on the more lightly loaded circuits but still remains of enough importance to require the use in some cases of networks to equalize the distortion of phase.

In this discussion of very long circuits I have talked of telephone circuits. In the case of both telephone and telegraph circuits the fundamental requirements are the same, namely, the propagation of currents within a certain range of frequencies without excessive distortion and without interference from other electric circuits. The principal difference in the problems is in the range of frequencies which is important in the two cases, that for telegraph being much lower and more limited in extent than that for telephone. Another difference is that in the case of telephony phase distortion is important only in producing different time of arrival of different components, whereas in telegraphy the effect of phase distortion in distorting wave shape is also of importance. The telegraph problem can, like the problem of transients in telephone lines, be approached theoretically from the performance of a circuit when a potential is applied suddenly at one end. It has been shown, however, that the treatment of the circuit in terms of its steady state characteristics for the propagation of alternating currents over a range of frequencies leads to results identical with those reached by the transient treatment, and for most cases the steady state method of treatment rather than the transient method of treatment is found to be more convenient to handle for purposes of circuit and apparatus design.

ELECTROMAGNETIC THEORY

There is a further gap which it is to be hoped can in the future be bridged for those students who are sufficiently advanced to become familiar with the general electromagnetic theory. To what extent it is practical to teach general electromagnetic theory to undergraduates is a question which is perhaps beyond the scope of this paper. However, those five differential equations as formulated by Maxwell and Lorentz which form the general mathematical statement of the fundamental discoveries of Ampere, Faraday and the other pioneers of electric science are the Magna Charta of electric science of today, and with the rapid development of the electrical arts in various directions constant recourse must be had to these fundamental equations for the establishment of correct electrical principles.

The simplified electric circuit theory which we have just discussed, which may be called the classic theory, serves very well for the great bulk of problems of electrical transmission of today. However, already there are situations both in the power transmission art and in the communication art in which the approximations which these equations involve are not valid, and for the solution of practical cases recourse must be had to the more general equations. These practical cases include the distribution of current in the earth when one side of a circuit is grounded, the inductive effects produced in other electrical circuits from a grounded circuit, and the transmission characteristics of submarine cables in which the sea water forms a part of the return path.

The classic circuit theory expresses the electrical quantities in terms of the total currents flowing in conductors and the voltages between these conductors, and expresses the aggregate energies in terms of inductances and capacities, and the dissipation in terms of resistances. The general equations of the electromagnetic theory express the electric quantities in terms of elementary current and charge densities, and the electric and magnetic fields are expressed in terms of field strengths. These, then, are the rigorous equations in differential form. In the classic theory the current and charge densities and field strengths are integrated into more easily manipulated totals. In other words, the electric circuit theory deals with macroscopic or large scale phenomena and the electromagnetic theory deals with microscopic or small scale phenomena.

What are the approximations involved in the classic theory and what conditions must be met for these to be good approximations? This matter has been treated in a very interesting way in some recent papers by Mr. John R. Carson. In brief, Mr. Carson's papers point out that the classic circuit theory applied to transmission lines involves the following assumptions:

1. That the solution is concerned only with conditions at some distance from the terminals of the circuit and can therefore ignore the changes in distribution of electric and magnetic fields near the terminals known as end effects. That means that the electric and magnetic fields are propagated along the line in the same way as the currents and voltages.
2. That the propagation constant (per centimeter) is very small compared with unity and that the real part of the propagation constant is not large compared with the imaginary part, that is, the attenuation is not large compared with the phase change.
3. That in the conductors the loss due to the transmission current (that is, the axially flowing current) is large compared with the loss due to the charging currents.
4. That in the dielectric the propagation of energy is nearly parallel to the axis of the conductors and the dissipation in the dielectric is negligible.
5. That the fields of the currents and charges are propagated at an infinite velocity, that is, that radiation is neglected.

These assumptions, it can be shown, are very good for the ordinary case of an efficient transmission system. The effect of modification of the field at the terminals influences only a few feet of the line and is negligible in amount. Assumptions 2, 3 and 4 can very readily be shown to be true from the characteristics of the conductors and dielectrics involved in transmission, and as regards neglecting of radiation Mr. Carson has shown that for the ordinary transmission system the losses by radiation are in the order of one ten-thousandth of those in the conductors.

It is to be noted, however, that these assumptions place certain limitations on the application of the classic theory which are important in certain cases. The limitations are as follows:

1. The electric and magnetic fields are accurately expressed only for points relatively near the conductors. At great distances from the conductors the radiation field becomes important in comparison with the inductive field because of the much more rapid rate of decrease in intensity of the inductive field with distance.
2. The electric and magnetic fields are not accurately expressed near the terminals of the circuits.

3. The approximations do not apply if the conductors are quite imperfect or if the dielectric is highly dissipative. This affects the application in certain practical cases as indicated above.
4. The classic theory does not apply to circuits of the usual dimensions for extremely high frequencies in the order of millions of cycles.

From the standpoint of the best appreciation of the fundamentals of the electrical arts it might be said that the ideal course for students in electrical theory would start with the fundamental discoveries of Ohm, Oersted, Ampere, Faraday and Henry, pass through the generalized mathematical statement of the laws which they discovered to the general electromagnetic equations of Maxwell and Lorentz, and then from this focal point derive the various approximations of electric theory as applied to the various electrical arts; electric light and power, electric transportation, telephone, telegraph and radio. Unfortunately, teachers and students as well as the rest of us are hampered by questions of time and this approach is not proposed as a practical undergraduate course at the present time.

CONCLUSION

Electrical science and its practical applications are undergoing a very rapid development and expansion. The science of today is the engineering of tomorrow. These facts result in increasing importance in the mastery by the engineering student during his time at college of the electrical principles of broadest general usefulness, rather than learning specific applications of these principles. By a mastery is meant such an appreciation of the scope and limitations of the principles that he is able to apply them correctly to new conditions as they come up.

It is not intended to express a judgment on the extent to which the curricula of engineering schools should go in presenting electrical theory, and it is, of course, recognized that different schools have different conditions to meet which will naturally result in somewhat different courses. It is not proposed that the specific forms of electrical theory applying directly to telephone problems should be taught.

It is proposed for consideration, however, that whatever the scope of general electrical principles which is taught, these be so presented that the student have a clear picture of what they mean and of how and where they apply, and that he also should appreciate the relation to the general principles of any specific cases presented and the approximations which they involve. As far as practicable, all principles should be related to the general electromagnetic theory, the fundamental basis of all our electrical science.