Some Theoretical and Practical Aspects of Noise Induction*

By R. F. DAVIS and H. R. HUNTLEY

This article discusses the physical processes of induction between neighboring power and telephone lines and describes means by which certain phenomena of interest in this connection have been qualitatively demonstrated to power and telephone employees.

Introduction

EARLY in the development of the power and telephone industries, serious problems were encountered because of induction between neighboring power and telephone circuits. In 1885, about 150 representatives of Electric Light Companies assembled in Chicago and discussed the many problems of interference with telephone service due to induction which were even then coming up. This meeting resulted in the formation of the National Electric Light Association.

Prior to this time all telephone circuits were grounded, that is, they used a single wire with ground return, and so were very susceptive to inductive disturbances. There was also a great deal of interference between different telephone circuits on the same line (that is, cross-talk) so that conversations on one circuit could be overheard on others. General John J. Carty, then working in Boston, had been doing a great deal of work on this subject and by about the end of 1885 had not only developed the metallic telephone circuit, which employs two wires and does not use the earth as part of the circuit, but also had worked out methods of applying transpositions. These developments afforded such a large reduction in the susceptiveness of the circuits to external influences that the problems of coordination existing at that time were largely solved.

However, with the expansion and development of the power and telephone industries, new problems of coordination arose, and the nature and control of the phenomena involved have been the subject of continuous study by both industries. While a great deal has been learned about the technical phases of the problem and the best methods of handling it, the coordination of the plants of power and telephone companies in such a way that safety and service are promoted with minimum expense still involves important problems. These problems not only concern the engineers who are responsible for plant design and for technical advice, but also enter into the work of the field forces who

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actually construct, operate and maintain the plants and into the considerations of management. Naturally, the best results can be secured if all concerned have a thorough understanding of the subject and appreciate each other's requirements and points of view.

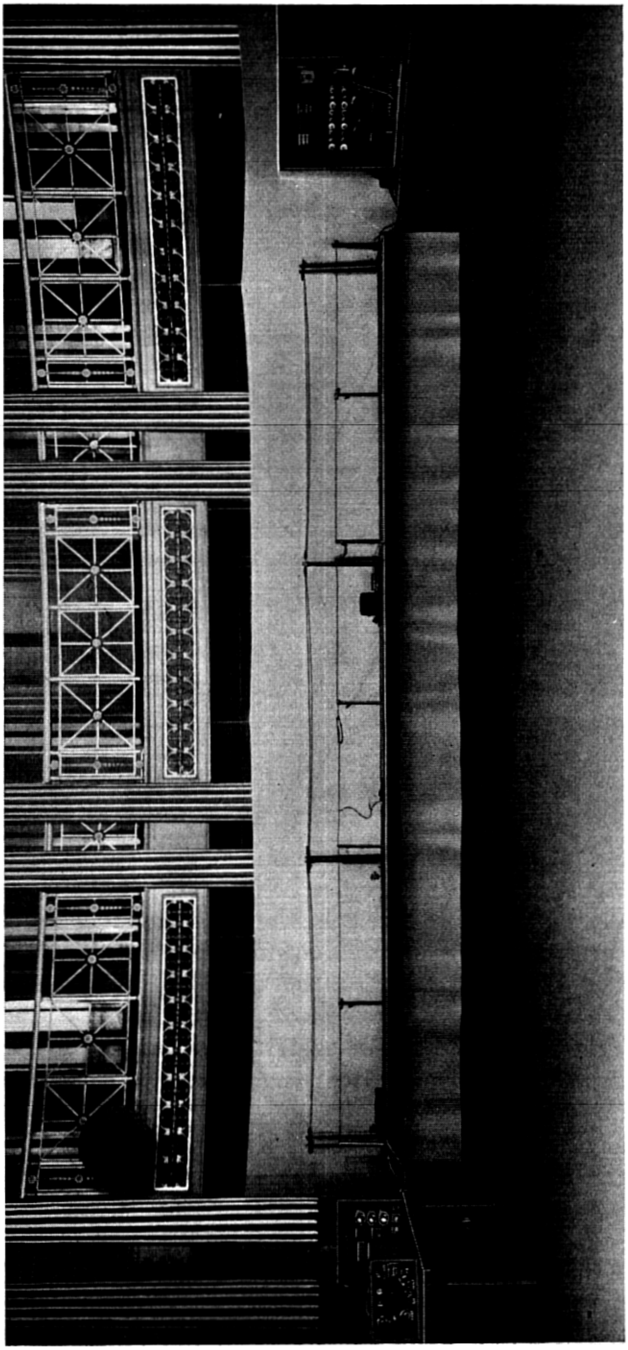
In promoting the mutual understanding of this subject which is so desirable, it has been found helpful in some cases to use demonstrations of the principles underlying the work accompanied by explanations in everyday language. One of the demonstrations which has been shown before a number of audiences of power and telephone people with this in mind has to do with noise frequency induction and employs the miniature lines and apparatus shown in photograph No. 1. A considerable amount of interest has been aroused by these demonstrations and many of the people in the audiences have found complete or partial explanations of some specific problems which have been troubling them.

In order to illustrate the manner in which the miniature lines and apparatus may be used to demonstrate principles of noise frequency induction, there follows a description of this apparatus and a discussion of the processes of induction along the lines usually followed in the demonstrations.

Fundamentals of Problem

The problems concerned with inductive coordination arise due to the fact that wires transmitting electricity necessarily have electric and magnetic fields about them which may under certain conditions cause voltages to appear in other wires which are in these fields. This phenomenon is called induction. The voltages and currents used in power transmission are much greater than those used in speech transmission so that there are practically no situations in which the currents and voltages on telephone systems affect power system operation due to induction, but situations do arise in which power system voltages and currents affect telephone system operation.

The effects of induction in a given situation of proximity between power and telephone circuits are dependent upon the characteristics of both the power and telephone systems and upon the coupling (due to the electric and magnetic fields) between them. It is theoretically possible for a power line to be so constructed and maintained that it would cause no induction into a nearby telephone circuit. Such a power line would be said to have zero "inductive influence." Likewise, it is theoretically possible to have a telephone circuit so constructed and maintained that it would be unaffected by any electric or magnetic fields set up by power systems. Such a telephone circuit would be said to have zero "inductive susceptiveness." Also, of



Photograph No. 1.

course, regardless of the characteristics of the power and telephone circuits, if the separation between them could be very great, there would be no "inductive coupling" and consequently, no induction from one into the other. Practically, of course, neither power nor telephone systems can be constructed so as to have zero influence or susceptiveness, and it is frequently impracticable to separate them sufficiently to make the coupling negligible. The practical coordination problem, therefore, is to work out the most convenient and economical method of controlling the factors so that inductive interference is avoided.

In the practical problem of inductive coordination between power and telephone systems there are often two more or less distinct aspects to be considered. One of these aspects is concerned with the possibility of extraneous currents in the telephone circuits which have frequencies within the range used in transmitting speech and which may, therefore, cause "noise" in the telephone receivers at the ends of the circuit. This phenomenon may arise during the normal operation of power and telephone systems although abnormal conditions on either system may result in increasing the noise during the existence of such abnormal conditions. The other aspect commonly referred to as "low frequency induction," is associated almost entirely with faults to ground on power systems and is primarily concerned with the possibility at such times of high induced voltages at fundamental power system frequency. This article, however, is confined to the noise aspect of the problem.

Demonstration Apparatus

In order to qualitatively illustrate some of the factors involved in noise induction, a miniature inductive exposure as shown in the photograph referred to previously, may be used. The demonstration circuits consist essentially of a miniature three-phase, three-wire power line and a two-wire telephone line which are set parallel to each other on a grounded copper screen and are connected as shown schematically in Fig. 1. The power line can be energized in various ways from an ordinary three-phase power distribution circuit through suitable transformers. The telephone line is connected to an amplifier and loud speaker so that the noise on the telephone circuit under various conditions can be heard. Both lines can be transposed independently or in a coordinated manner and unbalances can be inserted in the telephone circuit. The particular connections and arrangements of the lines and apparatus used in each of the demonstrations are described as that demonstration is discussed.

With an inductive exposure of the limited dimensions available, it is impracticable to secure results which can be related in a quantitative sense to field conditions. Also, such effects as the shielding between

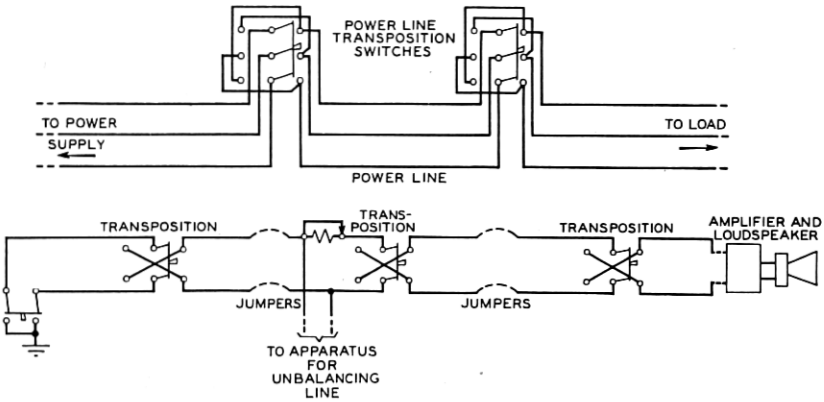


Fig. 1—Schematic of demonstration circuit.

the various telephone circuits on a multi-wire line, propagation effects, etc., cannot be shown. Furthermore, the exposure is a great deal more regular than those usually encountered in practice so that, for example, a higher effectiveness of transpositions than is usual can be secured. However, many of the fundamentals of the problem can be illustrated qualitatively.

Nature of Magnetic and Electric Induction

It is often desirable to consider effects of magnetic and electric induction separately, particularly in the technical analyses of specific problems. This is not only because the physical processes and the effects of voltage and current induction are quite different but also because the power circuit voltages and currents are often affected differently by changes in conditions. "Electric induction" is a term used to refer to induction due to the voltages on the power line, while "magnetic induction" is used in connection with the inductive effects of currents.

Considering electric induction first, perhaps the simplest method of visualizing the phenomenon, is by means of the capacitances involved with a single power wire and a single telephone wire as shown in Fig. 2. Neglecting the impedances outside the exposure (which are shown dotted in Fig. 2) the voltage of the power wire to ground (E_P) divides over the capacitances C_{TP} and C_{TO} in proportion to their impedances (that is, in inverse ratio to their capacitance values). The induced voltage on the telephone wire may therefore be expressed mathematically as:

$$E_T = \frac{C_{TP}}{C_{TO} + C_{TP}} E_P.$$

Where there are numerous power and telephone wires, capacitances exist between every possible combination of wires, and of wires and ground, resulting in a complicated network, but the principles involved are the same as in the simple case discussed above.

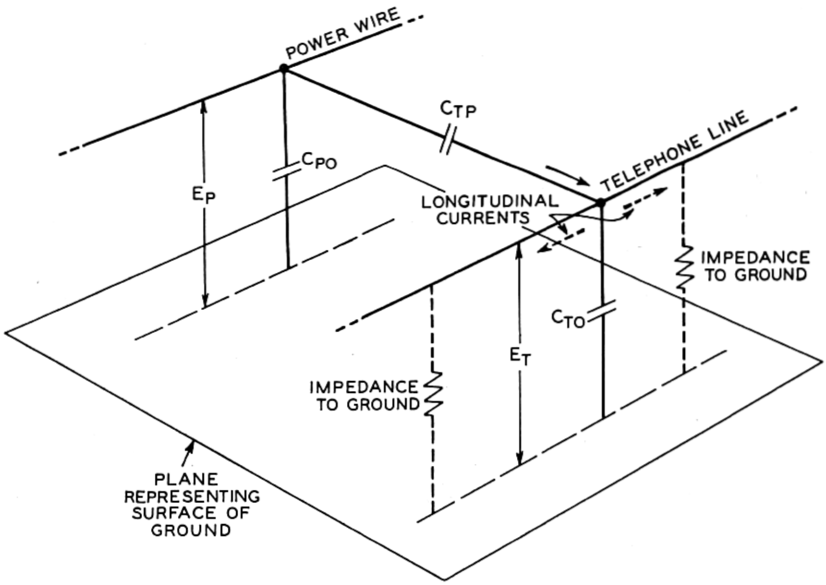


Fig. 2—Fundamental of electric induction.

The point of particular interest is that the potential of the telephone wire tends to be the same all along its length and, if it is perfectly insulated from ground, extends only through the length of the exposure, and has no equipment on it, this potential is independent of the length of the exposure (this is the condition shown in Fig. 2 if the impedances to ground are neglected). This is because, while all of the capacitances in the above equation are proportional to exposure length, the *ratio* $\frac{C_{TP}}{C_{TO} + C_{TP}}$ is independent of length. However, in the usual field case, the circuits extend beyond the exposure and have equipment connected between them and ground so that there are impedances to ground outside the exposure (as shown dotted in Fig. 2) through which longitudinal currents will flow. The net voltage to ground under these conditions is equal to the total of the longitudinal currents in the two directions times the impedances to ground looking in the two directions considered in parallel and, since these impedances are usually much smaller than the impedance through which the current reaches the telephone line (capacitance C_{TP}), this voltage is usually much smaller than the *induced* voltage (see equation above). Since the impedance of C_{TP} controls the total longitudinal current, this current will be practically independent of the telephone circuit impedances to ground and will be proportional to exposure length. It will also be proportional to the frequency of the harmonics in the inducing voltage (since the impedance of a capacitance is inversely proportional to frequency). Hence, for given telephone circuit impedance conditions (outside the exposure) the voltage to ground will be proportional to exposure length and to the frequency of the inducing harmonics in a uniform (electrically short) exposure.

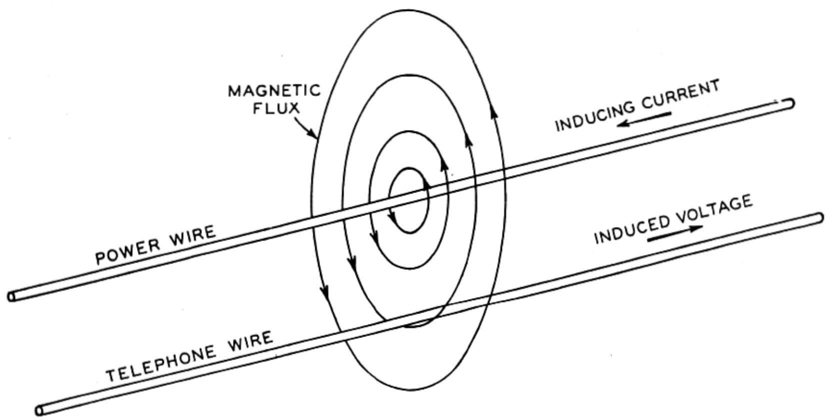


Fig. 3—Fundamental of magnetic induction.

Considering magnetic induction, the current in the power wire sets up a magnetic field which alternates at the frequency of the current. If a telephone wire is located in this field, a voltage is induced *along* it which is proportional to the rate of change of the magnetic flux just as a winding in a transformer has a voltage induced along it. This phenomenon is illustrated in Fig. 3. The voltage between the telephone circuit and ground varies from point to point along the circuit and depends on the distribution of the impedances to ground as well as on the distribution of the induced voltage. Also since the voltage acts along the circuit and the part induced in each short length adds directly to those in all other short lengths, the total induced voltage is directly proportional to the exposure length in a uniform (electrically short) exposure. Also, since the rate of change of magnetic flux is proportioned to frequency, the induced voltage will be proportional to the frequency of the harmonics in the inducing current.

The demonstration which shows the fundamental difference in the action of electric and magnetic induction is shown in Fig. 4.

1. In Fig. 4-*A* the arrangements for demonstrating electric induction as well as the way the induced voltage acts through the impedance to earth in the exposure are shown. In the setup the power line is energized at about 200 volts, balanced 3-phase, but since the far end is open the current in it is negligible. Consequently only electric induction is present in appreciable amount. Since the voltage to ground of the telephone circuit is the same over its entire length, grounding it at any point reduces the voltage at all points. This is shown in the demonstration by the great reduction in the noise to ground as heard in the loud speaker when the switch at the far end of the line is closed thus grounding the line.
2. In Fig. 4-*B* the arrangements for demonstrating magnetic induction as well as the manner in which the induced voltage acts are shown. In this setup the power line is energized at about 17 volts, 3-phase and has a load such that the current is about 15 amperes in each wire. Due to the low voltage and the relatively large current, magnetic induction is predominant. Since the induced voltage acts *along* the circuit, it can be prevented from acting on the amplifier input by opening the circuit at any point. This is indicated in the demonstration by the fact that the noise in the loud speaker is much greater when the switch at the far end of the line is closed than when it is open. (This is, of course, the exact reverse of the conditions when electric induction was being demonstrated.)

In the demonstrations the lines used are very short electrically. For circuits which are long enough so that propagation effects must be considered, the results of grounding or opening the far end of the circuit may be considerably different than for electrically short circuits.

Inductive Coupling

General

In discussing inductive coupling, it is necessary to consider not only the metallic power circuit and the metallic telephone circuit but also the

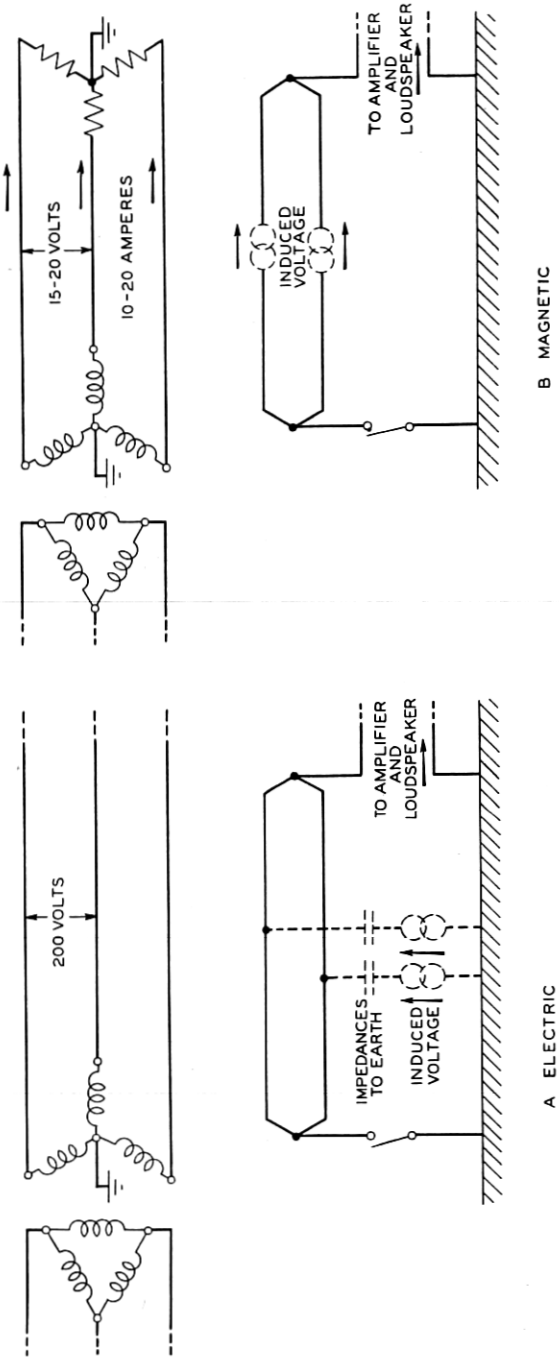


Fig. 4—Demonstration of electric and magnetic induction.

circuit composed of the power wires in parallel with ground return and the circuit composed of the telephone conductors in parallel with ground return. This is because, while the power to customers is usually transmitted over metallic power circuits and telephone conversations between telephone customers are usually over metallic telephone circuits, the circuits composed of the wires and ground in both systems enter into the induction picture unless the systems are perfectly balanced (which, as pointed out previously, is impracticable).

Considering the power system first, it is customary to divide the line currents and voltages into residual and balanced components. The balanced currents are the components which add up vectorially to zero. The residual current is the vector sum of the line currents and is that which remains after the balanced components are taken out. Similarly, the balanced voltages are the components of the voltages to ground which add up vectorially to zero and the residual voltage is the vector sum of the voltages to ground.

Thus it is seen that the balanced voltages and balanced currents are confined to the line wires while the residuals act in the circuit composed of the line wires in parallel with earth return. For a three-phase circuit the effect is that of a single-phase voltage equal to one third the residual voltage applied between the line wires and earth and a single-phase current equal to the residual current flowing out in the three phase wires in parallel and returning via the earth (or metallic paths other than the phase wires if such exist).

Whether appreciable residuals exist on the power system depends on many conditions, some of which are discussed later.

Considering the telephone circuit, the voltages, as pointed out in connection with the discussion of the theory of magnetic and electric induction, exist along the conductors or between them and earth. However, these voltages may not be identical for the two conductors of a metallic circuit and the vector difference exists as a voltage acting between the two wires. This voltage which, of course, tends to send current around the metallic circuit (and hence noise in the receivers at the ends of the circuit), is often spoken of as due to "direct metallic-circuit induction." The average of the voltages between the two wires and earth is often spoken of as "voltage to ground" and the currents in the two wires in parallel are often spoken of as "longitudinal-circuit" currents. The effects of these voltages to ground and longitudinal-circuit currents on telephone circuits which are not perfectly balanced are discussed later.

All of the factors which have been mentioned, that is, balanced and residual components, direct metallic induction, longitudinal circuit currents, etc., enter into the consideration of coupling. It is, of course, impracticable to do more in this discussion than consider some of the more important aspects of this phase of the subject.

In general, it can be said that except for very small separations where rapid changes in coupling may occur with changes in the relative positions of the circuits, all of the types of coupling will become smaller as the separation between the power and telephone circuits increases. The rate at which the coupling falls off with increasing separation depends on many factors. For example, the coupling involved in direct metallic induction generally falls off faster with increasing separation than does the coupling affecting the longitudinal telephone circuit. Likewise the coupling affecting the induction from balanced currents and voltages generally falls off faster than that from residual currents and voltages.

In order to demonstrate that, in general, the coupling is reduced by increasing the separation, the telephone line in the exposure is moved in such a way as to change the separation and it is noted that, as the separation increases, the noise decreases and vice versa.

For a uniform exposure, the amount of noise in an untransposed telephone circuit exposed to an untransposed power circuit will generally be approximately proportional to the length of the exposure, provided the total exposure is electrically short. (For long exposures, this proportionality may not hold because of phase-shift, attenuation effects, etc.) In order to illustrate the effect of changes in length of exposure, one-third, two-thirds, and all of the telephone line in the miniature exposure are employed successively and it is noted that the volume of sound from the loud speaker is approximately proportional to the length of the exposure. The direct proportionality between noise and exposure length does not hold for exposures to which coordinated transposition layouts have been applied as the resultant noise in such cases depends largely on the effectiveness of the coordinated layout. The effects of transposition are discussed in the following.

Transpositions in Power Circuits

Transpositions in power circuits are used primarily to accomplish two results. The first of these is the reduction, within exposures, of the induction from balanced currents and voltages. The second is the equalization of the admittances to earth and the series impedances of the power wires in order to limit the residual voltages and currents. In this discussion only the first of these two results (that is, reduction of induction due to balanced currents and voltages within the limits of inductive exposures) will be analyzed.

The balanced voltages in a three-phase power system form a symmetrical set of vectors equal in magnitude and 120 degrees apart in phase or may be readily analyzed into two such symmetrical sets of vectors. In either case, of course, the vector sum is equal to zero. In spite of this symmetry of voltages the induction to another conductor from the three balanced voltages is not necessarily zero since the coupling between each power wire and any other wire such, for example, as a wire of a telephone circuit, depends largely on its position with respect to such other wire. Since the spacings of the power conductors must be sufficient to provide adequate insulation, the distances from the various power conductors to the telephone conductor will usually be different and the inductions from these conductors will, therefore, be different and will not total zero. If the positions of the power conductors are rotated 120 electrical degrees periodically, however, the induction from the balanced components tends to be neutralized in each three successive equal lengths since the telephone line is thus exposed equally to all of the power wires. Such an arrangement of three successive equal lengths with two transpositions between them is called a transposition "barrel." The action of a barrel in neutralizing induction into adjacent circuits due to balanced voltages is illustrated in Fig. 5. It can be seen from this figure that the phase of the induc-

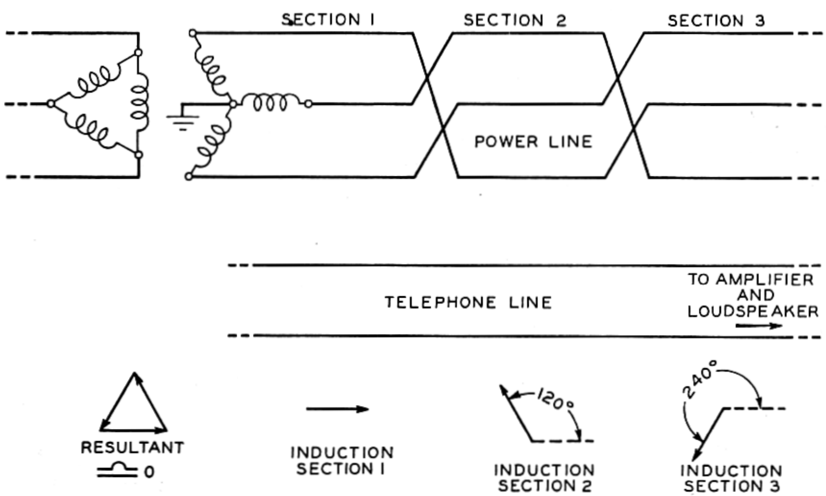


Fig. 5—Effect of power transpositions on induction due to balanced voltages.

tion into an adjacent circuit is rotated 120 degrees by each transposition so that in three sections the vector sum of the inductions would become zero if the inductions from the sections were identical in magnitude and exactly 120 degrees apart in phase. As a general rule, however, the actual inductions from the different sections are not identical in magnitude nor exactly 120 degrees apart in phase because of irregularities in the pole spacing and dimensions of the parallel and because of the fact that electrical waves take finite times to be propagated over the wires and hence do not have the same phase in successive lengths. For the usual distances encountered, the phase shift at fundamental frequency is small but it may be appreciable for the higher harmonic frequencies.

The analysis outlined above for balanced voltages can also be employed for balanced currents. When the load on the power line is not symmetrical the balanced currents will not be equal in magnitude and exactly 120 degrees apart in phase even though the vector sum is zero. However, these line currents may readily be divided into two sets of currents each of which may be represented by a set of vectors of equal magnitude and 120 degree phase displacement. The induction from each set of vectors may be neutralized by power transpositions (subject to the same limitations as for balanced voltages) and it follows, therefore, that the induction will be neutralized for their combination.

Transpositions in power systems affect the induction from residuals only to such extent as they may affect the magnitude of the residual voltages and currents (by providing better balance to earth). This is because the residuals act on the wires in parallel (as pointed out previously) so that interchanging the positions of the wires will not directly affect the inductive field about them.

To demonstrate the effect of power circuit transpositions on induction due to balanced and residual voltages, the miniature power circuit can be transposed to form a complete barrel. When the power circuit is energized with balanced voltages, a substantial reduction in noise from the loud speaker occurs when the transpositions are cut in. When the line is energized with residual voltage, however, cutting in power circuit transpositions does not cause any change in the noise from the loud speaker. In actual exposures, both balanced and residual voltages and currents may be present so that the effectiveness of power circuit transpositions will depend upon the particular conditions in each specific case.

Transpositions in Telephone Circuits

As in the case of power circuits, telephone transpositions have, from the standpoint of noise, two functions. The first is the equalization of admittance unbalances to earth and to other conductors, of the conductors of the particular circuit under consideration. The second is the reduction of noise due to direct metallic-circuit induction. (A third purpose, which is closely allied with the first and second, is the limitation of crosstalk coupling between the various telephone circuits on the same line.)

Within an inductive exposure, slightly different voltages may be induced on or along the two wires of a telephone circuit as pointed out previously. By transposing the wires frequently, they can both be exposed to the power system more or less equally and the voltages induced in them will tend to be equalized. The difference and hence the noise-metallic due to direct metallic-circuit induction thus is reduced. This is illustrated in Fig. 6. If the induction on the two sides of a transposition is identical in magnitude and phase, complete neutralization can be secured. In actual cases, however, these voltages are not identical in magnitude and phase because of irregularities in the exposure, irregularities in pole spacing, etc., and because of the phase shift and attenuation which were discussed in connection with power system transpositions.

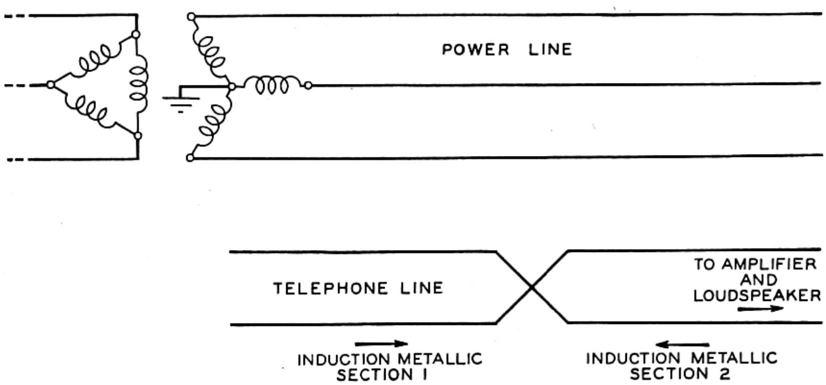


Fig. 6—Effect of telephone transposition on metallic noise.

Since the voltage to ground and the longitudinal circuit current due to either electric or magnetic induction, act on the telephone wires in parallel, telephone transpositions do not reduce them.

To demonstrate the effects of telephone circuit transpositions, the miniature telephone circuit is transposed. It is noted from the decrease in the noise from the loud speaker that, when the telephone circuit does not contain high resistance joints or other important unbalances, a substantial reduction in the noise metallic occurs when the telephone transpositions are cut in. However, no effect can be noted on the noise to ground.

Coordination of Transpositions

In order to summarize the effects of power and telephone circuit transpositions, Fig. 7 has been prepared. While this table applies only to transpositions within an exposure, it will be recalled that telephone and power system transpositions outside of exposures may have an important bearing on the balance of the circuits.

Transpositions	Induction From	Effect on Telephone Noise Met	Effect on Telephone Noise To Ground
Power.............	Balance V.	Yes *	Yes
Power.............	Residual V.	No	No
Power.............	Balance I.	Yes *	Yes
Power.............	Residual I.	No	No
Telephone..........	All Types	Yes	No

* Power transpositions will reduce metallic noise on untransposed telephone lines. With telephone lines transposed the effects of power transpositions on metallic noise due to direct induction may be small.

Fig. 7—Summary of effects of transpositions within inductive exposures.

In some cases, it may be desirable to reduce not only the noise-metallic due to direct metallic-circuit induction but also the longitudinal-circuit noise due to balanced currents or voltages. An inspection of the table indicates that this may be done by transposing both the power and telephone circuits. In order to secure the greatest value from the transpositions in such cases they should be installed in such a way as to effectively "coordinate" with each other. In such coordinated layouts, the power circuit transpositions (where used) are largely relied on for reducing the longitudinal-circuit noise on the telephone circuits due to induction from balanced components and the telephone transpositions are largely relied on for minimizing the noise-metallic due to direct induction between the wires. Fig. 8 is a schematic diagram illustrating the principle of coordinated transpositions. It will be noted that the following considerations have been adhered to:

1. The telephone circuits are balanced, that is, both wires occupy both pin positions for equal lengths, between successive power circuit transpositions. This is necessary in order to ensure as close an approach as practicable to equality of induction on both sides of each telephone transposition.
2. The power circuit is transposed in a complete barrel. If the exposure is long or irregular, more than one barrel might be required.

In multi-wire telephone lines, the telephone transpositions are, of course, much more complex than those illustrated in Fig. 8, but in the systems designed for use in inductive exposures, so-called "neutral" points are established between which the circuits may be subjected to a uniform exposure. Consequently in a coordinated system of transpositions, it is ordinarily desirable that the neutral points in the telephone transposition system fall opposite or nearly opposite transpositions in the power system or other important electrical changes in the power system or in the exposure.

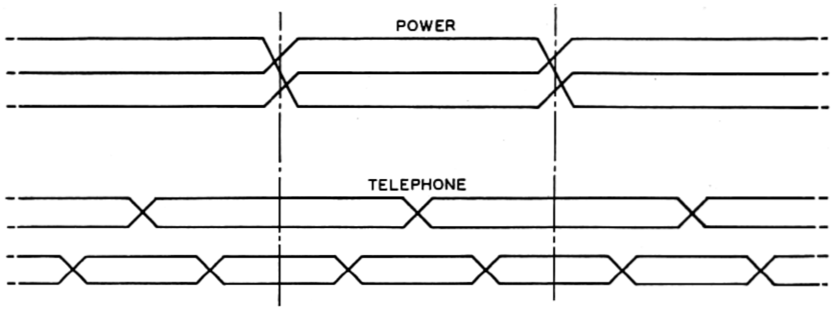


Fig. 8—Schematic layout of coordinated transpositions.

To illustrate the above, the demonstration apparatus is arranged to secure a coordinated layout. When the coordinated layout is cut in, only a relatively small amount of noise from the loud speaker is heard, and it is observed that the insertion of small series or shunt unbalances in the telephone circuit does not materially increase this noise (i.e., the telephone circuit is not particularly critical as regards unbalances) as long as the supply system is energized by balanced voltages only. When residual voltage is used on the miniature supply line, the longitudinal-circuit noise on the telephone system is higher and the telephone circuit is more critical as regards unbalances.

Inductive Influence of Power Lines

In considering some of the factors affecting the inductive influence of power lines, it should be recalled that, theoretically, a power system could be so constructed that it could set up no external electric or magnetic fields and consequently would have negligible influence. It is, as previously mentioned, impracticable to construct power lines in this way and consequently, the factors controlling the deviations from this condition require consideration.

Among the factors affecting the inductive influence of a power line are the amount of line current, the operating potential, the configuration of the wires, etc. It does not seem necessary to demonstrate these, but there are two additional factors of importance, as follows, which will be discussed:

1. The wave shape of the currents and voltages.
2. The magnitude (and wave shape) of residual voltages and currents. (Residuals were discussed briefly in connection with inductive coupling.)

Wave Shape

It is recognized as commercially impossible to build rotating machinery entirely free from harmonics. It is further recognized that some distortion of wave form is inherent with power transformers which must employ iron in their magnetic circuits. Harmonics are of interest from the standpoint of noise induction, since they may induce voltages of frequencies within the range ordinarily used in telephone message circuits. Induced voltages at such frequencies have much greater interfering effects (from the standpoint of noise) than does the voltage normally induced at the fundamental frequency. The approximate relative interfering effects of voltages of different frequencies in typical telephone circuits are shown in Fig. 9 which is a so-called "noise weighting" curve.

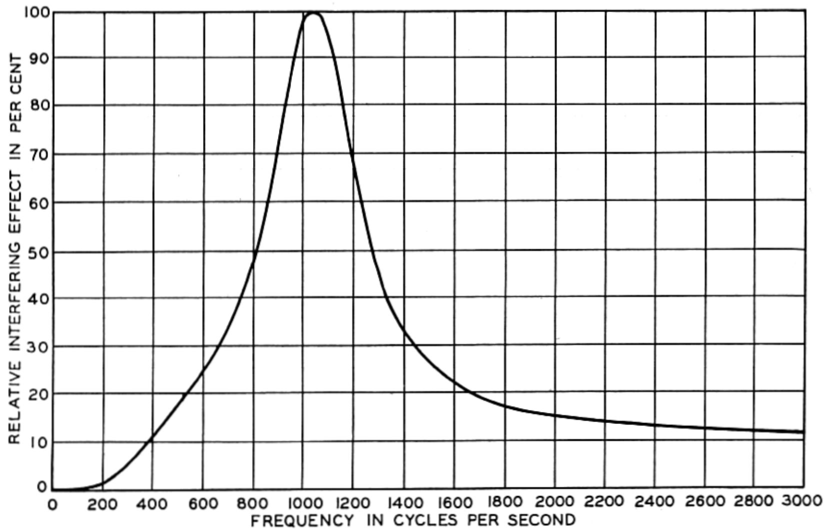


Fig. 9—Curve showing approximate relative interfering effects of voltages of different frequencies across a telephone circuit.

The demonstration set-up for impressing voltages of two different wave shapes on the untransposed power line is shown in Fig. 10. With the switch in the "normal" position, the wave shape is that taken directly from the commercial power supply. A wave shape of voltage having greater harmonic content than that of the commercial voltage, can be secured by throwing the switch to "distorted." The operation of the circuit is then as follows:

1. The commercial power supply is connected to the 10-volt windings of the transformers through balanced resistances which are so proportioned that the voltage drop due to the magnetizing current is sufficient to reduce the voltages across the windings to about 10 volts.
2. The resistances form such a large proportion of the total impedances presented to the incoming circuit that the currents through the windings are controlled almost entirely by them and, since they are non-inductive, this current has approximately the same wave shape as the voltage of the power supply. Therefore, since the magnetizing harmonics cannot appear to any large extent in the magnetizing current, they appear in the voltage across the transformers and the voltage wave is, therefore, distorted.
3. The distorted voltage wave on each transformer is stepped up between the 10 and 115 volt windings and is impressed on the line at about 115 volts to neutral.

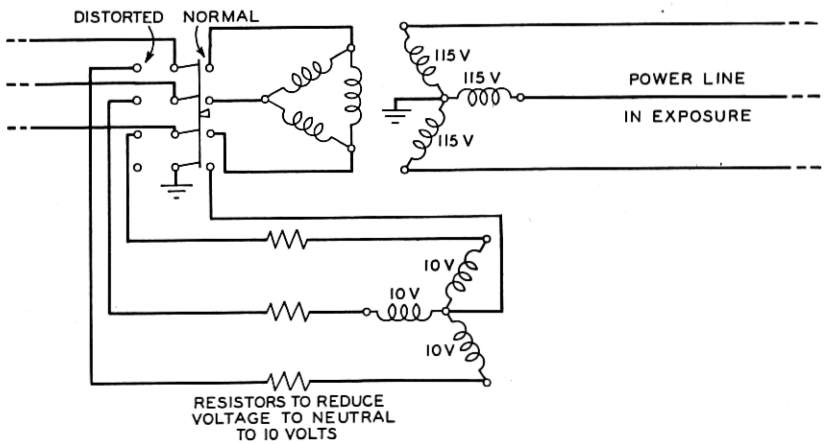


Fig. 10—Arrangement for comparing the inductive influence of balanced voltages of different wave shapes.

Figure 11 is an oscillogram showing the "normal" and "distorted" wave forms and it will be noted that they have about the same r.m.s. values although the distorted wave is much more irregular indicating the greater harmonic content. When the switch is thrown from "normal" to "distorted," the noise from the loud speaker increases and its characteristic sound is changed, indicating the effects of increasing the harmonic content of the voltage wave.

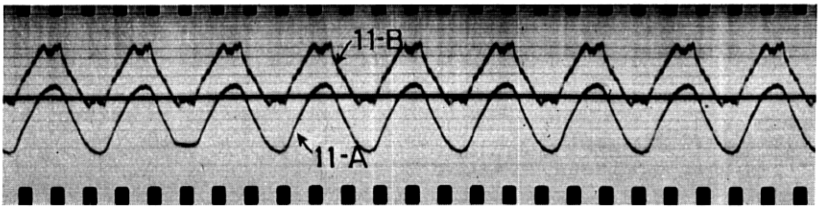


Fig. 11—Oscillograms of normal and distorted balanced voltages.

11-*A*—Impressed voltage,
11-*B*—Balanced distorted voltage to neutral.

In practice, harmonic voltages and currents may arise not only from generating and transforming equipment but also may occasionally arise from some particular load equipment such, for example, as certain types of rectifiers or rotating machinery.

Residual Voltages and Currents

The inductive influence of a voltage or current of a given magnitude and wave shape depends to a considerable extent on the dimensions of the circuit in which it acts. For balanced currents or voltages (or balanced components of the actual currents or voltages on line wires), which, as discussed before, are confined to the wires of the power circuit, the dimensions of the circuit are much smaller than for the residual currents or voltages which involve the earth as part of their circuit.

In order to illustrate the relative inductive influences of a given magnitude and wave shape of voltage, when acting in a balanced manner and as a residual, the miniature power line is energized in two different manners. First (the normal manner) the voltage is impressed on it through a bank of transformers connected "delta" on the supply side and "Y-grounded" on the line side. With these connections, the voltages impressed on the three line wires are approximately equal and 120 electrical degrees apart and thus are closely balanced. Next, using the same transformer connections, the line wires are energized in parallel to earth and consequently, the vector sum (residual) is equal to three times the normal phase-to-neutral voltage. The power circuit connections used are shown in Fig. 12 and the telephone circuit connections used are the same as shown in Fig. 4-*A*. The increase in the noise from the loud speaker when residual voltage is used shows that the influence of the power line is greater under these conditions.

In addition to the effect of residuals in increasing the inductive influence of a power line, the induction due to residuals is not affected by transposing the power line (as was pointed out in connection with the discussion of coupling).

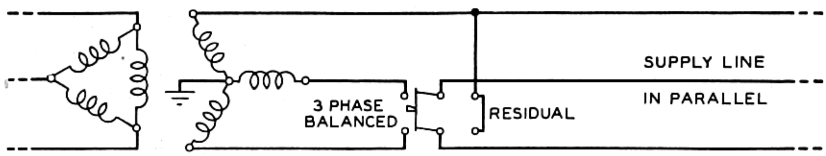


Fig. 12—Arrangement for comparing balanced and residual voltages or currents.

It may be of interest to examine briefly some of the causes of residual voltages and currents. For example, in a three-phase system, harmonic currents or voltages-to-neutral which are odd multiples of three times the fundamental frequency are in phase in all three line wires and hence tend to be residual. Such triples can be present in appreciable amounts only with certain types of power apparatus and connections.

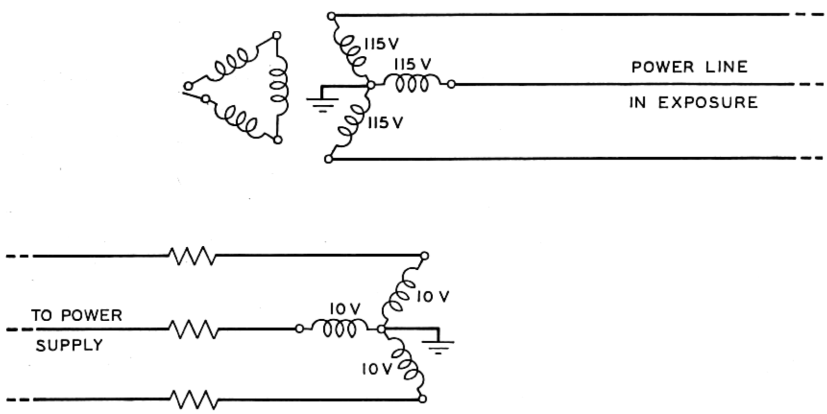


Fig. 13—Arrangement for showing added inductive influence due to triple harmonic voltages.

Perhaps the most important condition giving rise to triple harmonic frequency residual currents or voltages is the connection of grounded-neutral Y-connected generators which have triple harmonic voltages between line and neutral, directly or through Y-Y connected transformer or Y-connected auto-transformer banks (with no or small tertiary windings, and with grounded neutrals) to power lines. The use of Y-Y banks may also cause triple frequency residuals on the lines due to the magnetization characteristics of the transformers themselves although when used with Y-connected grounded generators, the transformer effects are usually less important than the generator effects (unless the "triples" in the generator are unimportant or are suppressed).

To demonstrate the effect of triple harmonic currents, the arrangements shown in Fig. 13 have been set up. This set-up is similar to that used in showing the effect of differences in wave shapes of balanced voltages except that, to show the added effect of triple harmonic residuals, the delta winding is opened. This removes the path for triples to circulate within the transformer bank and permits them to be impressed on the line. Figures 14-*A* and *B* are oscillograms showing the effect on the wave shape of the voltage to neutral of opening the delta. The noise from the loud speaker increases when the delta is opened showing that the triple harmonics cause an increase in the influence of the power line.

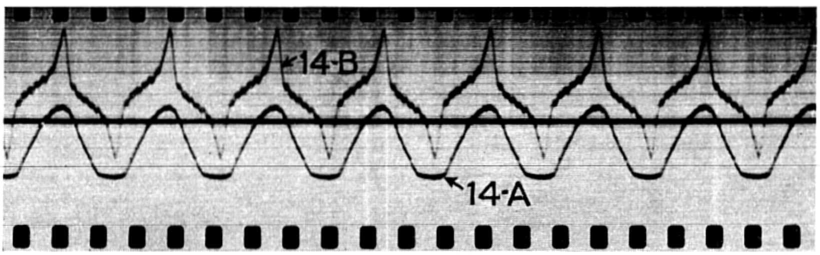


Fig. 14—Oscillograms showing voltage wave shape including triple harmonics.
14-*A*—Impressed voltage,
14-*B*—Distorted voltage to neutral, including triple harmonics.

An interesting demonstration showing the relation as regards residuals of triple and non-triple harmonics on an otherwise well balanced three-phase system can be performed as follows:

1. The untransposed power line is first energized with balanced distorted voltages as described previously. The amount and character of the noise are observed closely.
2. Triple harmonic voltages are added by opening the delta winding on the transformer bank. Under these conditions, the induction from both the triple and non-triple harmonics can be recognized by the differences in the character of the sounds.
3. The power line is now transposed and the noise due to the non-triples practically disappears leaving the noise from the triples unaffected.

This illustrates the residual character of the triples since, as shown previously, the power system transpositions do not affect the induction from residuals.

Single-Phase Extensions

One of the special conditions under which residual currents or voltages (particularly of the non-triple series of harmonics) are set up on a power system is where single-phase circuits are connected metallically to 3-phase circuits. With such a connection, the inductive influence of both the single-phase and 3-phase parts of the power circuit may be affected. Briefly the conditions are as follows:

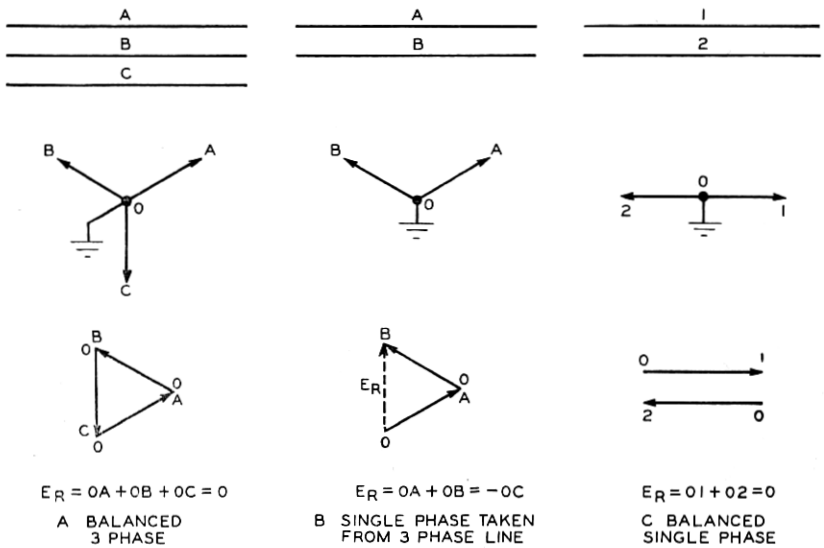


Fig. 15—Comparison of residual voltages in perfectly balanced 3-phase line; a single-phase tap from 3-phase line, and a perfectly balanced single-phase line.

Single-phase portion

1. On the single-phase portion of the circuit, a residual voltage exists which ordinarily is approximately equal to the normal voltage to ground of a phase wire. This is readily evident from an inspection of the vector relations shown on Fig. 15-*B*. Fig. 15-*C* shows that there is nothing inherently unbalanced in single-phase circuits; it is only when they are connected directly to a three-phase circuit or have some unbalanced connections that they have residuals on them.
2. Figure 16 shows schematically the arrangements used to illustrate the effects of metallically connecting a single-phase circuit to a three-phase circuit. By throwing the four-pole, double-throw switch, the noise to ground in the miniature telephone circuit (exposed only to the single-phase circuit) with the single-phase

portion isolated from the three-phase portion by a transformer and with it metallically connected can be compared. With the transformer connected (thereby creating a condition similar to Fig. 15-*C*) the noise in the loud speaker is much lower than when a metallic connection is used and thus indicates a substantial reduction in the residuals.

3. The demonstration setup is so arranged that the single-phase portion can be transposed. With the single-phase portion metallically connected to the three-phase portion, transposing the single-phase portion causes relatively little change in the noise from the loud speaker. However, when the single-phase portion is isolated from the three-phase portion by the transformer, transposing it further reduces the noise materially. When the single-phase portion is connected metallically to the three-phase portion, the induction is largely due to residual voltage and as such is not affected by the power circuit transpositions. When it is connected through the isolating transformer, however, there is no residual voltage present and the induction, being due to balanced voltages, is materially reduced by the power transpositions.

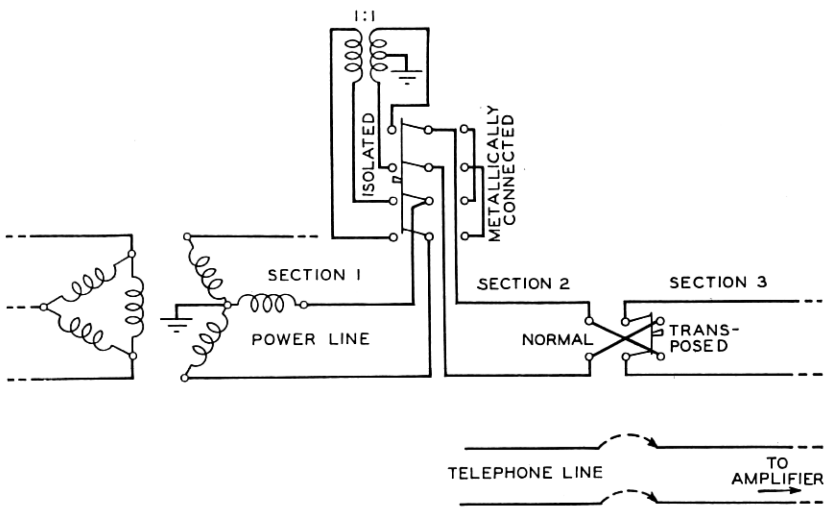


Fig. 16—Influence of single-phase extension to three-phase power line.

Three-phase portion

1. As far as the three-phase portion of the line is concerned, the single-phase extension acts as additional admittance to ground on two of the wires. Consequently if the single-phase extension is long,

the admittance unbalances between the various wires and ground may be fairly large.

2. In considering the effects of the admittance unbalances, there are two conditions which must be considered; where the transformers supplying the three-phase portion are "Y grounded" on the line side, and where they are "delta" on the line side. When the supply transformers are connected delta on the line side, there is no path for residual current into the transformers and the voltages of the conductors to earth adjust themselves so that the net charging current to earth is zero (although there will be some interchange of charging current between various portions of the network). This condition requires unequal voltages to earth, the voltages of the wires having the higher capacitances being lower than those of the lower capacitance wires. This generally gives a residual voltage.
3. When the supply transformers are connected Y-grounded on the line side, the voltages of the wires to ground are controlled by the transformer voltages and the principal effect of a single-phase extension is a tendency to cause residual current.

The discussions above apply particularly to power systems which are electrically short at all of the important harmonic frequencies present. If the systems are long enough so that propagation effects (particularly "quarter wave-length" effects) must be considered at any of the important harmonic frequencies present in the voltage or current waves, these simple analyses must be modified. These propagation effects cannot be demonstrated with the apparatus available and will not be discussed further except to point out that they are not infrequently encountered in field problems.

Inductive Susceptiveness of Telephone Circuits

As pointed out previously, theoretically a telephone circuit could be constructed so that it would not be affected by any fields which would be set up by nearby electrical systems and hence would have zero susceptiveness. However, as in the case of the power line, it is not practicable to build such ideal telephone lines and consequently, the consideration of telephone lines in inductive exposures has to do with the deviations from perfection in this respect.

As was indicated earlier in this article, the metallic type of telephone circuit is now usually used. The grounded system which uses one wire with earth return, was employed exclusively in the very early days and is still used in some cases, particularly in sparsely settled areas.

The grounded circuit represents completely unbalanced conditions since the sides of such a circuit have a separation comparatively great compared to that of a metallic circuit. Consequently, the inductive susceptiveness of a grounded circuit is much greater than that of a metallic circuit, even if the latter is not transposed. Furthermore, a grounded circuit cannot be transposed practicably. To illustrate the difference in the susceptiveness of the two types of circuits, the telephone circuit of the demonstration set up has been arranged as shown schematically in Fig. 17 so that either of the two types of circuits may be obtained. The power circuit arrangements are as shown in Fig. 4-*B*. The large reduction in the noise from the loud speaker which occurs when the connections are changed from grounded to metallic, shows the decreased susceptiveness of the latter type of circuit.

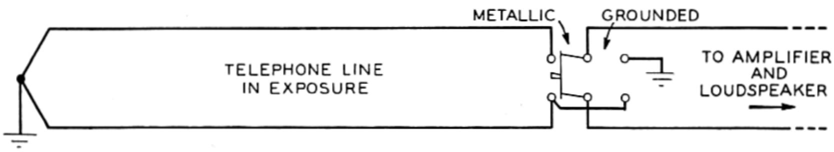


Fig. 17—Comparison of noise in metallic and grounded circuit.

For metallic circuits, the inductive susceptiveness depends on a number of factors such, for example, as the spacing of the wires, the power levels, and the circuit balance. Some of these are discussed below.

Spacing

Since the direct metallic induction (which, as discussed before, is a function of the difference of the voltages induced on or along the two sides of the circuit) is about proportional to the distance between the two sides of the circuit, this separation is of interest from the standpoint of the circuit susceptiveness. The smaller the spacing of the wires, all other things remaining the same, the smaller ordinarily will be the direct metallic induction and the noise-metallic from this source.

Power Level

Another important element in determining the inductive susceptiveness of a telephone circuit is the power level of the telephone waves transmitted over the circuit. The more powerful the telephonic currents at a point, the less they will be interfered with by a given amount of noise power which may be induced in the circuit at that point. This is particularly important on long toll circuits where the telephonic power level may be materially affected by the spacing, power carrying capacity and adjustments of the telephone repeaters usually used in such circuits.

Balance

In order that a telephone circuit may be perfectly balanced, the series impedances of the two sides must be identical in each element of length and the admittances of the two sides to earth and to other conductors likewise must be identical.

Since it is impracticable to construct telephone circuits of perfect symmetry, unbalances exist and these are classified as "series impedance" and "shunt admittance" unbalances. By a "series impedance" unbalance is meant a difference between the series impedances of the two wires composing the circuit. Such an unbalance may be caused, for example, by a joint which does not have a negligible resistance. If a "bad" joint exists, the longitudinal currents due to the induced voltages encounter unequal impedances in the two wires. Consequently, the currents in the two wires tend to be unequal, the difference causing current through the terminal impedances and hence causing metallic circuit noise. The effect of a high resistance joint depends upon the magnitude of longitudinal current along the wires as well as the unbalance in resistance caused by the joint. To illustrate the effects of a high resistance joint, the demonstration set-up is arranged to minimize the noise-metallic due to direct induction (by transposing it) and the high resistance joint is then inserted. (See Fig. 18.) The large increase in the noise from the loud speaker indi-

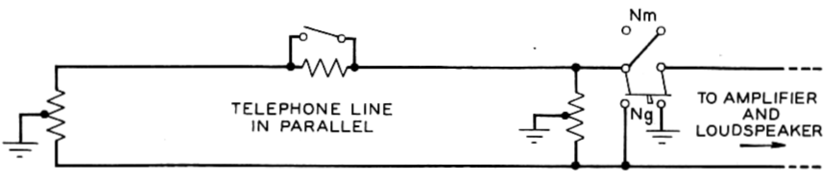


Fig. 18—Arrangement for showing effect of high resistance joint in telephone line.

cates the effect of the joint on the noise-metallic. On the other hand, listening to the noise-to-ground when the joint is inserted, one can detect no effect.

Admittance unbalances are generally due to either unbalanced capacitances or leakages to earth of the two wires. Such unbalances when acted on by the noise to ground cause more current to flow to ground from one side than from the other. Part of this current flows around the metallic circuit and causes noise-metallic. To illustrate the effect of an admittance unbalance, a small condenser or a high-resistance leak can be bridged between one wire of the telephone circuit and earth in the demonstration apparatus. As before, the effect of the unbalance on the noise to ground is negligible, but it may cause a material increase in the noise-metallic.

While a 2-wire metallic telephone circuit has been used in the discussions, the same principles apply to a phantom circuit. In considering the effects of unbalances, transpositions, etc., on phantom circuits, the two wires composing each of the side circuits from which the phantom is derived may be considered as being in parallel and treated as if they were single conductors. With this method of treatment, the discussions of a 2-wire circuit can also be applied to a phantom circuit, bearing in mind, among other things, that with four wires to treat with instead of two, an unbalance in any of the four wires will react on the phantom circuit as well as on the side circuit of which it is a part.

While for simplification the demonstration has been confined to the effects of unbalances in the line conductors, it is evident that similar effects can result from the equivalent series or shunt unbalances in terminal equipment in central offices, in subscribers' sets, cables, etc.

Interconnection of Balanced and Unbalanced Telephone Circuits

One of the factors which is of interest in connection with noise on telephone circuits is that which is concerned with the phenomena which occur when a well balanced and a poorly balanced telephone circuit are connected together. It was pointed out previously that a well balanced and transposed telephone circuit may be relatively quiet even if it is exposed to induction. Also, if a poorly balanced circuit is not exposed to induction, it may be quiet. If, however, the exposed, well balanced circuit and the unexposed, poorly balanced circuit are connected together either at some point along the line or through a cord circuit not containing an isolating repeating coil, the overall connection may be noisy since the interconnection in effect unbalances the otherwise well balanced circuit.

To demonstrate this the conditions shown in Fig. 19 are set up. The metallic portion of the circuit at the left of the diagram is exposed to the 3-phase power line but is well transposed and balanced. The grounded circuit, shown at the right of the diagram, is not noticeably exposed.

The noise heard when the loud speaker is connected to the metallic circuit (although it is exposed) is relatively low. Likewise, the noise on the grounded circuit is relatively low. When, however, the grounded circuit is connected to the metallic circuit the noise on the overall circuit immediately rises because of the unbalancing effect of the grounded circuit.

It will be recognized that the general principles involved in this last demonstration are essentially the same as those which were involved in the demonstration of the effect of a single-phase extension to a 3-phase

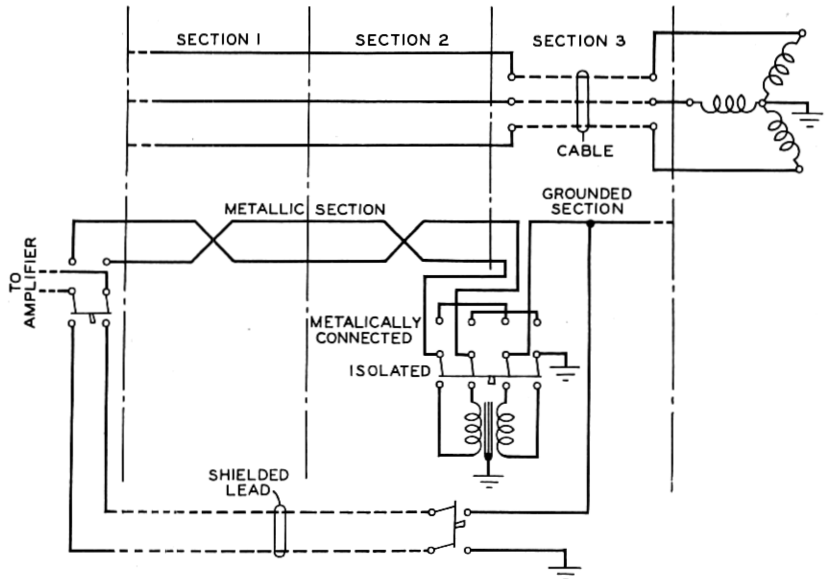


Fig. 19—Effects of interconnecting metallic and grounded circuit.

power line. In the case of the single-phase extension, it was possible to reduce the inductive influence by isolating the single-phase part from the 3-phase part by means of an isolating transformer. Following the same line of reasoning, it should be possible to reduce the effect of the connection between the metallic and grounded parts of the telephone circuit by means of an isolating transformer. Inserting a repeating coil between the metallic and grounded portions provides such isolation and it is noted from the reduction in noise when this repeating coil is inserted, that the conditions are essentially the same as when the grounded portion is disconnected from the metallic portion. (This whole analysis and demonstration, of course, applies only when the grounded portion is unexposed since the grounded circuit is totally unbalanced and hence would quite likely be noisy if it were subjected to direct induction.)

Carrying the similarity of these two demonstrations a step farther, it will be recalled that it was shown that when the single-phase and 3-phase portions of the power circuit were metallically connected, transposing the single-phase portion resulted in relatively small reduction in the inductive influence because the induction was primarily a function of the residuals on the line. Similarly when the metallic and the grounded circuit are metallically connected, it is observed that the transposing of the metallic circuit produces a relatively small reduction in noise. However, if the repeating coil is inserted between the metallic and grounded circuits it is observed that transposing the metallic portion materially reduces the noise on the overall connection, since the transpositions reduce direct induction in the metallic circuit and the noise to ground is not given an opportunity to react on the unbalances.