Some Aspects of Low-Frequency Induction Between Power and Telephone Circuits *

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This article discusses the phenomena involved in low-frequency induction between power and telephone circuits and describes a demonstration which has been developed to illustrate certain of them.

INTRODUCTION

IN the practical problem of inductive coordination between power and telephone circuits, there are two aspects to be considered:

1. Induction within the frequency range used in transmitting speech which may result in disturbing noise in telephone receivers. This phenomenon is usually associated with the normal operation of power and telephone systems although abnormal conditions in either system may result in a large increase in the noise.
2. Induction at the fundamental frequencies used in the transmission of power. This is commonly referred to as "low-frequency induction" and in some cases may reach such magnitudes as to interrupt telephone service, constitute a hazard to telephone employees and produce other detrimental effects. Induced voltages of magnitudes sufficient to cause operating difficulties in telephone circuits occur usually only under abnormal power circuit conditions which produce large currents in the earth. Under normal circuit conditions, three-phase power circuits are so nearly balanced with respect to ground at their fundamental frequency that induction at this frequency is rarely sufficient to seriously affect well balanced telephone circuits.

Both types of induction have been and are being intensively studied cooperatively by the power and telephone industries. Much of this work has been handled through the Joint General Committee of the National Electric Light Association and Bell Telephone System which was formed in 1921 and it is now being carried forward by the Joint General Committee of the Edison Electric Institute and Bell Telephone System.

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* This paper appeared in somewhat different form in *Amer. Railway Assoc. Proc.*, June, 1934, under the title "Demonstration of Low-Frequency Induction Between Power and Telephone Circuits" by H. R. Huntley.

Since the inductive coordination of power and telephone plants inherently involves the characteristics of both systems as well as the physical relations between them, problems can be effectively handled only by joint consideration in each specific case. As pointed out in a previous article dealing with noise induction,[1] effective cooperative action depends upon an adequate mutual understanding of the principles involved in coordination. Many of these principles can be demonstrated using comparatively simple apparatus.

This article describes a demonstration that has been developed to illustrate some of the more important factors concerned with low-frequency induction between power and telephone circuits, together with a discussion of this subject along the lines which would be followed in presenting the demonstration.

DEMONSTRATION APPARATUS

The demonstration apparatus consists of two separate arrangements as follows:

(*a*) For many of the demonstrations, a miniature inductive exposure, consisting of a three-wire power line and a two-wire telephone line can be used. The power line is energized at a comparatively low voltage from a three-phase bank of transformers. The telephone line can be grounded at either or both ends and by means of a voltage measuring device, consisting of an amplifier and a projecting meter, a qualitative indication of the voltage along it or between it and ground can be obtained.

(*b*) For other demonstrations, a fairly high voltage in the telephone circuit is required, but since it is impracticable to secure this voltage using the miniature inductive exposure, it is necessary to use an iron core transformer. In order to improve the safety conditions when using this higher voltage, the miniature lines are not used and the circuit is entirely separate from that used in the low-voltage demonstrations.

A power supply frequency of 60 cycles per second is used. The phenomena illustrated are, however, applicable for all other frequencies commonly encountered in power transmission and distribution circuits.

In a demonstration of this kind, where the exposure is compressed into a small space and where the amount of power available is limited, it is obvious that the results can have no quantitative significance. This demonstration, therefore, is designed only to provide qualitative illustrations of some of the principles involved.

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[1] "Some Theoretical and Practical Aspects of Noise Induction," by R. F. Davis and H. R. Huntley, published in *Bell System Technical Journal*, October, 1933.

FUNDAMENTALS OF PROBLEM—MAGNETIC INDUCTION

Induction arises due to the fact that any wire transmitting electricity is surrounded by electric and magnetic fields which may cause voltages to appear on other wires in these fields. The relative strengths of the electric and magnetic fields depend on the characteristics of the circuit, the former being a function of the voltage on the circuit and the latter a function of the current in it. Induction due to electric fields is commonly called "electric induction" while that due to magnetic fields is called "magnetic induction."

When a ground occurs on a power line there are two factors which influence the induction into neighboring telephone circuits:

(*a*) The residual voltage is increased, which increases the electric induction.

(*b*) The residual current is increased, which increases the magnetic induction.

Both from theoretical analyses and experience it is known that magnetic induction is more important than electric induction in most cases of low-frequency induction. Consequently, the demonstration is concerned only with magnetic induction, i.e., induction due to the power system currents.

The magnetic field about a wire faulted to ground and carrying fault current is shown in Fig. 1. This magnetic field varies in proportion to the current in the wire causing it. If other conductors, such as the pair of telephone wires shown in Fig. 1, lie within this field there are induced along them voltages proportional at every instant to the time rate of change of the magnetic flux which links the wires.

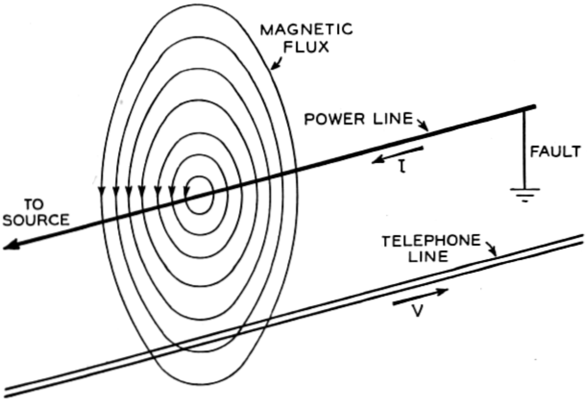


Fig. 1—Process of induction from currents.

Consider first that the inducing circuit carries direct current. In such a case, as long as the magnitude of the direct current does not change, the magnetic flux is constant and no voltage will be induced in a paralleling telephone wire. However, if the current in the inducing wire changes suddenly, the flux about it changes in the same proportion and voltage is induced momentarily in the paralleling wire. The magnitude of this impulse of voltage will be proportional to the rate at which the flux changes and the voltage will last only as long as the flux is changing. Rapid changes in the current in direct current circuits, with consequent voltage impulses on paralleling telephone circuits, may occur when power apparatus is turned off or on. Also, of course, if a short circuit occurs, the current may rise very rapidly and then fall very rapidly as the circuit breaker operates. While the consideration of these direct current phenomena are important in some situations, they are not included in this demonstration and will not be further considered.

In the alternating current case, the current in the inducing wire is continually alternating so that the flux about it is continually alternating. Consequently, there will be induced in a paralleling wire, an alternating voltage proportional to the inducing current. It should be noted particularly that the induced voltage acts *along* the wire rather than between the wire and ground.

General Nature of Phenomena

In applying these principles of magnetic induction to the low-frequency induction problem, only the conditions which exist when a power circuit is faulted to ground and before the current is interrupted (usually by the operation of circuit breakers) need be considered. The current of interest during this time is that which flows out over the power line wires and returns through the ground, called "residual" current. The voltage induced is along the telephone wires in parallel. Since the telephone circuits are metallic, the talking paths over them are usually not seriously affected by the fundamental frequency voltage unless this voltage causes the telephone protectors to operate. Service over grounded telegraph circuits may, however, be impaired even if the induced voltage does not reach values high enough to operate protectors, and the telephone circuits under this condition may be made noisier than usual.

It can be seen that the electrical phenomena in which we are interested will be affected by three basic factors. The first of these is concerned with the "magnetic coupling" between the power and telephone lines, considered with ground return for the reasons pointed out above. This coupling is a function of the strength and frequency of alternation of the flux set up at the location of the telephone line by a given amount of ground return current in the power line. The second factor is concerned with the amount of ground return current in the power circuit at the time of a ground fault since, for a given coupling, this will determine the strength of the magnetic field. The third factor is concerned with the conditions in the telephone plant which determine its reactions to a given induced voltage. Each of these three factors is taken up individually in the following discussion.

Since low-frequency induction between power and telephone circuits involves a series of separate and distinct occurrences, it is evident that the frequency with which ground faults occur on the power lines, the locations and circumstances of the various faults, the particular conditions in the telephone system at the time of such faults, etc., are also important. These matters are all subject to fortuitous variations so that there are many probability factors that must be considered in the study of any low-frequency induction problem. These probability factors cannot be demonstrated with the apparatus available.

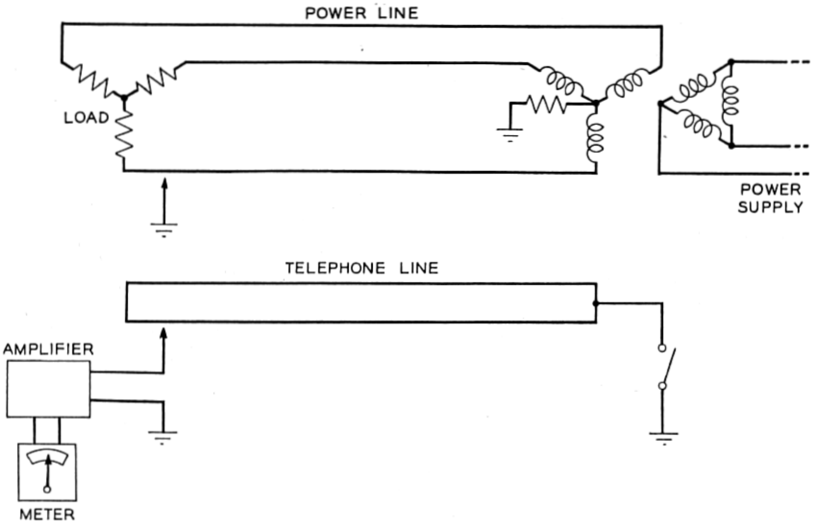


Fig. 2—Demonstration of nature of low-frequency induction.

In order to illustrate the general nature of the electrical phenomena, Fig. 2, which shows parallel power and telephone systems with the power line supplying a load, has been simulated using the miniature lines. The load current may be substantial in magnitude but is normally confined to the line wires and is commonly called "balanced current." Under this condition, the induced voltage is small. If, now, one of the power conductors is grounded, current will flow to ground at that point. This current is the "residual current" mentioned previously. When this is done in the demonstration in such a way that the residual current flows through the exposure, the voltage induced along the telephone circuit rises very materially. Also, since the induced voltage acts along the telephone circuit, opening the ground connection at the far end of the telephone line reduces the voltage shown by the meter to a very small amount.

That the power current causing the induction is unaffected by transpositions in the power circuit, can be shown by transposing the power circuit in the set-up. No appreciable change in the induced voltage occurs when this is done. Likewise the induced voltage, since it is induced along the telephone wires in parallel, is unaffected by telephone circuit transposition, as can be shown by transposing the telephone circuit. Consequently, the matter of power or telephone circuit transpositions can be neglected in the further analysis.

Coupling Factors

Using the demonstration arrangements, some of the basic factors in coupling can be observed. For example, since the voltage is due to magnetic induction and accumulates along the telephone circuit, the coupling should be proportional to the length of the (uniform) exposure through which the fault current flows. This can be observed by noting the reduction in induced voltage as the fault on the power line is moved from the end of the exposure toward the supply end. (In the demonstration, the fault current is the same regardless of the location of the fault.)

Likewise, if the voltage accumulates along the telephone circuit, the longitudinal voltage measured should be proportional to the length of telephone circuit exposed. This can be observed by again placing the fault on the power line at the end of the exposure and moving the measuring point along the telephone line. As this point is moved toward the grounded end, the indicated voltage goes down.

Another basic factor in coupling is its relationship to the separation between the lines. Generally speaking, the greater the separation, the smaller the coupling. How much coupling will exist for a given separation depends on a number of factors, one of which is the structure of the earth. This effect will be discussed first.

In the type of problem we are considering the telephone wires comprise one side of a long loop, the other side of which is the earth. Likewise, the power wires comprise one side of a loop, the other side being the earth. It is a well known fact that the magnetic coupling between two parallel loops at a given separation increases as the sizes of the loops increase. The sizes of the loops in the case being considered are determined by the distribution of the return current in the earth.

A great deal of theoretical and experimental work has been done in connection with the analysis of the distribution of current in the earth, and it has been found that one of the important factors is the "resistivity" of the earth. The effect of resistivity of the earth can be briefly summarized as follows:

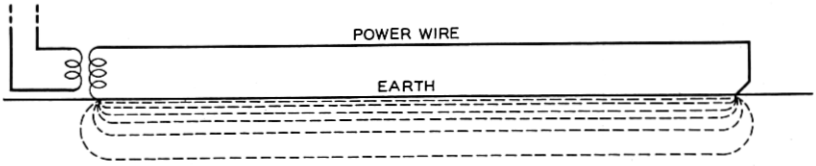
(*a*) Considering the outgoing and return paths for residual current on a power line, the mutual induction between the current in the wires and the return current in the earth tends to pull the earth currents together and to concentrate them under the line as near the surface as practicable. This action tends to decrease the coupling to an adjacent circuit by decreasing the effective separation of the sides of the loop.

(*b*) The resistance which the current encounters in flowing through the earth tends to make it spread out because, by so doing, the current density is reduced and the voltage drop is consequently reduced. This spreading out tends to increase the coupling to an adjacent circuit.

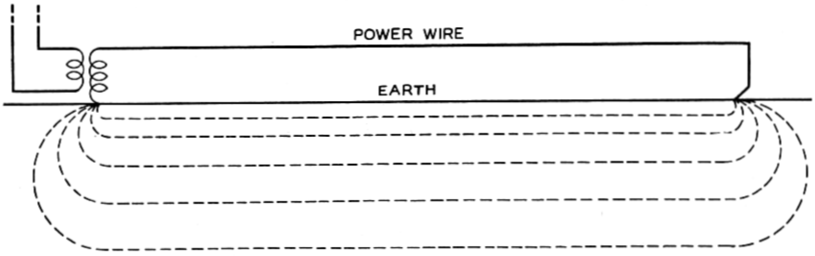
(*c*) The net distribution of the current in the earth is a balance between these two opposing tendencies and this distribution will be different for different resistivities of the earth. Generally speaking, the greater the resistivity of the earth, the more the current will spread and the greater will be the coupling to an adjacent circuit.

Figure 3 is a graphical representation of how the return current in the earth tends to spread with an increase in earth resistivity. While this figure shows only the vertical spread, a similar spreading also takes place horizontally.

The effect of the sizes of the primary and secondary loops on the coupling is greater when the loops are widely separated than when they are close together. For this reason, the effect of earth resistivity on coupling is much greater for wide separation exposures than for exposures where the lines are close together. Consequently, with high resistivity earth, the coupling not only is higher at all separations



A—LOW RESISTIVITY EARTH



B—HIGH RESISTIVITY EARTH

Fig. 3—Current distribution in earth of different resistivities.

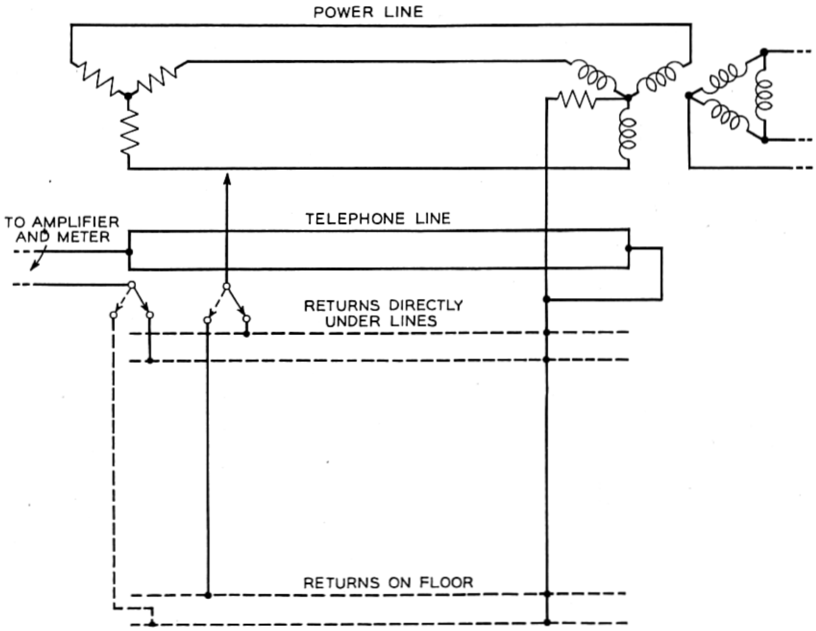


Fig. 4—Demonstration of effects of depth of return current in earth.

than with low-resistivity earth, but (except for very wide separations) the percentage reduction secured by increasing the separation a given amount is smaller.

Figure 4 shows a schematic of a demonstration set-up to show some of these effects. It is, of course, impracticable to employ earth of different resistivities in a demonstration of this kind, but the difference between return current which concentrates near the line and that which is more remote can be roughly indicated. In order to illustrate the fact that when the currents are concentrated closely under the line, the coupling falls off rather rapidly as the separation is increased, returns immediately under the lines are used and the telephone line is moved to change the separation. To illustrate that a wider distribution of current in the earth tends to increase the coupling and to make it less affected by separation, returns on the floor are used for both the power and telephone lines. It can be shown that:

(*a*) The induced voltage increases when the connections are changed from the upper to the lower returns.

(*b*) When the upper returns are used, *the percentage reduction* in induced voltage when the separation is increased, is greater than the percentage reduction when the lower returns are used and the separation is increased by the same amount, i.e., when the telephone line is moved between the same positions of minimum and maximum separation.

If the earth is not homogeneous, that is, has strata of different resistivities, the distribution of the earth current is distorted and varying effects are noted. Where local irregularities exist, marked and sometimes erratic changes in coupling may occur within comparatively short distances. An "effective" earth resistivity can usually be determined by test even where the earth is stratified.

Another important factor in determining the net coupling between power and telephone circuits is the effect of grounded wires or other linear grounded metallic structures along the inductive exposure. Voltages are induced in such grounded metallic structures in the same way as voltages are induced in telephone wires and these voltages cause currents. The magnetic fields accompanying these currents generally oppose those from the power wires and reduce the induction in the telephone circuit. The effect of such currents in grounded structures is generally spoken of as "shielding."

The amount and phase of the current in a grounded conductor in a given location and hence the shielding provided by it depend on the impedance of the conductor with earth return. Hence the shielding is increased when the resistance of the conductor and its ground connections is reduced.

In order to illustrate these effects, the demonstration shown in Fig. 5 has been set up. With the shield wire on the power line, the shielding effect can be shown under two conditions as follows:

(*a*) When the switch directly grounding the shield wire is closed the induced voltage in the telephone circuit goes down materially due to the shielding effect of the current in the shield wire.

(*b*) When, instead of grounding the shield wire directly, it is grounded through a small resistance, the reduction in induced voltage is much smaller because the resistance limits the current in the shield wire.

In order that a conductor may exert a shielding effect, it must have a substantial coupling to either the power or telephone line; i.e., it must be fairly close to one or the other. By moving the wire shown in Fig. 5 it can be demonstrated that:

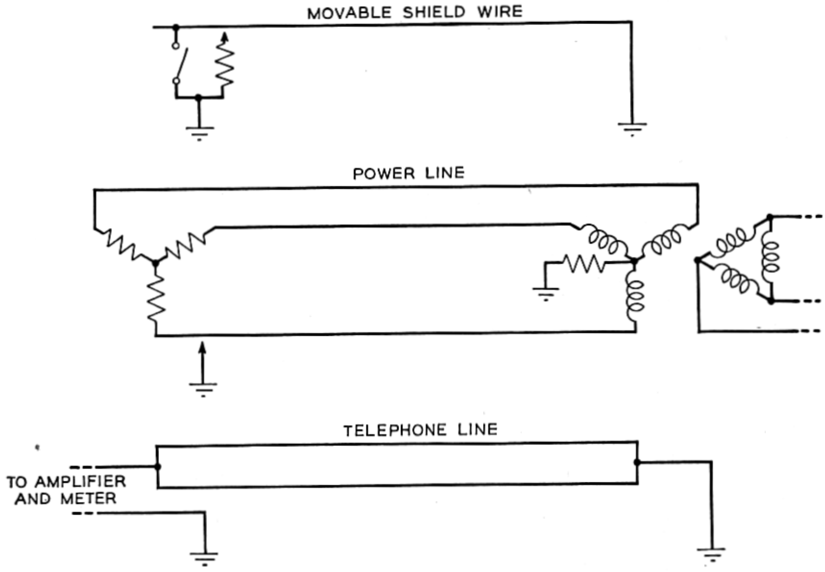


Fig. 5—Demonstration of shielding effect of grounded wire.

(*a*) With the shield wire on the power line or on the telephone line, substantial shielding is secured.

(*b*) If the wire is moved outside the exposure, the shielding is reduced to a small value.

While the demonstration shows only the effect of a grounded wire on or near the power or telephone lines, similar effects in varying degrees may be caused by such grounded metallic structures as underground pipe lines, railroads where the rails are bonded in long lengths, trolley lines, etc. In many situations the shielding effects of such structures may be substantial.

Another type of grounded conductor which may give substantial shielding is the metallic sheath of a telephone or power cable. A cable sheath will effect some shielding on conductors which are not enclosed by it in the same way as any other grounded metallic conductor, but the major shielding effect is experienced on conductors within the sheath. The shielding effect of a cable is, as in the case of a shield wire just demonstrated, determined to a considerable extent by its impedance with ground return.

Shielding due to a telephone cable can be demonstrated using the set-up shown in Fig. 6 and it is noted that:

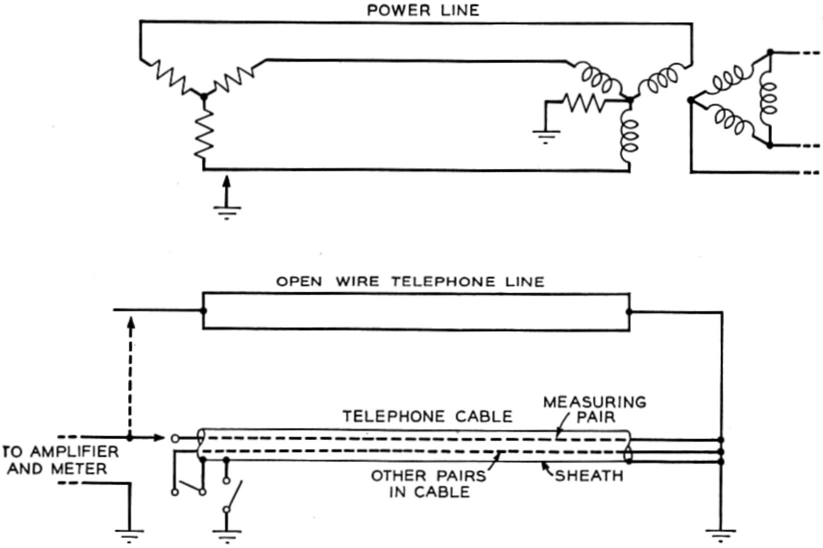


Fig. 6—Effect of cable shielding.

(*a*) The voltage along a conductor inside the cable is reduced when the sheath is directly grounded at both ends.

(*b*) If the effective resistance of the sheath is reduced by paralleling with it some of the conductors inside, the shielding is increased (i.e., the reduction in voltage is greater).

(*c*) When resistance is added in one of the sheath-to-ground connections, the shielding effect of the sheath and conductors is reduced.

(*d*) If the shield wire is grounded its effect is cumulative[2] with that of the cable sheath and conductors.

(*e*) The voltage along the open wires on the line is reduced when the cable is grounded at both ends. Here again, of course, the effect of the shield wire is cumulative[2] with that of the cable sheath and conductors.

The same shielding effects could be shown if the power instead of the telephone circuit were in cable. Also, of course, if there is more than one power or telephone cable, the shielding is increased. Iron armoring also tends to increase the shielding.

Power Circuit Conditions

Having illustrated some of the factors affecting coupling let us now review briefly the factors affecting the current in the power line at times of ground fault. Not only is the current flowing to ground under fault conditions on a power line usually greater than the current under normal operating conditions, but it is also a fact that a given current in a ground return circuit induces a larger voltage along a paralleling telephone circuit than the same amount of current if confined to the phase conductors. That the induced voltage depends on the amount of residual current can be demonstrated as shown in Fig. 7. Here a

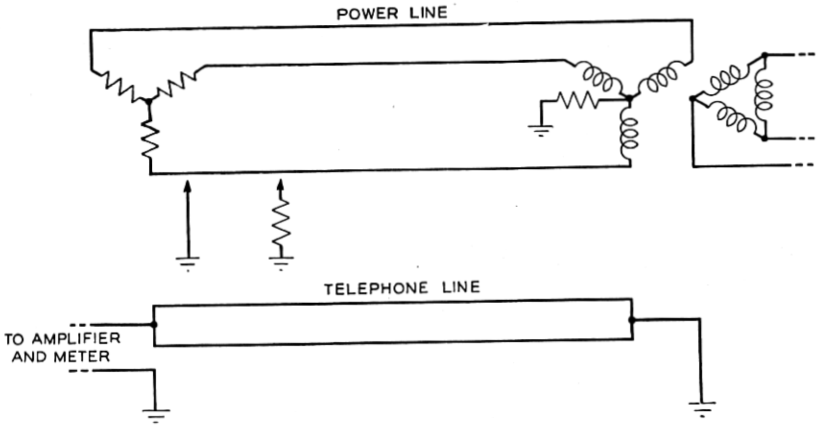


Fig. 7—Comparison of induced voltage with different amounts of residual current.

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[2] While the benefits are "cumulative," the individual effects are not directly additive due to mutual reactions between the different shielding conductors, the net effect being less than the total of the effects of each shielding conductor acting alone.

comparison is made between the induced voltage for two residual currents, one greater than the other. With larger current, the voltage indicated on the meter is larger. The resistance inserted in the fault to reduce the current in this demonstration might be thought of as simulating added impedance anywhere in the ground return circuit through the fault. For example, it might be thought of as simulating the effect of the line impedance which would be added if the fault occurred at some distance beyond the end of the exposure. Also, its effect is the same as would be produced by an increase in the reactance of the supply transformers or in the neutral-to-ground connection; or by an increase in the local resistance at the fault itself.

In analyzing the impedances further, there are two general types of power systems which must be considered: the "grounded neutral" and "isolated neutral" systems. These are illustrated in Fig. 8. In the grounded neutral system, the neutrals of one or more transformer banks are grounded directly or through impedance so that in the event of a fault, a path for current is established from the fault through the earth and back to the system through the neutral-to-ground connections. In the isolated neutral system there are normally no grounds on the system so that in the event of a fault the only path for fault currents is through the capacitances of the unfaulted phases to earth or through a second fault if one exists. Hence for a single fault, the fault current is limited to the charging and leakage current.

Figure 8-*D* shows for a grounded neutral system, the equivalent single-phase circuit for residual currents. In an actual line, the circuit conditions are, of course, usually much more complex than those shown. In even the simplest situations, there are usually other lines, generator points, or grounding points which supply some fault current. However, for the purpose of examining the fundamental phenomena, the simplified diagram can be used. As can be seen, the impedances which control the residual current are those associated with the fault, the line impedance, those in the transformer and generating equipment and the impedance, if any, in the neutral-to-ground connection. Impedances in any of these places tend to limit the fault current.

Figure 8-*C* shows a simplified diagram of the equivalent single-phase circuit of an isolated neutral system with a single-phase fault-to-ground. For this condition, it is evident that the fault-current path includes the capacitances to ground of the unfaulted phase conductors. In a small system these capacitances will be small and the fault current will, therefore, also be small, particularly if the voltage is not high. In extensive systems or systems having much

cable, the capacitances and hence the fault current may be fairly large, particularly if the voltage is high. Of course, in an actual system the capacitances to ground are distributed throughout the system so that the amount of residual current in the lines will vary from location to location, being a maximum at the fault and tapering to zero at the end of each branch of the system.

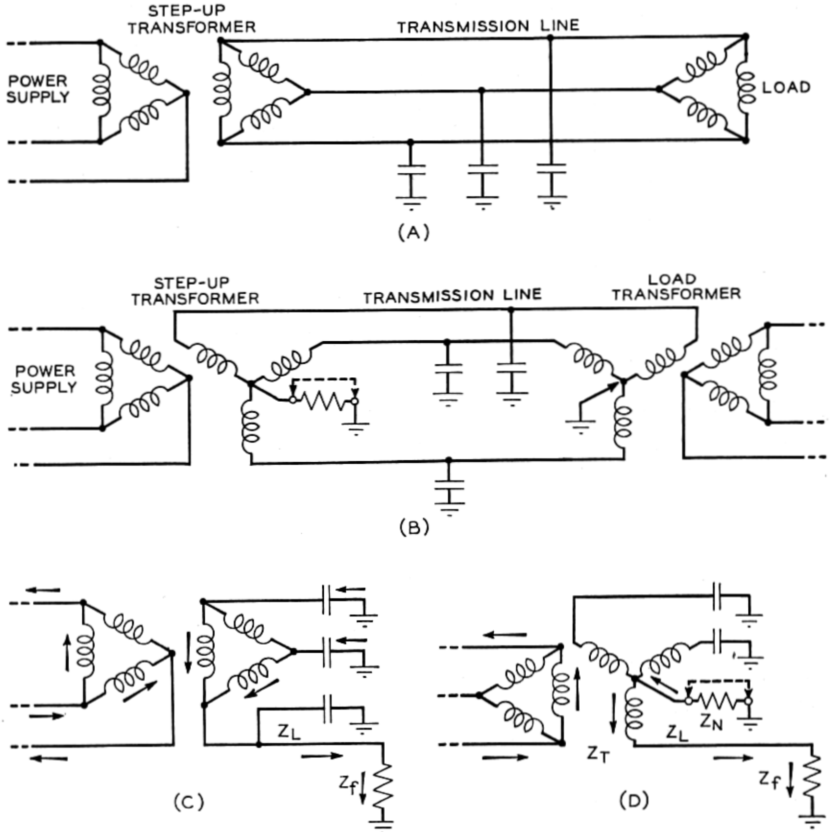


Fig. 8—Types of power systems. (*A*) Isolated neutral system under normal conditions. (*B*) Grounded neutral system under normal conditions. (*C*) Isolated neutral system with single fault. (*D*) Grounded neutral system under fault conditions.

If, in a power system, a second fault-to-ground occurs on another phase while the first persists, a large residual fault current will exist in the line between the faults even if the neutrals are isolated. Simultaneous faults on two phases at different points may occur on any type of system, but are more likely to occur on an isolated neutral system than on one in which the neutral is solidly grounded. This is due to the fact that for the isolated system, full phase-to-phase or possibly higher voltage is impressed between the unfaulted phases and ground, thus increasing the voltage stress on the insulation of the entire system during the time of fault.

Figure 9 shows a demonstration set-up to illustrate the effects of faults on an isolated neutral system which is small enough so that the capacitances are negligible. It will be noted that when a single fault is put on the line at the far end, no appreciable rise in voltage on the telephone line occurs. However, when a second fault is put on another phase at the near end, the induced voltage immediately rises. In order to illustrate that the current is residual only between the faults, the faults can be moved closer together. When this is done, the induced voltage decreases until, with the faults at the same point, it practically disappears. The small remaining voltage is largely due to balanced current induction due to the heavy load on the power line when two of the phases are shorted.

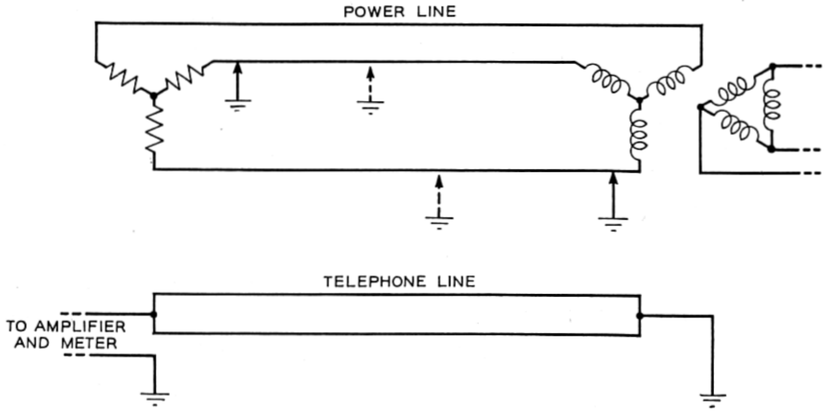


Fig. 9—Demonstration of effect of faults on isolated neutral system.

A system grounded through a neutral impedance, such as when resistance or reactance is included in the neutral-to-ground connections or when a high reactance grounding bank is used, partakes of some of the characteristics of an isolated neutral system. Generally speaking, the addition of neutral impedance tends to reduce the fault current, this effect being proportionately larger for faults near the neutral grounding points. This reduction in fault current tends to reduce the voltage induced on nearby telephone lines and in some cases may reduce the "shock" to the power system and the damage at the point of fault. On the other hand, increasing the neutral impedance tends to increase the difficulty of securing adequate selectivity in power system relay operation and to make a more complex relay system necessary. It also tends to increase over-voltages on the power system and to reduce the factors of safety for lightning arrestors.

In addition to the magnitude of the residual current, its duration is of importance since the length of time that the induced voltage persists on a telephone circuit has important reactions on its effects. For example, the chance of permanently grounding telephone protectors, with consequent interruption of service until the protector blocks are replaced, depends not only on the amount of current through the blocks but upon its duration. Likewise, many of the other effects, which are described later, are materially affected by the duration of the induced voltage. Since, except for self-clearing faults, the duration of fault current is determined by the time of operation of the relaying system, the reliability and speed of operation of the latter is an important factor. There are many types of relaying systems and it is not practicable to go into a discussion of them here except to point out that rapid and reliable relaying is usually simplest on a solidly grounded neutral system. For systems with large impedances in the neutrals, it may be difficult to secure rapid fault clearance, particularly if the system layout is complicated. For isolated neutral systems, rapid relaying on ground faults may be very difficult or impracticable.

Telephone Circuit Conditions

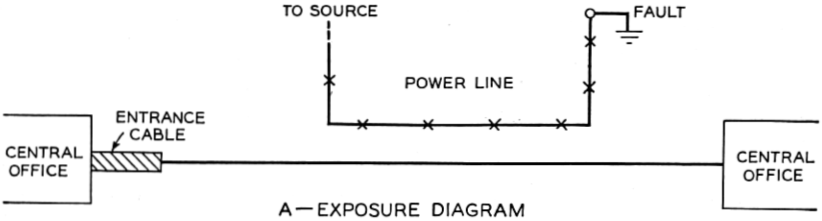
The voltage due to magnetic induction accumulates *along* the telephone circuit and can be represented as a voltage in series with the telephone wires. Figure 10 shows schematically how this voltage acts. The two sides of the metallic telephone circuit are assumed to have the same induced voltage and impedance and are shown here replaced by a single equivalent conductor. The total voltage which is equal to the product of power line fault current and coupling is represented by a number of generators connected in series through impedances representing, in total, the line impedance inside the exposure. At the ends of the exposure are connected impedances representing those in the line and between line and ground outside of the exposure. The longitudinal induced voltage acting through the series and shunt impedances of the telephone line will produce the following conditions of interest:

(*a*) Voltages between the telephone wires and ground at various places along the telephone line.

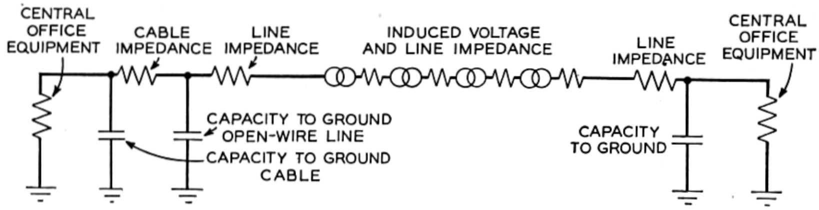
(*b*) Current in the longitudinal telephone circuit.

(*c*) Voltages between different wires on the telephone line.

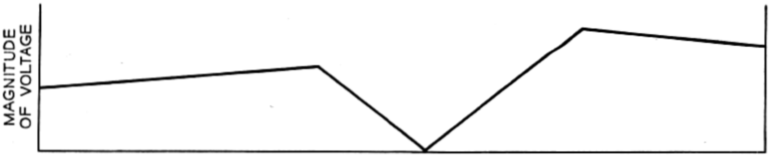
Telephone circuits are supplied with protective devices. The part of the telephone protective system of most interest in connection with low-frequency induction is the carbon-block protector. This device provides a small air gap between carbon surfaces one of which is connected to the telephone conductor and the other to ground or cable sheath. When an excessive voltage is impressed on the telephone conductor an arc is established in the air gap thereby grounding the conductor. Protectors are located at central offices and at other points, such as at junctions of open wire and cable where it is desired to limit voltages on telephone wires due to lightning, contacts with power systems, induction, and other extraneous voltages.



A—EXPOSURE DIAGRAM



B— DISTRIBUTION OF ADMITTANCES AND IMPEDANCES



C—DISTRIBUTION OF VOLTAGE-TO-GROUND

Fig. 10—Distribution of voltage to ground before protectors operate.

In analyzing the distribution of induced voltage between a telephone circuit and ground assume first that no protectors are operated. Under this condition, the voltages to ground on the telephone wires at various points are determined by the impedances between the wires and ground along the line and at central offices where equipment is connected to them. The voltage to ground at either end of the exposure is equal to the longitudinal current times the impedance-to-ground seen looking away from the exposure at that end. Figure 10-*C* illustrates how the voltages may distribute due to the distribution of impedances between the wires and ground along the line and in the central office equipment. Of course, in practice, the variety of impedance distributions encountered is almost infinite and the corresponding voltage distributions vary over a wide range.

If voltage-to-ground at any point where protectors are located exceeds the operating voltage of the protector, the protector operates and three things happen:

(*a*) The voltage-to-ground at the place where the protector operates is reduced to a low value. This makes the longitudinal voltage pile up at the protectors at the opposite end, and in most cases, they will also operate.

(*b*) The operation of the protectors at the two ends completes a loop consisting of the telephone circuit and ground so that the induced voltage will cause current to flow through both protectors.

(*c*) The voltages-to-ground on the circuits on which protectors have operated are changed and redistributed and the voltages on the other telephone circuits are also changed and redistributed due to shielding, as discussed later.

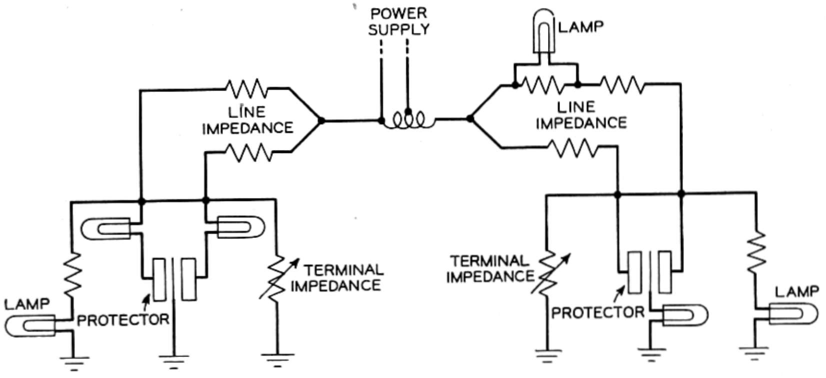


Fig. 11—Demonstration showing effect of terminal impedance on voltage distribution.

All of these effects take place within a very short time after the longitudinal voltage is applied so that for all practical purposes they can usually be considered as being instantaneous.

In order to illustrate these phenomena, the demonstration shown in Fig. 11 can be used. In this demonstration the longitudinal voltage is impressed by means of a power transformer in order to secure a sufficiently high voltage. A general idea of the relative magnitudes of the voltages at the two ends can be had by observing the brilliancy of the voltage measuring lamps. By varying the slide wires which control the terminal impedances the proportions of the total voltage which appear at either end are changed and an idea of the changed distribution can be obtained by observing the changing glow of the measuring lamps. Finally the voltage at one end can be increased enough to cause the protectors at that end to operate, whereupon the measuring lamp goes out and the small protector lamp lights. Immediately the other protectors operate, as evidenced by the voltage lamp going out and the protector lamp lighting, and the line current increases as evidenced by the brilliance of the line current indicating lamp.

An important factor in the further analysis is the characteristics of the telephone protector. The arc takes place between two carbon surfaces. The gap between these two surfaces has a very high breakdown speed and a very low impedance after it is broken down. Another important characteristic from the standpoint of low-frequency induction is its tendency to become permanently grounded if heavy currents are discharged or if the discharge continues for some time. Consequently, the amount of current in the longitudinal circuit in the event of a breakdown and its duration are important factors in determining the chance of permanently grounding the protectors and causing the circuit to become inoperative until the blocks are changed. Duration is, of course, ordinarily a function of the duration of fault current on the power line as pointed out previously.

The amount of current through operated protectors is determined by the longitudinal voltage and the longitudinal impedance of the telephone circuit. If, for the moment, it is considered that only one wire is present, this current is simply the total longitudinal voltage divided by the total series impedance of the wire plus any resistance in the protector grounds. This can be seen from Fig. 11.

Ordinarily there are numerous circuits on an open-wire telephone lead or in a telephone cable. If the protectors on a number of these circuits break down, the current in each wire will be less than that which would exist were only one wire present as in the above illustration. This is due to the mutual impedance between the different telephone wires which causes the current in any one wire to reduce the current in the remaining wires. The *total* current in all of the wires of course increases as the number of wires on which protectors have operated is increased but not in direct proportion. Figure 12 illustrates this effect. The actual circumstances concerned in this phenomenon are, of course, that the wires which become grounded at their terminals through the operation of the protectors exert a shielding effect in exactly the same way as any other grounded conductor.

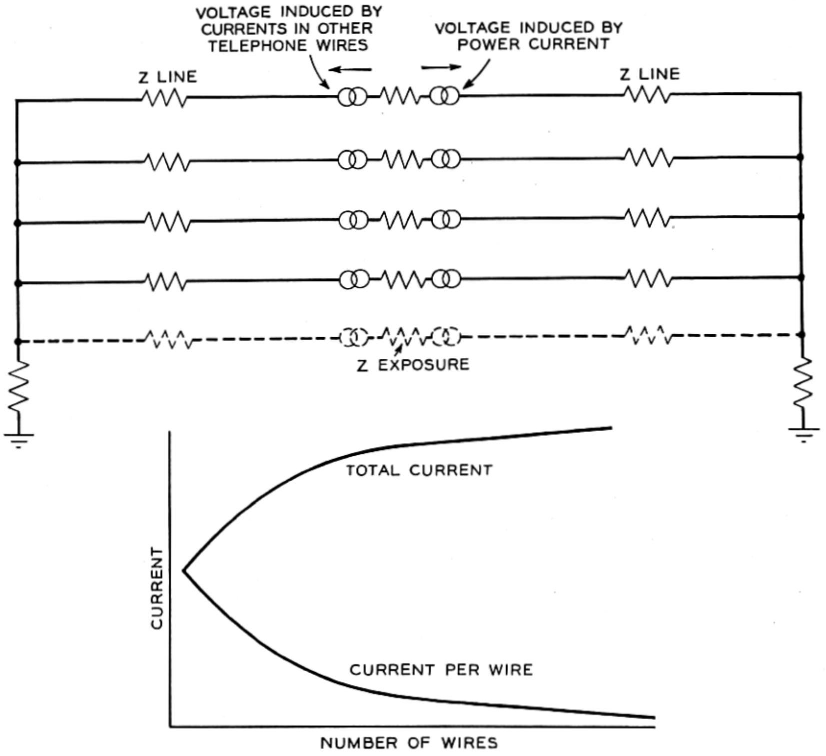


Fig. 12—Current in telephone wires.

The resistance of an individual wire is relatively high but if numerous protectors operate, the shielding may become fairly great, due to the closeness of the wires to each other and to the fact that a substantial amount of copper may be involved. Of course, this shielding is obtained at the expense of at least momentary interruption of the circuits on which protectors operate.

The shielding effect of current in grounded telephone wires is exerted on all telephone wires on the line regardless of whether the protectors on them have or have not operated. Consequently, what may happen on a large telephone line with a moderate induced voltage on it is that enough telephone protectors on different circuits operate to give a shielding effect on the remaining wires sufficient to reduce the voltages on them to values lower than will operate the protectors.

Another important factor is the voltage-to-ground at various places along the telephone circuit after protectors operate. With the protectors operated the voltage-distribution-to-ground can be evaluated from the longitudinal induced voltages, the longitudinal currents, and the series impedances in the circuit. As the simplest and perhaps most striking case, consider a telephone circuit which is solidly grounded due to operated protectors at the ends of a uniform exposure with a fault on the power line at the end of or beyond the exposure. This situation is illustrated in Fig. 13. The distribution of induced voltage along the line is uniform and the longitudinal current is equal to the total longitudinal voltage divided by the total series impedance. If the net drop in voltage is taken from either end to any point along the circuit, it will be found that the induced voltage accumulated over this distance is equal and opposite to the voltage drop over this same distance due to the current flow through the impedances in this section. Consequently, under these conditions the voltage-to-ground is zero at all points along the circuit. This is true regardless of the

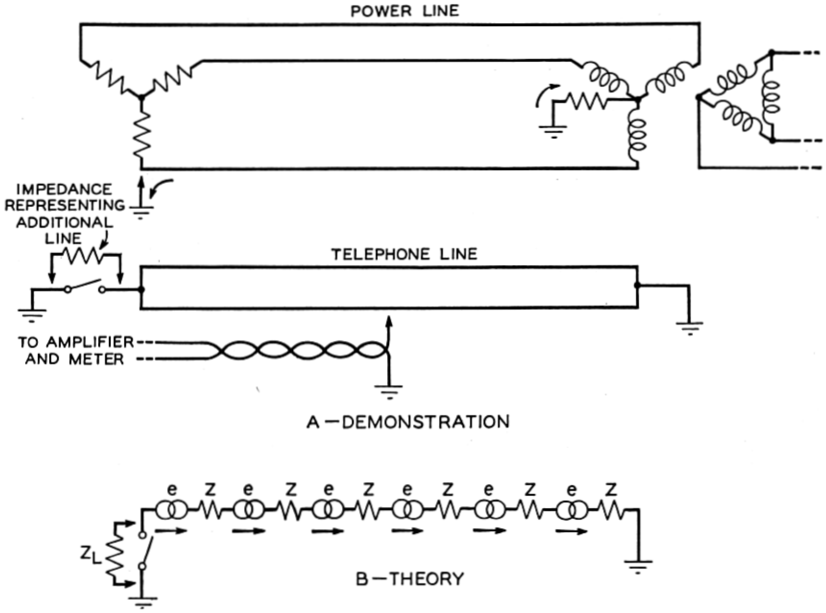


Fig. 13—Voltage to ground for telephone line grounded at ends where fault is outside of exposure.

magnitude of the induced voltage. Figure 13 also shows the set-up by which this fact can be demonstrated. It will be noted that, while there is a fairly high longitudinal voltage, the voltage between the wires and ground with both ends of the circuit grounded is negligible at all points along the line.

If the telephone line extends beyond the exposure, the effect of this portion of the line is to add impedance between the exposure terminal and the protector without adding a corresponding induced voltage. If a power line fault occurs at the end of the exposure, a voltage-to-ground will exist at this point equal to the current in the telephone line times the impedance outside the exposure. This situation can be illustrated in the set-up of Fig. 13 by leaving the power fault at the end of the exposure and adding a small impedance in the ground connection to the telephone line at one end. When this is done it will be noted that a voltage-to-ground exists at the end where the impedance is added and that the voltage-to-ground decreases as the measuring point is moved toward the other end.

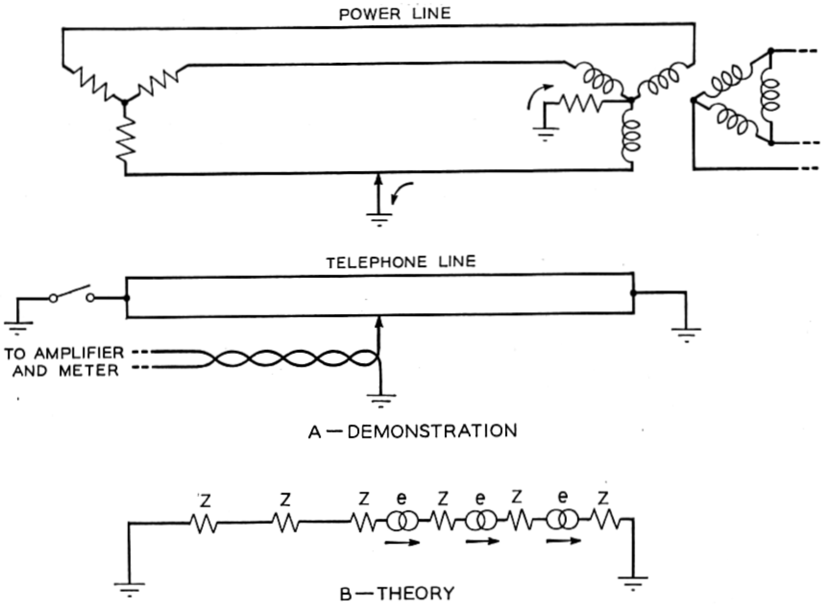


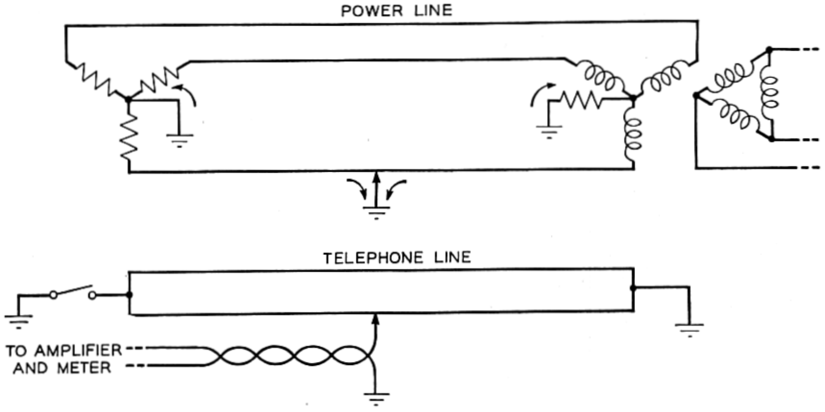
Fig. 14—Voltage to ground for telephone line grounded at both ends where fault is inside of exposure.

To illustrate that voltage-to-ground may occur under other conditions even though the telephone line is solidly grounded at the exposure terminals, consider the situation shown in Fig. 14. This represents the same exposure conditions as in the preceding set-up and the telephone circuit is solidly grounded at both ends, but the fault current instead of flowing through the entire exposure flows through only half of it. In this case the telephone circuit impedances are the same as in the preceding case, but only half of the induced voltage is present. Consequently, the amount of current through the longitudinal circuit is only half of that in the preceding case. Now if the net voltage drop from either end to the middle is taken, it will be found that it is equal to one-half of the total longitudinal voltage induced under the conditions shown. Figure 14 also shows the set-up for demonstrating this condition. In this case the longitudinal voltage is smaller than in the preceding demonstration, but if both ends are grounded and the voltage measuring device is moved along the line, the voltage-to-ground increases from one end to the middle and then falls off from the middle to the opposite end.

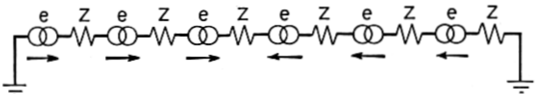
In the last two demonstrations, the fault current on the power line was fed from one end only, i.e., "single-end feed." It sometimes happens that the fault current may be supplied to a power line, at least during the initial stage of a disturbance, from both ends, i.e., "double-end feed." The double-end feed condition tends to reduce the overall longitudinal induction when the fault occurs inside the exposure. In the demonstration shown in Fig. 15 it may be observed that for the set-up with a fault at the middle of the exposure the symmetry is so good that the total longitudinal voltage is very small. However, with the telephone circuit grounded at both ends, a substantial voltage-to-ground exists at a point in the telephone circuit opposite the fault and this voltage-to-ground reduces to zero at the ends. As the fault is moved toward either end of the exposure, there is a tendency for the longitudinal voltage to increase and for the voltage-to-ground, with both ends of the line grounded, to decrease until the limiting condition brought out in Fig. 13 is reached.

The analysis of voltage-to-ground can be carried out for any combination of impedances and induced voltage distributions by totaling vectorially the voltage drops (including any voltage drop over protector ground resistance) and the induced voltages between a grounded point and the point at which the voltage-to-ground is desired. The same analysis can also be carried out regardless of whether one or numerous wires are involved as long as all of the wires are grounded directly or through arrestors at the same points. If some of the wires on a line are not grounded, i.e., the protectors are not operated, the analysis for these wires must be carried out on the basis of their admittance-to-ground as discussed previously. In such a case, the longitudinal voltage to be employed would be that remaining after correction for the shielding effect due to wires on which protectors have operated.

As mentioned previously, mutual shielding of the telephone wires on a line may prevent the operation of some protectors, particularly on a large line. Consequently, the exact analysis of the distribution of voltage-to-ground of all of the wires on a large line becomes very complex. Moreover, as is often the case, if impedance conditions are not uniform, such as where circuits are not coterminous, the complete analysis of the voltage-to-ground becomes even more complicated. Under such conditions it will generally be found that the distribution of voltage-to-ground along the different circuits is different, and consequently, voltages exist between different wires due to these differences in the voltage-to-ground. Likewise, voltages may exist between wires on which the protectors have operated and wires on which the protectors have not operated.



A—DEMONSTRATION



B—THEORY

Fig. 15—Voltage to ground for telephone line grounded at both ends where fault is inside exposure—double-end feed.

All of the above analyses have been made on the assumptions of continuous telephone wires. If a wire is opened at one point the longitudinal voltage, reduced by shielding from any currents which exist in other continuous wires, will appear across the "open." On a large line this shielding may, as pointed out previously, be so large that the voltage across the open is reduced to a fraction of the induced voltage.

Using the high voltage equipment which was used in connection with the demonstration of protector operation, "acoustic shock" can be demonstrated. Although strictly the term "acoustic shock" should be used only with reference to the effect on a person subjected to an abnormally loud sound, the term has also come to be used to designate a noise (usually transient) in a telephone receiver, the intensity of which is considerably higher than that of speech. It is produced by an excessive voltage across the terminals of the receiver.

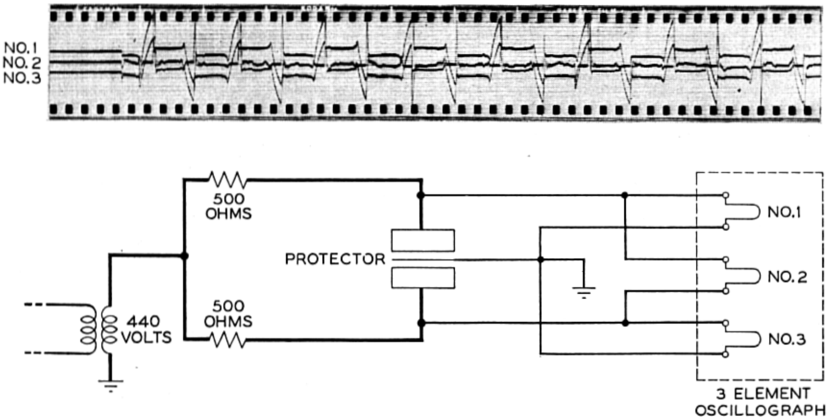


Fig. 16—Oscillograms showing voltages across protector blocks and resulting voltage across circuit, and schematic of test circuit.

The disturbances of this nature which are of primary interest in inductive coordination work are those which are liable to be experienced when a voltage high enough to cause the breakdown of protectors appears on a telephone circuit. This may be the result of low-frequency induction or may be produced by other causes, such as lightning or contacts between power and telephone circuits. Although induced voltages usually appear in equal magnitudes on the two sides of a circuit, the protector gaps on the two sides of the circuit discharge in an unsymmetrical manner with the result that a voltage higher than normal appears across the circuit. When this occurs a loud noise or rattle is produced in the receiver of a telephone set bridged across the circuit.

Figure 16 shows oscillograph traces of voltages measured across operating protector blocks. Each outside trace shows the voltage across one of the two blocks. It will be noted that the two traces are not identical. The middle trace shows the resulting voltage across the circuit. It is this voltage which may cause acoustic shocks. The very jagged outline of this trace indicates that many frequencies other than 60 cycles are present.

The demonstration of Fig. 17 can be arranged to produce acoustic shock. In this demonstration, sufficient voltage is impressed on the circuit to operate the protector blocks at one end. An operator's telephone set and a receiver are connected across the circuit at this end. When the voltage rises high enough to operate the blocks a relatively loud sound is emitted by the receiver.

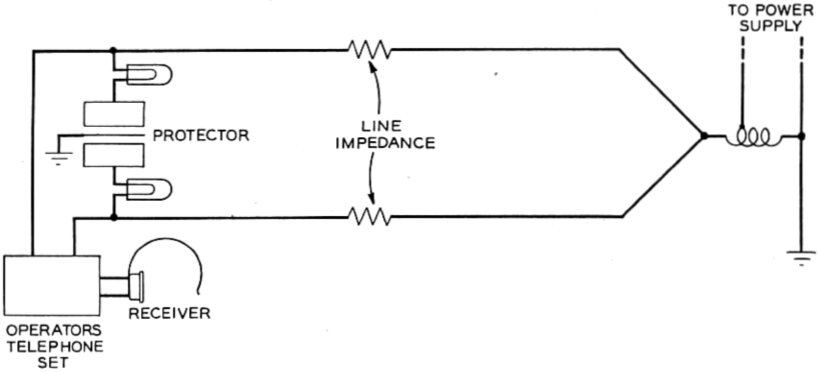


Fig. 17—Demonstration of acoustic shock.

Other effects may accompany the unsymmetrical discharge of the protector blocks. For example, the signals which are connected at the ends of the telephone circuits may operate and give what is commonly called a "false signal."

PROBABILITY FACTORS

In the preceding discussion, a number of factors were mentioned which may vary between different occurrences in the same inductive exposures. Among these may be mentioned the following:

(*a*) The impedances in the faulted circuit may vary between occurrences due to variations in the location of faults, variations in the effective fault resistance, etc. The effect of the variation in location of the fault, of course, is to change the line impedance in the faulted circuit and hence the fault current.

(*b*) The duration of the fault current may vary between occurrences due to variations in conditions which affect the speed of operation of the power circuit relays and circuit breakers. In some cases, of course, faults may clear themselves without circuit breaker operation and this introduces additional variations.

(*c*) Large variations in longitudinal voltage, voltage-to-ground, and current through protectors may occur with relatively small variations in the locations of faults when they occur inside inductive exposures.

(*d*) The shielding effects due to the operation of protectors on telephone circuits may vary considerably between different occurrences.

The variations in induced voltage duration, etc., between different occurrences are, of course, only part of the story. Obviously, the *total* number of faults which may occur on a power line in an exposure over a given period is equally important. This will be affected by numerous factors such as type of line, severity of lightning and other hazards, etc.

In addition, there are variations in the reactions on the telephone circuits. For example, the protector blocks used do not all break down at the same voltage and the fortuitous variations in the breakdown voltage may have an important bearing on the number of protectors which operate and consequently on the total shielding, current through protectors, etc. From the standpoint of possibilities of acoustic and electric shock, there are of course many other probability factors involved.

All of these factors are under investigation and our knowledge of them is increasing from day to day. It is probable, however, that low-frequency induction will always remain a subject in which quantitative analyses can tell only a part of the story.