Status of Joint Development and Research on Low-Frequency Induction *

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This paper deals with coordination of power and telephone systems with respect to induction at power system frequency, usually 60 cycles. The principal problem in this field relates to effects produced under abnormal conditions on power systems. The factors controlling the magnitude, frequency of occurrence, duration, and effects, of induced voltages, are discussed. Different types of protective measures, some applicable to power systems and others to communication systems, are outlined, including their respective advantages, limitations, and fields of application. The reaction on this problem of lightning and of situations involving liability of contacts between telephone wires and power wires is touched upon. The whole matter is treated from the standpoint of the comprehensive joint investigation of the interference problem which is being conducted by the N.E.L.A. and the Bell System.

INDUCTION at power system fundamental frequency, commonly called "low-frequency" induction, has different characteristics and produces quite different effects from induction at the noise frequencies discussed in the paper by Messrs. Blackwell and Wills. Since very little has been published on low-frequency induction, it seems desirable, in order to make clear what the Joint Subcommittee on Development and Research is doing on this subject, to explain the problem in some detail.

The disturbances in communication circuits due to low-frequency induction are in general discrete occurrences, coincident with accidental grounds or other faults on neighboring power lines, rather than being continuous and due to normal power line operation.

Three-phase power circuits, when operating normally, are so nearly balanced with respect to earth at their fundamental frequency, and telephone circuits of the ordinary type are relatively so insensitive at frequencies of 60 or 25 cycles, that induction at these low frequencies under normal power line conditions is rarely a practical problem. But when abnormal conditions, particularly faults to ground, occur on power lines, large unbalanced voltages and currents at fundamental frequency exist temporarily and at such times there may be induced in neighboring telephone circuits voltages which are hundreds of times as great as under normal operating conditions. The induced voltages under abnormal conditions may reach values sufficient to cause hazard

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to telephone employees or interruption to service. Although such abnormal conditions occur infrequently and usually last for only the very short period required to interrupt or clear the power circuit, the effects which may be produced are so serious that protection against this type of induction is an outstanding problem in the coordination of power and telephone systems. A large part of the subcommittee's work has for its object the development of means for controlling and minimizing such induced voltages and their effects.

While low-frequency induction is not usually severe except under abnormal conditions, power circuits which operate at any time on an unbalanced basis, or which are closely coupled to grounded wires capable of carrying large currents may, even under normal operating conditions, create a problem of low-frequency induction in paralleling telephone circuits in addition to setting up high-frequency disturbances as explained in the Blackwell-Wills paper. This is particularly true where the exposed telephone circuits are used for special services such as the transmission of radio broadcasting programs. Grounded types of telegraph and other signal circuits also are sensitive to low-frequency induction.

Classification of Factors Responsible for Inductive Effects

The same three class of factors which combine to underlie the noise-frequency problem appear also in the low-frequency problem. As they appear in the latter, these are:

1. "Influence factors" in the power system, which are concerned with the magnitude, duration, and frequency of occurrence, of unbalanced voltages and currents.

2. "Susceptiveness factors" in the communication system, which are concerned with the nature and seriousness of the effects produced by the induced voltages.

3. "Coupling factors" which determine the magnitude of the voltages induced in the communication system, per unit unbalanced voltage or current of the power system.

In the low-frequency induction problem, the coupling factors are largely dependent upon the characteristics of the earth and the relations of power and telephone systems to the earth. If the earth were an insulator instead of a conductor there could, of course, be no such thing as fault current in the earth and the coupling between power and communication circuits would be much less. It would not then be hazardous for a lineman when in contact with earth to touch a charged wire. Or if the lines were not in proximity to the earth, there would be no chance for a lineman working on the wires to get in contact with earth. Neither in power systems nor in telephone systems is it actually necessary that the earth be used as part of an operating circuit but, as the earth is a conductor, and power and telephone lines and apparatus are located on its surface, it is essential in both systems that the earth be taken into account in circuit problems and that paths to earth for protective purposes be established at certain points.

It must not be assumed, however, that the earth is a perfect conductor. For the most part the materials of which the earth's crust is composed are of relatively low conductivity. From numerous measurements in various places the average conductivity over considerable volumes of earth has been found to range from 10^{-11} to 10^{-15} abmho per cm. cube. The resistance of an earth path is therefore not zero but may be many ohms or even in some cases many hundreds of ohms. Most of this resistance is in the immediate vicinity of the electrodes and can be reduced by increasing the surface area of contact between electrode and ground.

In discussing the low-frequency induction problem, it is convenient to consider the factors controlling:

(1) The magnitude of induced voltages, (2) the frequency of occurrence of induced voltages, (3) the duration of induced voltages, and (4) the effects produced by induced voltages.

Factors Controlling the Magnitude of Induced Voltages

The magnitude of voltages induced in telephone systems in specific cases depends chiefly on the magnitude of residual currents and voltages resulting from power circuit faults to ground and on the exposure conditions.

Residual Currents and Voltages. A balanced power circuit is one in which the voltages from the various phase conductors to ground are equal and sum up vectorially to zero and in which the phase currents also are equal and sum up to zero. Under this condition all the currents in the circuit are *balanced* currents and all the voltages are *balanced* voltages. If, however, one phase develops a fault to ground, this relation becomes disturbed, the voltages to ground of the phases become unequal, and their vector sum, which is the *residual* voltage (3 times the so-called uniphase or zero phase sequence voltage) of the power circuit, is no longer zero. The currents in the three phases likewise become unequal and when added vectorially their sum, which is the *residual* current (uniphase or zero phase sequence current) of the power circuit, is no longer zero. In most low-frequency induction problems residual current is far more important than residual voltage.

Residual voltages and currents are equivalent to single-phase voltages and currents applied to a circuit consisting of the three line conductors in parallel as one side, and the earth as the other side. Their large inductive effects are due to the great dimension of the loop formed by this earth return circuit, much of the return current being effectively so deep in the earth that its neutralizing action is small. In the case of the balanced components, the inductive effect due to the voltage or current of one conductor is largely neutralized by the voltages or currents of the other two conductors.

The chief characteristics which determine the magnitude of the residual voltages and currents are (1) the power circuit voltage, (2) the impedances of the neutral ground connections, (3) the line and apparatus impedances, (4) the fault and earth impedances, (5) the sources of power supply, (6) the character of ground wires if used, and (7) the circuit configuration including ground wires.

When a fault occurs between a phase conductor and earth on a power system having neutral ground connections, these neutral connections, together with the fault, line conductors and earth, form a closed circuit for the residual current. Unless the neutral impedance is very high, e.g., approaching that of an isolated system, the shunting effect of the capacitance to ground of the line conductors may for most purposes be neglected and practically the same value of residual current exists at all points along the line between the fault and the neutral connection to ground. For simplicity, a system with a single line and single neutral ground connection may be assumed. With this picture in mind, it is clear that the value of the neutral impedance may be an important factor in determining the magnitude of the residual current. If the fault occurs near the point where the neutral is grounded, the line and apparatus impedances being low, a small impedance in the neutral may control the current. On the other hand, for faults occurring at points remote from where the neutral is grounded, the impedance in the neutral connection may have to be relatively large to materially reduce the residual current.

As one limit there is the solidly grounded neutral, i.e., no impedance is inserted and as good a ground as practicable obtained. This obviously permits maximum residual current when ground faults occur. Unless the grounding impedance is very high the residual current, and not the residual voltage, is the controlling factor in grounded neutral systems.

As the other limit there is the isolated neutral, i.e., the impedance from neutral to earth is infinite. In this case no residual current passes through the neutral. At the ends of the line the residual current is zero, gradually increasing to a maximum at the point of fault. The circuit for residuals is through the capacitance of the line to ground, the magnitude of this capacitance controlling the magnitude of the residual current, which is much less than with grounded neutral systems except in cases of double faults when it may be very large. With a single fault the residual voltage may be a more important factor in respect to induction than residual current.

The impedance of the fault itself depends upon a number of things, including the type of line construction and the earth conditions. The subcommittee has under way investigations to gather data on the range of fault impedances under different conditions. To determine the maximum residual current, the fault impedance may be taken as zero. In many instances, this approximation gives sufficiently close results, particularly if the fault is remote from the grounded neutral so that line, neutral and apparatus impedances are controlling. In case of conductors falling upon the ground, local earth conditions largely determine the fault impedance. On a steel tower line an insulator breakdown results in a relatively short arcing path to grounded metal, whereas, in wood pole construction, the pole itself introduces considerable impedance unless nullified by guys or other metal.

The foregoing discussion of residual current has been confined practically to the situation brought about by single faults to ground. Double faults at separate locations sometimes occur and these are equivalent to a phase-to-phase short circuit through the earth, giving a large residual current in the intervening section of line. If the two faults in such a case are on opposite sides of an exposure, very severe induction may result. Experience shows that double faults at separate locations constitute only a few per cent of the total faults occurring on grounded-neutral power systems but are a much larger percentage of the total faults on systems normally isolated from ground.

The presence of ground wires on a line may have considerable influence on fault impedance. Being connected to ground at frequent intervals, such wires decrease the impedance to ground where a breakdown occurs between a phase conductor and a ground wire or any metal in contact with a ground wire. A ground wire tends to increase the total residual current but on the other hand its controlling function, from the induction standpoint, is that of a shielding conductor tending to decrease the induced voltage.

Circuit configuration does not have a large influence on unbalances due to abnormal conditions, but it has an important effect upon any unbalance of a power circuit under normal operating conditions. To be balanced, the phases of the power circuit must be symmetrical with respect to each other and to earth. To the extent that the capacitances and inductances of the several phase conductors differ, residual voltages and currents will result. Transpositions afford a means for compensating for these circuit unbalances.

In cases for which protective measures are being considered, it is important to be able to estimate the magnitude of the residual current when faults occur at different points on the power system. Apart from inductive effects, this is a question of importance to power companies, since forecast of currents under different fault conditions is essential in the design and setting of protective relays. Much work has therefore been done by different investigators on methods of predetermining these currents. Helpful mathematical methods have been developed, though sometimes the results obtained by their use are open to question due to lack of accurate values of some of the important impedances. Proper allowance for fault impedance and the effect of ground wires is sometimes difficult to determine and in cases of complicated networks approximations usually have to be made. To facilitate the numerical computations, calculating boards of varying degrees of elaborateness have been developed. The subcommittee is investigating this matter and by experimental work is checking the results of estimates and acquiring further knowledge of the range of the variable factors. Through this work, it is hoped to increase the convenience and accuracy of these important computations.

Exposure Conditions.—The relationship between power and telephone lines with respect to the exposure conditions is defined by the "coupling coefficient" or "coefficient of induction," a factor which, when multiplied by the value of current (or voltage) in the power line, gives the resulting voltage set up in the telephone line. A power line and a neighboring telephone line have several different coupling coefficients corresponding to different conditions, such as, whether the induced voltages are due to power current or power voltage, to balanced or residual components, and whether they are voltages induced along the conductors (or to ground) or are induced directly in the metallic circuit. Low-frequency induction is predominantly magnetic in character and the coupling which is most significant is that between the power conductors and the telephone conductors, both considered with earth return. The induced voltages are due principally to "longitudinal circuit induction."

A number of dimensional factors affect the magnitude of this coupling, such as the length of the exposure, the separation between lines, and the locations of ground connections on the two systems. Local conditions as to earth conductivity and the arrangement of geological strata for some distance below the earth's surface, constitute other important factors. An accurate mathematical evaluation of the coupling between earth return circuits is difficult. Formulas have been developed under simplifying assumptions as to symmetry and homogeneity, which aid in explaining and interpreting experimental results and in predicting approximate values of coupling in cases where experimental measurements are not available.

Assuming uniformity of exposure conditions the coupling varies directly with length of parallelism, except for end effects or interactions between ground connections of the two lines. Increase in separation of the lines diminishes the coupling but the exact relationship depends upon the distribution of current in the earth which in turn depends upon the frequency and the earth conductivity. In many cases different strata of different conductivities are involved in the path of the earth current, which adds to the difficulty of correlating experimental and theoretical results. The effect of earth conductivity on coupling is accentuated as the lines are more widely separated. At roadway separation, large differences in earth conductivity affect the coupling only moderately; but at separations of one half mile to one mile, coupling values may differ by 20 to 1 or more, due to the range in value of earth conductivity. Irregularities in exposure conditions such as changes in direction of one or both lines, crossovers, and angular exposures of varying separation, are complications which frequently occur in practise.

The voltages set up in neighboring communication circuits by power currents are due usually to inductive coupling but in some cases are due partly or wholly to resistive coupling. It is seldom necessary in practical studies to try to segregate these two components of voltage, since their effects in the telephone system are not a function of the phase relationships of these components to the power line current which produces them. It is not unusual to speak of inductive coupling as including both inductive and resistive coupling.

Any grounded circuit in proximity to power and telephone lines within an exposure brings about a certain amount of shielding through the reaction of the currents induced in this conductor upon the primary magnetic field set up by the residual current in the power circuit. In this respect a shield wire acts like a short-circuited turn on a transformer. The effectiveness of the shielding depends upon the conductance of the shield wire, the manner and effectiveness of its grounding, and its position with respect to the power and telephone wires. Such a wire affords maximum shielding when closely coupled to either the power wires or the telephone wires, when its conductance is high, and when its ground connections are of low resistance.

The variation of coupling with separation and with earth conditions is of great practical importance in the coordinated location of lines. Most of the subcommittee's study of coupling, therefore, involves field investigations of the variation of coupling with separation under different earth conditions, and is furthermore directed toward devising convenient and accurate methods of predetermining coupling in practical cases. Also, by studying and correlating experimental data derived under different conditions and from widely separated parts of the country, the subcommittee hopes to arrive at a better empirical basis for estimating coupling. Some of the work on this subject has already been presented.[1]

Factors Controlling the Frequency of Occurrence of Induced Voltages

The frequency of occurrence of induced voltages in paralleling communication lines, while chiefly dependent on the frequency of occurrence of faults on the power line, is also somewhat affected by the location of the exposure with respect to the location of neutral grounding points. For example, if there is only one neutral ground, faults occurring between it and the exposure will produce relatively little induced voltage.

The frequency with which faults occur is usually traceable to features of electrical and mechanical design, the character and amount of insulation, and the location of the lines. Specifically, the factors which appear to be responsible for the majority of faults on power lines are: poor configuration, inadequate spacing and clearances, inferior insulation, lightning, fog, smoke and dirt, birds and animals, proximity of lines to external objects apt to interfere with operation mechanically or electrically, and certain mechanical features of design affecting the strength of construction, such as ineffective anchors, guys, or conductor and ground wire supports, particularly at angles and dead-ends, and insufficient bearing areas of subsurface structures.

Factors Controlling the Duration of Induced Voltages

The length of time faults are permitted to remain on a power system is controlled by the kind of protective relaying employed and by the type and condition of the circuit breakers and other terminal equipment. The type of relay system, the degree of sectionalization obtained, the adequacy of the circuit breaker as to speed and rupturing capacity, and the maintenance of the equipment are the most important factors.

[1] For references see bibliography.

Generally, the type of fault has little effect on the duration if there is sufficient current to operate the relays. Conditions have been noted, however, where the fault is of such high impedance that the current is not adequate for the operation of the relays. Such high impedance faults usually occur on wood pole lines and may result in burning of pins, crossarms and poles. They may also occur on steel tower lines as the result of branches of trees getting in contact with conductors.

Effects Produced by Induced Voltages

Low-frequency and transient voltages induced on telephone circuits may produce a variety of effects depending upon their magnitude and duration. These effects include service interruption, false signals, telegraph signal distortion, damage to plant, electric shock, and acoustic shock.

Telephone circuits are very low energy circuits, the voltage for talking purposes rarely exceeding one or two volts, with maximum current measured in milliamperes. For signaling purposes a maximum of 165 volts peak, is used with currents limited to about 0.10 ampere. For telegraph service the voltages are limited to 135 volts between wire and ground, while the current is limited to less than 0.10 ampere. By contrast, the voltages due to induction, in some cases of exposure, may be a thousand volts or more.

Service Interruption.—When the telephone protectors are operated by induced voltage the behavior of the protector discharge gaps depends upon the magnitude of the voltage and current and the length of time the discharge lasts. In cases where the discharge is not promptly extinguished or where the current is very high, the discharge gaps may become permanently grounded. This causes interruption to service until the affected protectors can be replaced, the time necessary for such replacement depending, of course, upon the protector locations.

False Signals.—False switchboard signals are likely to be coincident with protector operation. They produce a bad service reaction due to operators answering false calling signals and cutting off connections because of false disconnect indications.

Distortion of Telegraph Signals.—The induced voltages appear in just the same paths over the wires as the operating voltages of grounded telegraph. The effect of such induced voltages depends on their magnitude, character, and duration. Voltages much lower than those sufficient to operate the protectors may cause detrimental effects ranging from a slowing down of speed to complete failure. Where the duration is short, the effect may be limited to distortion of signals, or, if the voltages are high enough, to momentary interruptions.

Damage to Central Office or Other Telephone Plant.—The dielectric strength of the telephone plant is adequate for the voltages used in communication service, with appropriate factors of safety, but higher voltages may sometimes, notwithstanding the protective devices, cause dielectric failure, thus damaging the plant, particularly cables and wiring or apparatus in telephone offices.

Electric Shock.—Telephone linemen in the course of their work upon wires at relatively close spacing, cannot avoid getting in contact with the wires and if the wires were subject to sufficient induced voltage, the men would be liable to receive electric shocks. On severely exposed lines such voltages are liable to occur at any time, suddenly and without warning. Electric shock might either injure a lineman directly or startle him and cause him to lose his hold and fall from the pole. Voltage to ground due to induction appears not only within the exposed section of line but considerably beyond. A similar, and in some respects worse, condition may exist with respect to employees working on cable circuits which are either exposed or directly connected to exposed circuits. In cables the wires on which the foreign voltage appears are very close to the grounded metal sheath and usually also to other wires at approximately earth potential, as well as to the earth itself. This problem has become more difficult with the rapid growth of the telephone and electric power systems and is engaging the subcommittee's serious attention.

Acoustic Shock.—Acoustic shocks are liable to occur with the breakdown of telephone protector discharge gaps, which temporarily unbalances the circuit and causes a sudden and abnormally large current in the receivers. This current gives rise to sudden and severe flexures of the receiver diaphram, which produce loud sharp noises in the ear of a person using the receiver. Telephone operators, due to the nature of their work, are particularly liable to acoustic shocks, the effects of which range from minor reactions to severe general disturbances of the nervous system which may be painful and of long duration. In addition, if danger of severe shocks exists, the operating force may become fearful and the impaired morale seriously affect the service.

Types of Protective Measures

The foregoing effects of induction from paralleling power lines may be reduced by: (1) measures in the power system to limit the influence, (2) measures in the communication system to limit the susceptiveness and (3) coordinated location of lines or other means to reduce the coupling. As a solution in a specific situation, one measure may be sufficient or two or more measures may be required, depending on the conditions. The solution should afford the necessary protection without hampering the development or operation of either system. Where there are two or more alternative solutions, the one which is best from the engineering standpoint, including both the technical and economic aspects, should of course be applied.

Cooperative planning in advance of construction is especially important in situations involving low-frequency induction, because of the wide ranges in magnitude both of coupling factors and of residual currents. By advance notifications of construction it is possible to bring up for analysis the low-frequency effects which the proposed construction would bring about and, if necessary, to agree upon changes in the plans to prevent or reduce these effects.

As to the physical dimensions and relations of power and telephone lines which constitute an exposure there are no blanket rules for guidance; each case requires specific consideration. Due to differences in geological conditions and other variable factors, a given length of parallelism at a given separation might give satisfactory results in one location, whereas an exactly similar physical relationship of lines in another location might result in the communication system being rendered inoperative at times of power system fault. This fact emphasizes the necessity of advance planning and cooperative study of situations as they arise. Such cooperation may easily lead to a satisfactory solution of situations which at first seem very difficult. On the other hand situations which at first appear devoid of any possibilities of trouble may on careful study be found to require protective measures.

Protective Measures for Power Systems.—It will be evident from the foregoing discussion that protective measures to reduce the inductive influence of power systems should be directed to limiting the magnitudes of unbalanced currents and voltages, particularly under abnormal conditions, and to reducing the duration and frequency of occurrence of abnormal conditions. Of such protective measures some are concerned with fundamental questions of line and system design and must be incorporated in the construction plans, while other measures are of such a character that they may either be incorporated in the original construction or added later if found necessary as a result of subsequent experience or developments in either the power or telephone system.

Fault-Resistive Design and Construction.—As mentioned in the paper by Messrs. Harrison and Silver the methods employed in reducing the frequency of occurrence of faults are primarily involved in the design and construction of the power line, i.e., adequate insulation, clearances, and spacings, and so arranging the component parts of the structure that the line will in effect be fault-resistive. Increasing demands for better service by the public combine with considerations of inductive coordination to justify greater attention to fault-resistive line construction.

Faults may result from improper guying of poles, i.e., guys so located that the spacing between guys and conductors is inadequate, or the path from insulator to crossarm brace and thence to the guy is insufficient to withstand the voltages imposed. The conductor spacing may be inadequate or the configuration of the circuits may be such that the sudden unloading of conductors coated with sleet will result in their whipping together, or, if a ground wire is used, it may be so located that the unloading of sleet will cause the conductors to whip into the ground wire, or the design of the line, either steel tower or wood pole, may be such that inadequate strength is provided for the mechanical loads incurred.

Attention is being given to the location of lines as a material factor in limiting the number of outages resulting from external sources, such as lightning, broken trees, blasting, and automobiles. For example, lines built in valleys are less subject to failures due to lightning and wind storms than lines built over hills.

There is little need to call attention to the grade of insulation employed on power lines as recent lightning studies and papers have emphasized the importance of rationalization of insulation throughout the plant. By this method it is hoped that preferential points of failure would be established, thus permitting prompt restoration of service without damage to expensive equipment since most of the faults would be confined to the line.

The amount of insulation to be employed on lines is affected by topographical and climatic conditions. Lines in areas relatively free from lightning or shielded from lightning disturbances may, of course, employ less insulation without increasing the number of faults. On the other hand, lines built in areas where lightning is prevalent may justify not only higher insulation but also, on steel tower lines, the use of ground wires as an additional protection. Areas where salt fog, smoke, or chemical fumes are prevalent require special treatment as to the form of insulation used.

Laboratory tests and limited field experience indicate that a proper utilization of the inherent insulating properties of wood in structures may result in considerable improvement in line operation. The subcommittee is investigating the service performance of wood pole lines of differing designs with a view to determining how much may be accomplished in reducing the number and severity of faults by suitable arrangements of metal braces, fittings, guys, etc., to avoid so far as possible shunting out the insulation of the wood.

To the experienced designer the protective measures to be employed on lines subject to frequent faults are obvious, namely, the rearrangement and reconstruction of the tower or pole top to obtain greater spacing between conductors or greater clearance between conductors and other metal parts. In some cases spacing and clearances would be materially improved by utilizing a triangular configuration so that the conductors are not likely to come in contact with each other or the ground wire when sleet or other conditions cause whipping or dancing of the conductors. In other cases, merely a relocation of the point of attachment of guys would improve conditions without materially decreasing the strength of the structure.

Fault-Current Limiting Measures.—Resistors, or reactors, in the neutral ground connection of a power system provide a means of directly limiting the magnitude of the residual currents, except in cases of double faults. In cases where the residual currents can be so far reduced as not to set up induced voltages of high values in the communication system without reacting unfavorably on power system operation, this method alone may afford a satisfactory solution. In such cases it has the further advantage of reducing the stresses to the power system due to the fault current. Where it is impracticable to clear up a situation by residual current limitation alone, this method may be effectively used in combination with other protective measures.

The reduction in residual current which will be brought about by adding a given amount of impedance in a neutral ground connection can be estimated with reasonable precision. It is not so much this question therefore, that requires study by the subcommittee as it is the question of the limitations and costs of this protective measure, and its reaction upon the power system. Included in this work is a study of the relative advantages of inductance as compared with resistance for accomplishing such current limitation. The subcommittee has under observation a number of installations of current-limiting devices and is engaged in experimental and theoretical studies and in field observations by means of recording instruments to determine the possibilities of this type of protection.

In non-grounded power systems a single fault on a phase conductor results in the charging current of the system flowing to earth through the fault. The other phases, rising to full line voltage above the grounded phase, create a system unbalance which may manifest itself by induction in paralleling communication lines. In such cases the problem is one of electric induction except for the magnetic induction set up by the charging current.

When double faults occur on either grounded or nongrounded systems, severe magnetic induction is liable to result and under these conditions it is difficult to limit the residual current.

Shielding. Ground wires on a power line, while tending to increase the total residual current, serve the purpose of shielding by reducing the strength of the external electric and magnetic fields set up by the residual voltages and currents. The net effect of ground wires from the low-frequency standpoint is to reduce the voltages induced in paralleling communication circuits under abnormal power circuit conditions. The effectiveness of such shielding depends on the impedance of the shielding conductor and its ground connections. Under favorable conditions the induced voltage at 60 cycles in paralleling communication circuits may be reduced about 40 per cent by this method. Such ground wires, if used on wood pole lines, have a disadvantage in that they impair to some extent the insulating property of the poles.

High-Speed Circuit Breakers and Relays.—Very sensitive high-speed relay systems have been developed which, together with high-speed types of circuit breakers reduce the time duration of a power line fault to approximately 1/10 second, as compared with one half second to three seconds required by the older forms of relays and circuit breakers, thus tending to minimize the effects of induction. On the other hand inadequate relaying, or the omission of automatic circuit breakers, may extend the duration of faults to a point where the hazards to power apparatus are serious. High-speed breakers and relays are expensive and it is difficult to justify them solely as a remedial measure for induction, particularly as the speeds of operation now available for relays and breakers on power systems, have not reached values which make them a complete solution of coordination problems. However, with the increasing size and interconnection of power systems, high-speed relays and circuit breakers are playing and increasingly important part in promoting power system stability.

Periodic testing of relays and circuit breakers accompanied by complete overhauling at regular intervals, will do much to reduce the duration of faults and to prevent improper functioning of the equipment.

The subcommittee is following the developments in high-speed breakers and relays with much interest. If such devices should come into general use for all classes of service it is expected that they would materially improve the whole inductive situation.

Improvement in Balance.—As mentioned above, low-frequency induction between power and communication lines is sometimes experienced under normal operating conditions. On grounded telegraph and signal lines the trouble usually manifests itself by a chattering of telegraph instruments or by false signals. Improvement in balance of the power line by transpositions will in some cases correct the difficulty.

Protective Measures for Communication Systems.—In general, measures applicable to the communication system to prevent or reduce the effects of induced voltages take the form of arrangements or devices for removing or counteracting the voltages to ground or the currents in the telephone circuits which might be produced by the induced voltages.

Bell System Standard Protectors.—It is Bell System standard practise to equip all telephone circuits which are exposed to the liability of foreign voltages, with electrical protective devices. These devices are made in various forms and combinations for different plant and exposure conditions. The protector used at central offices and at subscribers' stations includes a discharge gap which operates at approximately 350 volts and a fuse which opens the circuit at about 10 amperes. Such devices are intended to offer a measure of protection against lightning discharges and against the voltages and currents resulting from accidental contacts with foreign wires or from low-frequency induction.

In order to protect telephone linemen or others working on open-wire lines against electric shock from induced voltages, it is necessary that the voltages between line wires, and between each line wire and ground, be kept low. The use of protectors at central offices does not so protect the linemen as the impedance drop on the line wires permits high voltages between wires and ground at other points, such as the terminals of the exposed section.

It appeared however, that protectors of the Bell standard type might be used on open-wire lines at locations immediately adjacent to exposures to limit induced voltages to ground. A number of installations of this kind have been made but observations over a period of time show that they introduce serious troubles as the protectors, being subjected to heavy discharges, often become permanently grounded thus interrupting service. It also sometimes happens, as all the line wires are not always equally exposed, that some of the protectors operate and others do not, resulting in objectionable voltages between line wires.

Relay Protectors.—In view of the inadequacy of existing forms of protectors for such use, the subcommittee is experimenting with a "relay protector." This device includes Bell standard protectors in combination with a relay which operates to short-circuit them upon the occurrence of a discharge, thus relieving the protectors of the duty of carrying the large discharge current and greatly reducing their tendency to become permanently grounded. In more recent types all the relays at a protector point are electrically interlocked, so that when any relay operates all line wires are grounded within a few cycles.

Several trial installations of relay protectors have been made and are under observation. To guard against voltages to ground within the exposure these protectors have to be placed within, as well as at the ends of, the exposed section of line. Where the longitudinal induced voltage is large, protectors are required at a number of points within the exposed section.

The effective application of such protectors requires grounds of the order of one or two ohms and an important feature of the investigation is to devise methods of constructing and maintaining such grounds at remote points along the line.

The subcommittee is investigating in the field and in the laboratory the effectiveness, cost, reaction on service, and other practical questions relating to the installation and maintenance of this method of protection.

Acoustic Shock Reducers.—Since acoustic shock due to induced voltages involves dissymmetrical discharges across the two sides of the protector, efforts have been made to devise a protector which would break down and discharge symmetrically, i.e., provide two reliable low-impedance paths for heavy discharges, which would at all times have very closely the same arcing impedance. Thus far the subcommittee has not been successful in developing a practicable protector of this kind.

For the purpose of equalizing the voltages on the protector during the discharge period, an accessory device termed a "discharge balance coil" is under investigation. It consists of two equal windings on a common core, each in series with the discharge gap of one side of the line, and so arranged that the fluxes set up by the circuits in the two windings are in opposition. The "booster" action of this coil tends to equalize the discharge currents. This reduces acoustic shock from induced voltages, provided all protectors are so equipped and the line itself has no large unbalances. When however, voltage is impressed on one wire only of a telephone circuit, as by accidental contact, these coils have a detrimental effect on the action of the protector in reducing voltage to ground, as they introduce impedance in the protector discharge path.

Development work is also being conducted on other types of acoustic shock reducing measures which do not attempt to prevent unbalanced current but merely to shunt it out of the telephone receiving circuit. Obviously a device acting on this principle to be successful must be practically instantaneous in operation. One of the most promising of such devices consists of a high ratio step-up transformer with its primary connected directly across the receiver to be protected. The secondary is connected to a low voltage discharge gap. Any abnormal voltage across the primary operates the discharge gap and the transformer becomes a low-impedance shunt. A number of field trials of these reducers applied to operator's receivers have been made. While not affording the full degree of protection desired they have been found to reduce substantially the severity of acoustic shocks and it is believed that they will be of considerable benefit in cases where some form of protection against acoustic shocks to operators is urgently required.

Another device based on the shunting principle consists of opposingly poled copper oxide rectifiers connected across the receiver. These have the property of greatly diminishing impedance with increasing voltage. The problem is to obtain a sufficiently sharp change in impedance with voltage, while avoiding a normal impedance so low as to cause serious transmission losses. As an aid to this end, biasing batteries are under investigation.

The committee has also investigated the saturating characteristics of a vacuum tube for acoustic shock reduction. The properties of a vacuum tube are such that the output current cannot be increased substantially beyond a definite value regardless of the input voltage. This feature can be made use of to limit shocks by a design which will pass currents substantially without distortion up to approximately the highest value of signal current used, thus cutting down the shock voltages which exceed the normal signals. While quite effective, this method involves apparatus which is more bulky and expensive than the transformer and spark-gap type reducer. Telephone repeaters accomplish this result to some extent and are being investigated by the subcommittee, to determine the quantitative reduction of acoustic shock by this means under practical conditions.

In cases where toll or trunk lines are exposed, an acoustic shock reducing device which could be placed at the ends of the lines would have the advantage of protecting subscribers as well as operators. Development work to obviate certain difficulties in using such a device is under way.

An effort is being made to develop a telephone receiver which will saturate between the values of current required for effective speech transmission and values of current which produce acoustic shock. This requires a sharp bend in the saturation curve of the iron employed in the receiver magnetic circuit. Until the development of permalloy, this feature was not approachable, but experimental permalloy receivers have now been developed, and, while it has not yet been possible to achieve the end sought without serious sacrifice in transmission, work along this line is continuing.

Improved Insulation.—A slight reduction of susceptiveness to interference by low-frequency induction could be secured by providing increased dielectric strength to ground in communication circuits and their associated apparatus. Another method would be to insulate or isolate all conducting parts of the communication system so as to prevent contact by employees or others with wires or apparatus which may carry a dangerous voltage. Neither of these appear practicable at this time.

Drainage.—Drainage is a method for controlling the parts of the circuit in which the induced voltages appear and causing these voltages to be consumed in those parts where they are least harmful. This is accomplished by connecting the telephone conductors to ground, preferably through balanced impedance coils, at certain points throughout the exposure. Assuming low resistance grounds at the drainage points, the resulting voltage to ground at such a point after drainage is established is limited to a value corresponding to the voltage drop over the impedance of the coil and ground connection. If this impedance is small compared to the other impedances in the drainage section, the voltage to ground at the drainage point is a small part of the total voltage induced in that section.

Under present conditions, the application of drainage is limited to special situations where interference with circuit testing and maintenance is of relatively minor importance and where superposed d-c. telegraph and carrier telephone are not used.

Neutralizing Transformers.—The neutralizing transformer is a device for introducing into an exposed communication wire a voltage in opposition to the voltage induced by the disturbing circuit, thereby to a certain extent neutralizing the latter. The neutralization is effected by means of transformer action, the primary coils of the neutralizing transformer being connected to conductors which are grounded at the terminals of the exposure (or section of exposure), so that the voltage induced in these conductors will send currents through the transformer primaries. These primary currents induce in the secondaries of the transformers voltages substantially in opposite phase to the voltages induced in the telephone wires by the power circuit. The secondaries being connected in series with the exposed communication wires, the neutralizing action is obtained.

On account of introducing crosstalk and adversely affecting telephone transmission and carrier, application of neutralizing transformers has been confined chiefly to telegraph circuits. No applications of these devices to power line exposures have been made. They are, however, being studied by the subcommittee to see whether the objections mentioned above can be overcome and to determine their possible field of application.

Shielding.—Shielding on a telephone line may be effected by special grounded conductors, by working conductors, or by cable sheaths. Miscellaneous structures such as pipe lines or rails in the immediate vicinity of an exposure also introduce more or less shielding. The employment on a telephone line of a high conductance shield wire, well grounded at the ends of the exposure and at intermediate points, may reduce the induced voltage by as much as 40 per cent at a frequency of 60 cycles. As bearing on the prevention of electric shock from induced voltages on telephone lines, shielding has a disadvantage in that it may, depending somewhat on the method of construction, add to the chance of a lineman making contact with grounded metal.

Use of Cable.—A metallic sheath enclosing the conductors of a cable is a type of shielding. The lead sheath of a 2⅝ in. diameter aerial telephone cable, if effectively grounded at the ends, as when directly connected to an underground cable sheath, reduces the voltages induced in the conductors within the cable by about 50 per cent at 60 cycles. The additional shielding brought about by the surrounding earth when such a cable is placed underground is negligible at low frequencies, although underground construction has an advantage in affording a low-resistance ground for the sheath. The large number of conductors in a cable afford mutual shielding which varies from a negligible to a considerable amount depending upon many factors, important among which is the extent of the cable beyond the ends of the exposure. If two or more cables are close to one another through an exposure, each benefits by the shielding action of the others, so that the shielding increases with the number of cables.

If the lead sheath of the cable is surrounded by magnetic material as by armoring or placing cable in iron pipe, the shielding may be largely increased. With the form of iron tape armored cable referred to in the Harrison-Silver paper, which is now in trial use, shielding at 60 cycles is about 80 per cent, assuming effective grounding. Armoring a cable increases its cost substantially but has an advantage apart from shielding in that the cable being protected by the armor against mechanical injury may be buried directly in the earth without conduit. The armor is protected by impregnated wrappings but its life has yet to be determined. The shielding afforded by this type of cable has been studied experimentally under practical field conditions. Other installations and studies have been made abroad. It is probable that there may be a field of use for this type of cable in situations for which it is best adapted.

Coordinated Location of Lines.—Since the magnitude of induced voltages for given power line conditions depends upon the inductive coupling of the two classes of lines, which in turn is dependent upon their relative location, particularly their separation and length of parallelism, it is possible by advance cooperative planning of new power and telephone line locations to minimize and in some cases to forestall inductive effects in the telephone system. If the cost of remedial measures which inductive exposures would render necessary can be avoided, additional expense in locating lines to avoid such exposures may be justified and where a complete solution is obtained in this way both parties secure greater freedom in the construction and operation of their lines. However, with the rapid expansion of both services, the possibilities of complete solution by separation of lines alone are becoming more and more rare, particularly for lines along highways.

Coordination of Grounding Practises.—The occurrence of a fault on a power system usually results in raising the ground potential at the points of grounding as well as at the point of fault, but if steps are taken to coordinate the grounding of the power system and the telephone system serving the power company, particularly at transformer and generating stations, the effects in the telephone system of the earth potential gradient caused by a power fault may be minimized. For example, if in a switching station the same ground should be used for the power system neutral and for the telephone system, a power fault might cause the switching station ground to rise many volts above the distant telephone exchange ground, and result in operating the telephone protectors and possibly interrupting service. If, however, independent grounds sufficiently separated are used at the switching station, or an insulating transformer is placed in the telephone circuit, the power neutral ground may rise in potential without unduly affecting the telephone system.

Comprehensive consideration of the low-frequency coordination problem involves a study of the reactions between the grounding practises employed by power companies and those employed in telephone and telegraph systems. There is considerable diversity in practise with respect to methods of grounding. Some power transmission lines and primary distribution lines are not provided with any designed grounds, although most such lines have grounded neutrals and a few lines are grounded in such a way that operating current flows through the earth. In built-up communities there are underground pipes, cables, and other structures along which current in the earth will flow to a greater or less extent. These structures have varying degrees of conductivity and some of them have, either by design or by accident, high resistance joints. Consequently the paths of earth currents are exceedingly complex. The conditions as to earth currents and earth potentials necessary to be known in order to work out any coordinated scheme of grounding would usually have to be determined by tests.

The different kinds of grounds to be considered include those on: power transmission circuit neutrals, lightning arresters, power distribution primary neutrals, power distribution secondaries, railway systems, building conduits, telephone protectors, batteries, ringers, telegraph circuits, lightning rods, electrolysis protection systems, various types of signal circuits such as fire and police alarm systems, and so on. The grounding practises for all these different systems should be carefully studied and coordinated in order to prevent so far as possible harmful reactions among them. Such a study of course goes considerably beyond the scope of this subcommittee.

Comparison of Different Protective Measures.—The ideal protective measure would be one which furnished adequate protection and had no unfavorable reaction from an economic or service standpoint on the system to which it is applied. However, the work thus far has not disclosed any measure which fully meets this ideal.

The relative advantage of different measures resolves itself into a question of the best technical results which can be obtained at the least over-all cost. The solution of problems consists of finding measures which afford the highest degree of protection which is practicable and reasonable under the circumstances. In the investigation of a specific case it may be found that certain protective measures can be combined with other work in such manner that the cost is not wholly chargeable to coordination for the reason that other results of value are secured. For example, shielding may be obtained at small cost if improvement of performance of a transmission line justifies the installation of ground wires; or, the benefits of shorter duration of induced voltage by the use of high speed circuit breakers and high speed relays may be secured in connection with a program for improving the stability of power systems.

No other measure affords such complete protection against all effects of induction as adequate separation. However, measures applied to power systems such as fault current limitation which strike directly at the source of low-frequency induction are of a basic character and permit a closer association of the two classes of lines, a very important consideration in congested areas. Measures which affect only the frequency of occurrence of faults, or their duration, while very helfpul, are not as effective from a protection standpoint as measures which limit the magnitude of residual currents and voltages.

As to measures which would allow telephone circuits to operate through a strong inductive field, the use of lead-sheathed cable surrounded by magnetic material seems to offer the physical possibility of affording the most effective protection. Precautions would be required, however, to prevent the shielding structure itself from rising to a dangerous potential with respect to earth. On open-wire lines where the occurrence of high induced voltages cannot be prevented, some form of protector for limiting the magnitude of voltage to ground seems to be a logical line of development.

Devices such as acoustic shock reducers, which protect only against a single effect of induced voltages, do not afford a solution of most specific situations, but have to be used in combination with other protective measures. In many situations, no single protective measure is adequate and if the exposure is severe several may be required.

In considering the effects which a new exposure may produce, all the relevant factors are capable of advance determination except frequency of occurrence of induced voltages, which has to be estimated on the basis of experience or judgment and a statistical analysis of line failures.

Selection of measures to be employed in specific cases should be made with the above considerations in mind to the end that the best engineering solution may be obtained irrespective of whether the protective measures are applied to the telephone system, to the power system, or to both.

Reaction of Physical Exposures and Lightning on Low-Frequency Induction Problem.—As telephone circuits which are exposed to induced voltages may also be exposed to possible contact with power circuits and to lightning, any comprehensive scheme of protection must take into consideration the high currents resulting from contact and the high voltage due to lightning. In this connection there are some points of difference in the reactions on the protection scheme of induction, contact, and lightning.

Contacts between power and telephone wires may occur at crossings or conflicts or they may occur on joint pole construction as described in the paper by Messrs. Huber and Martin. In any event such contacts can occur only where the two lines are in close proximity, whereas in cases of inductive exposure, a fault outside as well as inside the exposure, may produce disturbances in the telephone circuits. Moreover, in cases of contact, wire or structure failures are generally involved while faults may cause induction which do not involve falling wires. Contacts impose on the telephone line the full voltage to ground of the power conductor at that point, whereas induced voltage is usually only a fraction of the power circuit voltage. This does not mean that the imposed voltages due to contact are always higher than those due to induction, because the majority of exposures to contact do not involve the higher voltage circuits while the opposite is true regarding inductive exposures. In cases of contact only part of the wires of the telephone line are usually involved whereas in the majority of induction cases substantially the same voltage is induced on all the wires. The voltages imposed on a telephone line by contact as well as those by induction may extend over the full length of the conductors involved.

In addition to the effects of contact between wires of the two systems, there is a distinct class of hazard to linemen of both utilities introduced by situations of insufficient clearance due to improper construction or inadequate maintenance on the part of one or both utilities.

Voltages on telephone lines by lightning produce effects somewhat similar to the effects produced by power lines but lightning voltages differ from the other voltages in that their duration is much shorter. Lightning makes necessary protector discharge gaps of very high speed of operation in order to prevent serious over-voltages on the telephone system, whereas contacts with power circuits make necessary a protector of high current-carrying capacity.

Committee's Program of Work

The program of work on low-frequency induction undertaken by the Joint Subcommittee on Development and Research through its project committees is laid out to develop the essential facts bearing on the problem of telephone protection in a broad sense, including causes, effects, and remedial measures. The program covers not only the technical but also the economic aspects of the problem. The problems of lightning and physical contact under conditions of conflict or joint use are also included, as the measures finally adopted must protect against voltages from these sources as well as voltages induced by power systems.

Extensive field trials of all promising protective measures, are under way in order to determine their practicability under operating conditions. As the work progresses, it is expected to issue from time to time reports covering the applicability, efficacy, limitations, and conditions of use, of various measures. This should result in a better understanding of the problem and more effective and economical solutions of specific situations as they arise.

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