Status of Joint Development and Research on Noise Frequency Induction *

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The work of finding out the technical facts bearing on the problems of the physical relations of power and telephone circuits was intrusted to the Joint Subcommittee on Development and Research of the National Electric Light Association and the Bell System. This paper has to do with this fact-finding work so far as it concerns noise frequency induction.

The work on inductive coordination may be classified into three groups of factors:

1. Influence factors which concern the characteristics of the power circuits.
2. Susceptiveness factors which concern the characteristics of the communication circuits.
3. Coupling factors which concern the interrelation of power and communication circuits.

The paper discusses these various factors in detail and describes the work done by the committee or in progress regarding them. References are given to published reports and papers which present the results of technical studies already completed.

Many of the existing noise frequency induction problems have arisen because of the development of the art of the two industries without such close cooperation between them as now exists. It is becoming evident, from the work of this Joint Subcommittee, that while it is not practicable to design machinery and apparatus for power systems to be entirely free of harmonics, or to ideally balance either power or telephone circuits, it is possible to control these factors within limits which, in conjunction with the control of coupling obtainable by cooperative planning of routes and coordination of transpositions, permit satisfactory operation of both services without unduly burdening either.

THE Joint Subcommittee on Development and Research is the agency through which the National Electric Light Association and the Bell Telephone System carry out technical work on problems of physical relations which vitally affect their respective growth and operating practises. In the present paper and companion papers the status of this joint development and research work is described.

The present paper, Part II of the Symposium, is concerned with problems of induction in telephone circuits under normal operating conditions of power systems which results in noise. Part III of the Symposium treats of induction at the power system fundamental frequency, principally that occurring at the time of grounds, short circuits or other abnormal conditions of power systems. Part IV of the Symposium treats of the physical relations and of the special noise-

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frequency and low-frequency problems brought about by the close proximity of the two types of service when occupying the same poles.

The Joint Subcommittee on Development and Research has subdivided its work among eleven project committees and assigned to each the actual carrying on of specific research work. Certain of the project committees are engaged on the problems described in this paper, while the remainder are concerned with the development and research problems of the companion papers, Parts III and IV of the Symposium. The names of these project committees, together with a statement of the phase of the problem considered by each, is given in Volume I of "Engineering Reports of the Joint Subcommittee on Development and Research." [1]

Naturally the first steps taken by the Joint Subcommittee were the review and appraisal of existing information and the exchange of data between the two interests represented. This paper includes a statement of the problem, with some review of the factors involved, the results accomplished by the subcommittee and the work projected in connection with each factor.

CLASSIFICATION OF FACTORS CONTRIBUTING TO INDUCTION

There are certain characteristics of a power circuit with its associated apparatus that determine the character and intensity of the electric or magnetic field which is set up in the surrounding medium. These characteristics are termed "Influence Factors." [2]

Likewise, there are certain characteristics of a communication circuit with its associated apparatus which determine its responsiveness to external electric or magnetic fields. These characteristics are termed its "Susceptiveness Factors." [2]

There is a third group of factors which refer to the interrelation of neighboring power and communication lines by electric or magnetic induction or both. These are termed "Coupling Factors." [2]

Inductive interference is thus the manifestation in the telephone circuit of a combination of influence, susceptiveness and coupling; and inductive coordination consists in the control of factors in all three of these classes to the degree required for satisfactory operation of both services.

METHODS OF CONTROL

Physical Separation.—The first method which comes to mind for the control of inductive effects is that of physical separation obtained by placing the power and telephone lines on separate routes. A separation

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[1] For references see bibliography.

between lines of a few hundred feet practically eliminates the noise-frequency problem whereas the low-frequency problem may exist with much greater separations. Since the same customers desire both communication and power services, the two kinds of distribution lines are necessarily often located on the same streets and highways. Power transmission lines and toll telephone lines do not, in general, have to be placed on particular routes and, therefore, separation can often be employed where such lines are involved. Cooperative advance planning on the part of the utilities in laying out their plants makes it possible to employ separation where it is readily feasible and economical.

Frequency Separation.—Another method of fundamental importance is the use of frequency separation. By this method, circuits to be coordinated are arranged so as to be responsive to different frequencies or bands of frequencies, and comparatively unresponsive to the frequency or band of frequencies employed for the other circuits. It is thus possible to make many different uses of electricity involving transmission in the same medium. This solution is familiar to us in the coordination of radio services.

Fig. 1 shows a diagram of the various uses of the frequency spectrum for electrical transmission and the manner in which power and communication services are coordinated by means of frequency selectivity.

The first commercial electrical energy available was in the form of direct current. Shortly thereafter, alternating current was used for the transmission of power. The nominal frequencies of the current used for this service in the earlier days range from 16⅔ cycles to 133 cycles. In American practise the frequencies used for power purposes have practically settled down to either 25 or 60 cycles. There is one extensive 50-cycle system and a few odd frequency systems. These latter of 30, 33, and 40 cycles, and perhaps others, are being rapidly eliminated, due to the importance of interconnecting them with 60-cycle systems. At the present time, there is some tendency for the use of higher frequencies in special machine shop applications. This use, at present, is principally at 180 cycles and need not concern us here as its extent is usually confined within a factory building.

In message telephone transmission, the prime consideration is the transmission of intelligible speech. While the range of response of the human ear is from about 16 cycles to 15,000 cycles per second, human speech occupies a narrower range and a still narrower band is adequate for intelligibility. The present voice-frequency telephone circuits, especially the longer ones, operate within a frequency band of about 250 to 2750 cycles per second. The frequency selectivity at the edges of the band is not sharp, however, so that extraneous currents at frequencies outside of this band may also give rise to noise. This is particularly true at the lower end with some of the local exchange circuits. High quality telephone circuits for program transmission cover a wider range. This may be on certain circuits as much as from about

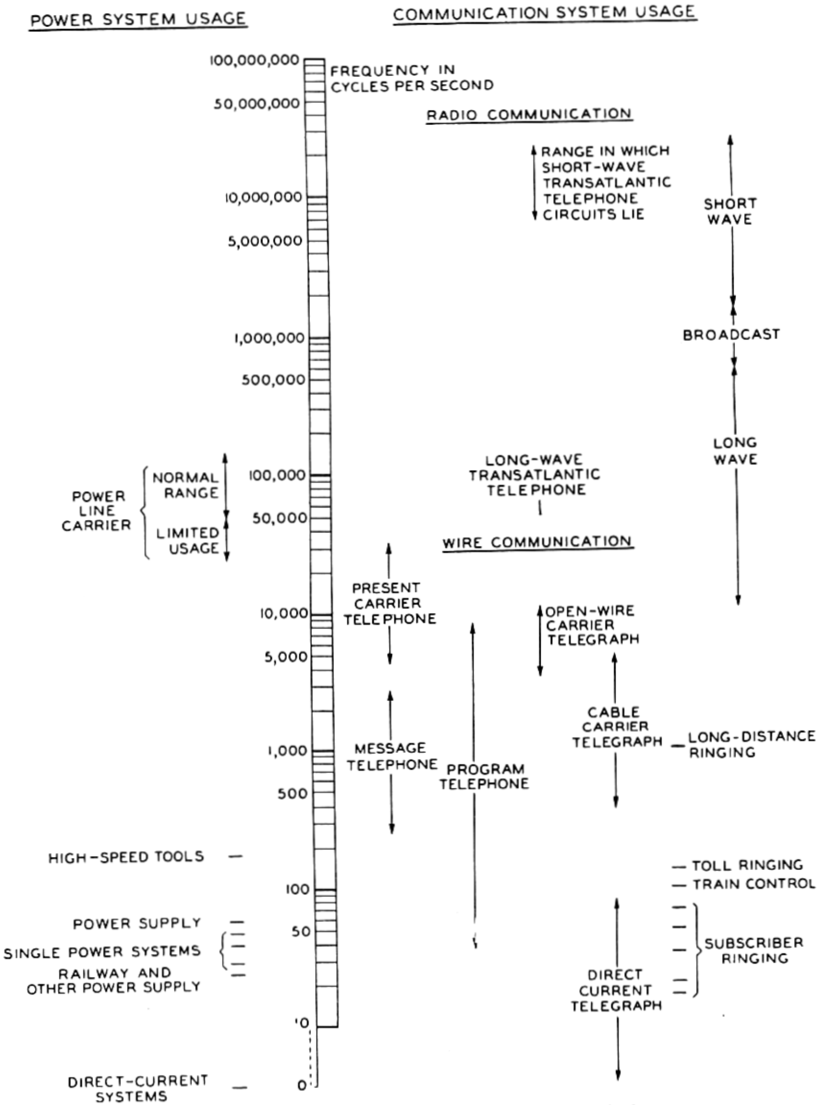

Fig. 1—Frequencies used for electrical transmission.

35 to 8000 cycles per second, thus overlapping the fundamental frequencies used for power transmission.

Control of Power Levels.—Coordination by frequency separation becomes inadequate when the power levels of the various classes of services differ greatly as with power and telephone services. Thus, although incidental powers at harmonics of the power circuit fundamental frequency are negligible in comparison to the power at the fundamental frequency, they are large compared to the power employed in the telephone circuits and fall directly within the frequency range of the telephone circuits.

While the powers involved in telephone transmission are small as compared to those on power lines, they are in turn large as compared to the acoustical power received from the talker or delivered to the listener. The ordinary telephone transmitter is an amplifier, delivering to the line several hundred times the voice power which actuates the diaphram. On the other hand, the receiver requires an electrical power a hundred or more times that which it delivers as sound to the listener's ear.

It is obvious that the relative levels of harmonic-frequency power in the power circuits and voice-frequency power in the telephone circuits are of major importance in inductive coordination. These considerations have had large influence in the power field in the control of wave-shape of rotating machinery and transformers, and in the telephone field in fixing limitations on such factors as wire sizes, spacings of repeaters and instrument efficiencies.

Balance.—Among the most important methods of coordinating power and communication circuits is the control of their respective balances to ground and to each other. A power circuit with absolutely balanced voltages and currents impressed, and with the various conductors arranged in such a way that they would not establish external electric or magnetic fields, would not have any effect on any type of neighboring communication line.

Likewise, a telephone circuit in which there were no unbalances and in which the conductors were arranged in such a way that in the presence of an electric or magnetic field they would not have any voltages induced between them would not become noisy from any neighboring power circuits. Such an ideal state is impossible, but much has been accomplished by care in the design of the lines and equipment and by the transpositions of the conductors.

Shielding.—It is possible to materially reduce electric fields by interposing between disturbing and disturbed conductors grounded conductor surfaces known as shields. Magnetic fields can likewise be reduced by interposing conducting paths which circulate current to set up counter magnetic fields. The power and telephone cables in use are probably the simplest examples of shielding. A cable sheath is almost 100 per cent effective as a shield for electric induction, either on a power cable or on a telephone cable. The sheath is less effective as a shield for magnetic induction, because of its finite conductivity. It does not seem feasible at this time to obtain anywhere near perfect magnetic shielding.

FACTORS CONTRIBUTING TO NOISE FREQUENCY INDUCTION

Influence Factors

There are two characteristics of a power system which are of primary importance in determining its inductive influence upon neighboring telephone systems, i.e., its wave-shape and its balance. The wave-shape is determined by characteristics of apparatus associated with the system. The balance is determined by the degree of symmetry of the supply voltages, load impedances, and of the series impedances and shunt admittances of the lines. While it is not practicable to design rotating machinery or other apparatus using magnetic cores entirely free from harmonics, or to realize ideally balanced three-phase systems, it is practicable to control both these factors within limits which, in conjunction with a similar degree of control on the coupling and in the susceptiveness of the communication circuits, permit satisfactory operation of both services without unduly burdening either.

The work on influence factors which has been conducted by the Joint Subcommittee on Development and Research has, therefore, been directed for the most part toward the study of the wave-shape characteristics of power systems and apparatus and methods for their improvement and the investigation of factors affecting the balance of the power systems and method for their control.

Wave Shape.—In initiating its work on influence factors, the Joint Subcommittee found little information available as to wave-shape which might be expected on operating power systems equipped with various types of apparatus. In order to obtain a broad picture of wave-shape conditions as they exist in the field, the Subcommittee conducted an extensive survey of wave-shape conditions on 34 operating power systems in the eastern half of the country. The program was arranged to obtain information as to the average and range of magnitudes of harmonics present in various types of transmission and distribution systems under normal operating conditions, to observe the relation between the wave shape of generating machinery under open-circuit conditions and under load, to study the effects of various transformer connections on wave shape, and to observe the effects on wave shape of various types and magnitudes of load.

The measurements made included analyses of the phase-to-neutral and phase-to-phase voltages and phase currents on a large number of generators, transmission lines and distribution feeders. Wherever practicable, data were obtained as to the balance of the operating systems by measurements of residual voltages and residual currents. Measurements were also made of the Telephone Interference Factors[3] of the voltages and currents. Where telephone circuit exposures suitable for test purposes existed, noise measurements were made on the communication lines to aid in determining the relation between power-system wave-shape and balance and telephone circuit noise. The actual measurements were for the most part conducted by the operating companies with the cooperation, during the first part of the testing program, of representatives of the Joint Subcommittee.

The mass of data accumulated during this survey is being summarized in several technical reports which it is anticipated will yield much valuable information pertaining to the wave-shape problem. An important practical application of these data will be in connection with the prediction of wave-shape conditions on new lines which are to be involved in exposures with communication systems and on which noise estimates are desired.

In general, the survey data indicate that the magnitudes of the harmonics present in voltage and current diminish with increasing frequency, with the exception that a pronounced dip occurs in the region from 800 to 1500 cycles. This is, no doubt, a result of the efforts of the machine designers to closely control the harmonics in this important region. Frequencies above 2000 cycles become extremely small except where these may be introduced on the power circuits by superposed carrier communication or signaling services. In general, the frequencies used for such services have been in the range from 50 to 200 kc., which is above the range employed for carrier communication on telephone lines.

In the general survey of wave-shape, no efforts were made to select feeders involved in cases of inductive interference. Aside from the survey work, however, representatives of the Subcommittee have participated in a number of investigations of such cases in which power-system wave-shape was an important factor. Much valuable data as to wave-shape conditions under which coordination difficulties are experienced have been obtained from these studies, while in obtaining these data the Subcommittee representatives have been of service to the local companies in the solution of the particular problems.

A limited amount of theoretical work has been carried on having to do with the effects of load on the harmonics observed in the open-circuit voltage of rotating machines. This work which was based on Blondel's two-reaction theory was supplemented by laboratory tests on several small machines. It was found that the reactions which take place within the rotating machines, particularly when two or more are operating in parallel, are so complicated as to practically preclude accurate computations of the effects. However, the data obtained from this investigation have been valuable in connection with later studies.

Balance.—A balanced power circuit is one in which the voltages between the various phase conductors and ground are equal in magnitude and sum up vectorially to zero and in which the phase currents are also equal in magnitude and sum up vectorially to zero. In a three-phase system where the currents or voltages are not equal but do sum up to zero, the currents or voltages can be resolved into two balanced three-phase systems, one of positive phase sequence and one of negative phase sequence. In cases where the currents or voltages do not sum up to zero they contain a single-phase component which is usually termed residual or zero-phase sequence component. Any three-phase system can be resolved into its balanced and residual components and each treated separately. The coupling for the residual components is usually much larger than for the balanced components and is therefore frequently of major importance in coordination problems. Differences in the magnitudes or departures from phase symmetry of the three impressed phase-to-neutral voltages, load or line unbalances, give rise to residual currents or voltages.

Experience has indicated that the outstanding factor in the unbalance of power systems is the existence of triple-harmonic voltages and currents which may arise either in rotating machinery or in transformers which are connected in star with grounded neutral. Since the triple-harmonic voltages in the three phase-to-neutral legs are in phase, they act in a path consisting of the phase conductors and an external return as, for instance, a metallic neutral or ground.

A large measure of control may be exercised on the magnitudes of the triple-harmonic residual voltages and currents by the use of certain transformer connections and by not operating the transformers at high flux densities.

The magnitudes of triple-harmonic residual currents in grounded-neutral systems may be minimized by the use of star-delta connected transformers, in which case nearly all the required triple-harmonic current circulates in the delta. The opposite extreme occurs with star-

star connections in which case the full triple-harmonic magnetizing current flows in the two systems which the transformer interconnects, the relative magnitudes in each depending on their relative impedances. Where a star-star bank is connected at one terminal of a line, with a star-delta at the other, the neutrals at each end being grounded, practically the entire third harmonic required by the star-star bank may be expected to circulate in the line connecting the two.

An effective method of control for cases in which star-star connections are required due to phase relations is the provision of a third set of windings or tertiaries in the transformers, the impedance of the tertiaries with respect to the other windings being sufficiently low to furnish an adequate path for the triple-harmonic magnetizing current. An alternate method of control, which also provides like phasing on the two sides of the bank, is the use of zig-zag connected transformers.

In four-wire multi-grounded neutral distribution systems, it has been found helpful in controlling the residual triple-harmonic currents from the single-phase load transformers to provide star-delta connected banks at various points in the network with neutrals connected to the system neutral. In some cases, these have been three-phase load banks, in others, special banks installed as a method of control.

The subcommittee is continuing its work on wave shape and balance through a laboratory study of transformer harmonics and transformer connections. These tests are being made on small model transformers, typical of the designs which are used for large sizes on transmission systems. It is planned to develop the theory applicable to harmonics from transformers on three-phase systems from the work on these laboratory models. It is planned to supplement the work by tests on large transformers in the manufacturer's shops and in the field.

A number of severe noise situations have been created during the past few years when star-connected generators, operating with grounded neutral,[4,5] have been connected directly or through star-star transformer banks to transmission or distribution systems. The interference in these cases resulted from triple-harmonic residual components impressed on the system by the particular generator operating with the grounded neutral. The magnitudes of these currents depend on the triple-harmonic components in the generator phase-to-neutral voltage and the impedance to ground of the system. The methods of control which have been successfully applied in these cases include the following:

1. Isolating the generator neutral and supplying the system ground through a suitably designed transformer bank.
2. Grounding the neutral of only those generators designed to be free from triple harmonics in their phase-to-neutral voltage.

3. The use of selective devices such as reactors or anti-resonant circuits commonly called "wave traps" in the generator neutral for suppressing the disturbing triple-harmonic components.

Non-triple harmonic residual voltages and currents may exist from differences of phase-to-neutral load impedances and from differences in the capacitances to ground of the three phase wires.

In multi-grounded neutral four-wire systems differences in the single-phase loads connected between the individual phases and the neutral may be important sources of residual current. A considerable measure of control may be exercised by restricting the size of single-phase areas and balancing the load on the different phases.

Capacitance unbalance to ground may be due to single-phase branches on three-phase distribution systems. Usually, the more important effect is that on the single-phase branch where the residual voltage is practically equal to the phase-to-neutral voltage. The unbalancing effect on the three-phase system may be minimized by equalizing the lengths of the branches connected to the several phases. The residual voltage on the single-phase branch can, where necessary, be eliminated by the use of isolating transformers or by converting to a three-phase branch.

Capacitance unbalance may also be due to dissymmetry in the arrangement of the wires of the circuit to each other and to ground. These unbalances are lowest in triangular configurations of the wires and largest when all the wires are in the same vertical or horizontal plane. With multi-circuit lines, a considerable measure of control may be obtained by suitable phase interconnection of the circuits. Transpositions are also effective in controlling these unbalances.

Coupling Factors.—The coupling between power and communication circuits is, of course, determined by the degree of their proximity, but it may be greatly modified by the balance of the two classes of circuits to each other and with respect to ground. While the most direct and certain method for reducing coupling is to avoid proximity, means are available for minimizing the coupling where necessary.

The work on coupling of the Joint Subcommittee on Development and Research, in the voice and carrier-frequency range, has been directed toward two objectives: (1) development of improved methods for predetermining the coupling to be expected in new cases of exposure, and (2) development of improved methods for reducing coupling for given degrees of proximity.

Several years ago the California Joint Committee on Inductive Interference [6] completed an extensive series of computations on coefficients of induction which were expressed in the form of curves for various physical relationships of power and telephone lines. These coefficients indicate the voltages induced in short, isolated, untransposed telephone circuits by unit voltage and current on similarly untransposed power circuits. They do not include the small separations involved with jointly used poles.

These curves and others based on them have been used for many years in determining relative coupling, when comparing different exposures, different routes involving various degrees of exposures, different configurations of power and telephone circuits and for other comparisons where all factors were substantially equal in the situations being compared, except those involved in determining the coefficient of induction. For these purposes they have been very useful. Methods have not, however, been available whereby these coefficients could be used for computing noise where transposed circuits were involved and where many telephone wires were on the line, which exert an important shielding effect on each other.

The Joint Subcommittee on Development and Research has been conducting experimental studies both for highway and wider separations, and those occurring with jointly used poles, so that the effects of transpositions and of mutual shielding of the many wires involved might be properly taken into account in determining the noise currents in the metallic circuits.

In determining the coupling between power and telephone circuits, it is desirable to differentiate between the effects of the balanced and residual components of the voltages or currents of the power circuit, between the effects of voltages and those of currents, and on the telephone line between induced voltage which acts directly in the metallic circuit, termed "metallic-circuit induction," and that which acts in the circuit composed of the wires with ground return, termed "longitudinal-circuit induction."

Since the residual components act in a circuit having ground as one side with the wires in parallel for the other, while the balanced components are confined to the wires of the system, the coupling for the residual components is much greater than for the balanced components. The coupling for the balanced components may be reduced by the use of power-circuit transpositions, while such transpositions have no effect on coupling for the residual components.

The distance between the power and telephone wires is usually large as compared to the spacing of the wires of the telephone circuit, so that the longitudinal induced voltages are large as compared to the metallic-circuit voltages. The effect of the telephone transpositions being merely to equalize the relations of the two sides of the telephone circuit to the power circuit, such transpositions do not change the magnitude of the longitudinal voltages, but do reduce the metallic-circuit voltages.

The relative magnitudes of inducing voltages and currents differ widely among various power circuits, and may vary greatly with time on any given circuit. They will also differ considerably at a given time and on a given circuit among the various frequencies involved. For this reason it is necessary to consider separately the coupling arising through the electric and magnetic fields.

Voltages induced in metallic circuits for the separations between lines usually encountered are practically proportional to the spacing of the wires of the telephone circuit. Voltages induced in eight-inch spaced pairs are thus approximately two-thirds of those induced in 12-inch pairs, while those induced in phantoms on 12-inch spaced side circuits are twice those induced in the sides. The longitudinal voltages are, however, practically independent of the wire spacing so that the contributions which these voltages make to noise in the metallic circuit are unchanged except as the change in spacing may affect the balance to ground.

Spacing of the wires on the power circuit and their configuration also have an important effect on the coupling for the balanced voltages and currents, the coupling, in general, increasing as the spacing increases. Coupling for the residual components is, however, affected only to a minor degree by the spacing and configuration. Much information bearing on these matters is included in the material on coefficients of induction published by the California Commission referred to above.

Measurements of coupling have been made by the subcommittee in a number of situations. These have included cases of (1) exposure of overhead transmission lines and open-wire toll telephone circuits at highway separations, (2) overhead distribution lines and subscribers' telephone cables in joint use and at street separations and (3) overhead distribution lines and subscribers' open-wire circuits in joint use. Information was obtained on coupling both for voltages and currents and for the balanced and residual components. The results of the work on overhead distribution lines and subscribers' telephone cables have already been published.[7] The other data are to be published as soon as they are prepared in suitable form.

The work on overhead distribution lines and subscribers' circuits is relatively complete, covering a wide range of conditions typical of those encountered in the field. Various arrangements of primary and secondary conductors covering single-phase and three-phase, three-wire and three-phase, four-wire systems were investigated. The shielding effect of the telephone cable was determined and, with the open-wire subscribers' telephone circuits, the shielding effect of the various telephone wires on each other.

For telephone cable circuits when the sheath is grounded at either one or both ends, the inductive effect of the power circuit voltages on the wires enclosed is negligible as compared to that of the power circuit currents. Furthermore, because of the close association of the wires of a pair in the cable and the frequent twist, the metallic-circuit induced voltages are negligibly small as compared to the longitudinal voltages so that, in general, only the magnetic longitudinal coupling factors are of importance in these situations.

The work further indicates that, for most practical problems involving overhead distribution lines of the multi-grounded type and subscribers' cable circuits, a knowledge of the coupling for the residual or unbalanced currents is sufficient, the effect of the balanced currents being relatively unimportant. However, in cases where the line currents are particularly heavy or contain exceptionally large harmonic components, the balanced currents become important.

In the range of frequencies used for telephone transmission the ratio of open-circuit voltage induced on a telephone line through electric induction to inducing voltage on the power circuit is substantially independent of frequency. When the exposed section of line is connected to the remaining section of the telephone line or to terminal apparatus, a current is set up which is approximately proportional to the frequency of the induced voltage. The circuit will perform as if there were a small condenser connected between the power circuit and telephone circuit and the induced current experienced will be proportional to the frequency and the magnitude of the inducing voltage on the power circuit.

The coupling between power and telephone circuits for currents is in the nature of a mutual inductance, so that the voltage induced in the telephone circuit is proportional to the magnitude of the inducing current in the power circuit and its frequency.

This statement applies strictly only to induction from the balanced current components. Induction from residual current in the power circuit is complicated by the effect of the finite conductivity of the earth. With increasing frequency the earth currents tend to be closer to the surface and the coupling with the telephone circuit tends to increase less rapidly than would follow from proportionality with frequency. The departure from linearity is not large in the frequency range from 250–2750 for highway separations and for joint use.

Transpositions afford one of the most powerful means available for controlling coupling of power and open-wire telephone circuits in given situations of proximity. Transpositions operate by neutralizing, in one section, inductive effects which arise in a closely adjacent section. It is evident that, in order for transpositions to be fully effective, conditions must be substantially alike among the various sections to be neutralized as regards relations of the power and telephone circuits to each other, to ground, and among the various circuits on each line. This latter condition more often applies to the telephone lines, as they usually comprise many circuits.

These conditions require that balanced and coordinated systems of transpositions be provided between each point of discontinuity in the exposure. By "discontinuity" is meant any point at which an important change takes place in the physical or electrical conditions of the circuits, such as loads, branch circuits, series impedances, etc.; any change in configuration, in the separation of the two classes of circuit or in their position relative to ground or to some other circuits which may be associated with either power or telephone circuits closely enough to appreciably modify the induction.

In addition to meeting these conditions, the telephone transpositions must also satisfy the requirements for minimizing cross talk among the various telephone circuits. This, in general, requires telephone transposition arrangements of considerable complexity. For this purpose standard transposition arrangements are available,[8] adapted for different lengths depending upon the distances between the successive discontinuities.

In most cases unavoidable irregularities occur in the spacing of poles, in distances between power and telephone circuits, in presence of shielding objects, such as trees, and in height of poles, which it is not possible to treat as discontinuities and take into account in the transposition design. In cases where these irregularities are large, the effectiveness of the transposition arrangements is greatly impaired. The extent to which the effectiveness of such arrangements is imparied due to these non-uniform conditions is a problem not easily susceptible to mathematical analysis and reliable information is not now available. The subcommittee is planning to investigate this problem experimentally by tests on a number of situations involving operating circuits.

Susceptiveness Factors.—The degree to which telephone transmission is adversely affected by noise-frequency induction depends not only upon the magnitudes of the induced voltages as determined by influence and coupling factors, but also upon the susceptiveness factors of the telephone system. These include the manner in which the induced voltages and currents are propagated to the circuit terminals together with the reactions of the circuit unbalances, thus relating the current in the terminal apparatus to the induced voltages, the sensitivity of the receiving apparatus and the operating power level of the telephone circuits.

Propagation Effects and Balance.—Important differences exist with respect to propagation effects and balance between open-wire and cable circuits and between toll and exchange systems.

As pointed out in the discussion of coupling, only the magnetically induced longitudinal voltages and currents affect telephone cable circuits. Because of the absence of electric induction and direct metallic-circuit induction and because of the important shielding effects exerted by the cable sheath and the various telephone circuits on each other, telephone cable circuits are much less susceptive than open-wire circuits.

In open-wire telephone systems consideration must be given both to electric and magnetic induction and to voltages directly induced in the metallic circuit as well as to those induced in the longitudinal circuit. In a line composed of a number of circuits, the currents set up in any one circuit depend, not only upon the voltage induced in that circuit and its impedance, but also upon the currents and voltages which are set up in the rest of the telephone circuits on the line. It is not possible, therefore, to calculate the induced currents merely from a knowledge of the magnitudes of the currents and voltages on the power circuits and the coupling between the power circuits and isolated pairs of wires on the telephone line, considered independently.

These mutual effects among the various telephone circuits exist both within and without the exposed sections. Thus, the propagation of the induced voltages and currents along any one circuit is influenced both by the electrical conditions of this circuit and also by the conditions of all other wires on the line. Additional complexities arise in the propagation of the induced voltages and currents, because of non-uniformity in impedances to ground at terminals, points where circuits join or leave the line, and where lengths of cable may be used at terminals or at intermediate points. The impedances to longitudinal induced voltages and currents vary over a wide range depending on the number of wires on the line, the relative position of the exposure and the circuit terminals and the occurrence of sections of cable. Due to reflection effects from these irregularities, peaks of current and voltage may exist along the circuits which are large as compared to the corresponding magnitudes at the exposure terminals. If circuit unbalances happen to exits at these maximum points, metallic-circuit voltages and currents thereby introduced are increased.

While the distribution of longitudinal voltages and currents among the various wires upon the telephone line depends upon the nature of the inducing field in which it is placed, the experiments of the committee have shown that a satisfactory degree of approximation for studying propagation effects can be obtained by energizing all wires on the line simultaneously at the same potential from a common source. An extensive experimental study has been made in this way by the committee in which the magnitudes of the longitudinal voltages and currents at various points along the line have been measured as well as metallic-circuit currents set up through the unbalances at the sending and receiving ends of the line.

By making measurements of this sort on a considerable number of lines of different types of construction and different transposition arrangements, it is hoped to obtain statistical data whereby the metallic-circuit voltages and currents at the circuit terminals may be determined from the magnitudes of longitudinal voltages and currents as measured at exposure terminals.

Unbalances in toll circuits are the result of commercial variation from the balanced condition, since the circuits are designed to be symmetrical. These unbalances may consist of resistances in joints, capacitance or inductance unbalances due to irregularities in transposition spacing or to omitted or unspecified transpositions, or differences in the impedances of apparatus connected in series with the wires or between them and ground. These unbalances are fortuitous both as regards their magnitudes and location along the toll circuits. Some increase in importance with frequency and others decrease. These, combined with the irregularities in the propagation of the longitudinal voltages and currents, cause the resulting metallic-circuit currents in individual circuits to vary in an erratic fashion with frequency. The general trend is one of proportionality, independent of frequency within the important range, between the longitudinal currents and voltages at the exposure and current in the metallic circuit at the terminals. Taking into consideration the effects on coupling, the currents at the terminals increase approximately in direct proportion to the frequency of the inducing voltage or current on the power circuits.

Because of the lower susceptiveness of cable circuits together with the high degree of balance of the terminal apparatus and because of the more general use of private rights-of-way, cases of noise-frequency induction into toll cable circuits have been comparatively infrequent. For this reason the attention of the subcommittee as far as toll systems are concerned, has been directed toward open-wire circuits.

In exchange circuits certain inherent unbalances exist due to the arrangements employed for supervisory signaling, for selective ringing, and for coin box service. The supervisory system utilizes a low impedance relay connected in series with one side of the central office interconnecting circuit. The selective ringing scheme involves connecting the ringer windings from one side of the line to ground at the station set. For the coin box service, a coin-collect relay winding is connected between one side of the station set and ground. These unbalances have been investigated in detail by the committee and the results have been published [7] as described later.

The unbalance of party lines due to the ringer ground is usually much more important than that of the central office interconnecting circuit due to the supervisory relay. Both are, in general, more important than the cable unbalances. Coordination difficulties between telephone exchange systems and power distribution systems thus usually involve the party-line circuits before the individual-line circuits are affected.

The controlling unbalance in the exchange plant when in cable being in the nature of an inductance between one side of the line and ground, its importance decreases with increasing frequency of the induced longitudinal voltage. This effect largely counter-balances the increase in coupling with frequency. Thus, in most situations involving joint use of poles by distribution circuits and exchange cable telephone circuits, induced currents of the third and fifth harmonics of the power circuit fundamental frequency assume chief importance.

Exceptions are cases where outstanding harmonics in the range between 800 and 1500 cycles are present on the power circuits. In these cases, particularly where the exposures are long, the central office apparatus unbalances may be more important than those of the party-line station apparatus.

The method which has been found most generally applicable for reducing the susceptiveness of exchange cable circuits is the grounding of the cable sheaths. This reduces through shielding the magnitudes of the longitudinal voltages and currents. Special station sets having lower susceptiveness have been used in specific cases where their use appeared to be the best method.

Power Level and Sensitivity. The magnitudes of the induced currents in the telephone system having been determined by the influence factors, the coupling, and the unbalances of the telephone circuits, the degree to which they impair telephone service depends upon their intensity as compared to the intensity of the telephone currents.

Consideration has been given by the subcommittee to the possibility of increases in power levels (a) on local exchange circuits and (b) on toll circuits. Little promise has been found in the proposal to raise voice power levels in the local exchange plant as a means of reducing the effects of noise. As previously pointed out, present telephone transmitters materially amplify the power received from the voice so that the electrical power on the telephone line is some hundreds of times greater than the acoustic power applied. In development work on telephone transmitters, telephone engineers are proceeding on the basis that more is to be gained by improving the frequency response of the transmitter than can be gained by mere increase of power. This line of development has, of course, the effect of raising power levels at frequencies where they have been relatively low.

Two proposals for application to the toll telephone plant were studied. One would involve changing the repeaters now in use at terminals and at intermediate points to a more powerful type and equipping all toll circuits with terminal repeaters of this same type. This would permit raising the power levels without altering the relative levels of the various telephone circuits and thus would not change the crosstalk. Another would involve such changes only on certain long toll circuits, leaving the remainder of the circuits at their present levels. As the result of a trial installation, it was found that to realize any appreciable change in level on these circuits, very extensive changes would be required to avoid crosstalk from the higher level circuits to the remaining ones which were not changed.

The levels employed in carrier telephone circuits, while somewhat lower than those used on voice-frequency open-wire telephone circuits at the receiving end, are higher at the sending ends than the corresponding voice-frequency levels. Since the power system harmonics in the carrier-frequency range normally are small as compared to those in the voice-frequency range, carrier-frequency open-wire systems experience considerably less noise from power systems.

Effects of Noise.—The actual voice power level on telephone circuits varies over a wide range, depending upon the particular user, his distance from the telephone central office, and by the transmission loss in the connection between the two subscribers. Impairment caused by a given amount of line noise on the circuit may also vary over a considerable range, depending upon the voice power level and the noise in the room where the telephone is being used. The method in use by the Bell System for an engineering basis in considering the effects of noise on telephone conversation is to substitute for the noise increases in the transmission loss of the circuit. Thus, the circuit with its actual loss and noise is represented by a circuit of lower noise and increased transmission loss. These added losses are known as Noise Transmission Impairments and are abbreviated N. T. I. The N. T. I.'s were determined from articulation tests and judgment tests made on noisy and quiet circuits, and were set up on the basis of typical talker volumes, transmission equivalents, and amounts of room noise at the station terminals. Additional transmission loss was added to the quiet circuits so that noisy and quiet circuits gave equal articulation or were judged by the observers to be equivalent in their transmission performance. Thus, the N. T. I.'s are used to indicate an additional transmission loss or impairment which is occasioned by the presence of the noise.

The articulation and other tests on which these N. T. I. ratings were based are now being supplemented by tests conducted under the direction of the subcommittee. Measurements are being made of the effects of various magnitudes and sorts of line noise in the presence of typical amounts of room noise, as determined from a room noise survey made by the subcommittee, and for representative toll connections and talker volumes. The line noises being employed are those found typical from an extensive survey made by the subcommittee on open-wire toll circuits throughout the country. These tests will afford a basis for comparing various methods of measuring line noise, including ear comparison methods now in general use and new visual meter methods now under development. Thus, this work should lead to a mutually acceptable method for measuring noise and a basis upon which agreement may be reached as to the impairment in telephone transmission caused by noise.

Published Results.—As various phases of the technical work being done are completed, they are published in the form of Engineering Reports which are released by the Engineering Subcommittee of National Electric Light Association and Bell Telephone System. Eight reports, of which five refer to matters concerning noise-frequency induction, have already been issued. Other reports dealing with this subject have been recently approved by the Engineering Subcommittee and will soon be issued. Certain other technical results which have come from the Subcommittee's work have been presented by various individuals connected with the work in papers before the A. I. E. E. Still other results have been published in brief articles in the N. E. L. A. *Bulletin*.

One of the problems upon which the technical work of the committee has been completed and published is that of inductive coordination of primary distribution systems and exchange telephone circuits in cable. The results of this work are given in detail in a report [7] entitled "Minneapolis Joint Use Investigation." This report includes information on influence factors applying to various types of power distribution systems, including three-phase, three-wire and three-phase, four-wire systems with various arrangements of neutral grounding, data on coupling between various typical arrangements of these systems and telephone cable circuits, and information on susceptiveness characteristics of telephone systems, including unbalances of lines and apparatus. To facilitate the use of this information in the day-by-day coordination problems handled by the operating companies, a summarizing report [9] entitled "Short-Cut Methods for Calculating Noise in Local Telephone Subscribers' Circuits in Cable Due to Exposures to Power Distribution Circuits" has been prepared. This report presents empirical formulas for estimating noise-frequency induction and includes a brief discussion of the technical factors involved and the approximations underlying the formulas. Means are described for reducing influence by the control of triple-harmonic exciting currents and load unbalances of power distribution circuits, and for reducing susceptiveness by grounding telephone cable sheaths and by controlling the unbalances of the telephone station equipment. The information should be useful to engineers of the operating companies in the cooperative planning of routes to avoid induction troubles.

While a large part of the experimental work connected with the problem of joint use of local open-wire subscribers' circuits and power distribution circuits has been completed, the detailed technical reports have not yet been completed for publication. However, a summarizing report [10] which it is believed will largely fill the needs of the engineers of operating power and telephone companies has been completed. This is entitled "Short-Cut Methods for Calculating Noise in Open-Wire Subscribers' Circuits Due to Joint Use Exposures to Power Distribution Circuits."

Three reports have been issued dealing with the problem of coordination of open-wire toll circuits and overhead transmission and distribution lines. The first [11] discusses the "Termination of Isolated Exposure Sections to Obtain Normal Metallic-Circuit Currents," which affords a means of taking into account the shielding effects present when the line is in normal operating condition. The second report [12] describes "A Method of Measuring the Balance of Open-Wire Telephone Circuits with Respect to Longitudinal-Circuit Induction," which should be useful to the field in the making of special tests and in supplying statistical data of value for estimating noise effects on open-wire line circuits. The third report,[13] dealing with "Methods of Measuring Noise on Open-Wire Toll Circuits," is a detailed presentation of the various types of tests for studying noise problems on toll lines, and includes a discussion of the method of analyzing the test data.

Another report [5] deals with "The Effects on Inductive Coordination of Generators Feeding Directly on the Line and Operating with

Grounded Neutrals." This report includes a detailed discussion of the factors involved and describes methods which have been developed for control of the triple-harmonic residual currents and voltages which occur with this method of operation.

The results of the work done by the subcommittee on a survey of room noise in telephone locations were described in a recent paper.[14] While this was an incidental phase of the general study on effects of noise on telephone transmission, it was felt to be of timely value, particularly in respect to the methods of measurement employed. Using the results of the data obtained in surveys of wave shape on operating power systems and analyses of noise current on telephone circuits, a paper [15] was prepared on the frequency response characteristics of telephone transmitters and receivers. This paper indicated that there appeared to be no advantage, in reducing effects of noise, in shifting the resonance points of telephone transmitters and receivers from their present region, as the frequency distribution of the noise currents was such as to give a minimum in this resonance region.

At the time that the joint work was started the need arose for considerable special apparatus to make the measurements which were required. Some of the important pieces of apparatus for the work in the voice-frequency range were sensitive single-frequency voltmeters and ammeters. These needs were taken care of by the development of sensitive analyzers whereby single-frequency voltages or currents could be selected from complex wave shapes on either power or telephone circuits. One form of this apparatus has been described in a paper before the Institute [16] and another in a serial report [17] of the National Electric Light Association.

In connection with the survey of room noise, a room noise meter was developed. This was described in the paper [14] previously referred to which presented the results of this survey.

FURTHER WORK OF THE SUBCOMMITTEE

When the subcommittee started its work there was before it an accumulation of technical problems which had arisen as the arts developed without such close cooperation as now exists. The statements given above regarding various phases of the subcommittee's work on noise-frequency induction indicate the substantial progress which has been made in the solution of these accumulated problems. They convey also a general picture of the work which the subcommittee has immediately before it.

It must not be thought, however, that when these accumulated problems have been solved the work of the subcommittee will be completed and its efforts discontinued. This cooperative work must always bear a relation to the total development efforts of both the power and communication fields. As has already been pointed out, this work is concerned with two electrical arts which have been particularly noteworthy for their success in constantly developing their technical methods and expanding their services. These developments will surely continue and constant consideration of the physical problems of coordination is needed to insure that such developments act to steadily improve rather than to make more difficult the coordination of power and communication circuits.

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