The Inductive Coordination of Common-Neutral Power Distribution Systems and Telephone Circuits *

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Early installations of three-phase, four-wire power distribution systems of the multi-grounded or common-neutral type in some cases created noise problems involving neighboring telephone circuits. Operating experience, studies of specific situations and comprehensive cooperative research over a period of years have developed means of largely avoiding difficulties of this character. The relative importance of various features of the power and telephone systems which have been found to affect the noise induction problems involved is discussed and the general cooperative procedures, most helpful in conversions to or extensions of these types of power distribution systems, are outlined.

Introduction

PRIOR to about 1915, delta-connected 2300-volt, three-phase, primary circuits were used extensively for the distribution of electric current. While some distribution networks throughout the country still operate in this manner, the marked increase in load densities, starting about 1915, often made the retention of the 2300-volt delta system impracticable. In a few instances the development of the particular network was at a point where it was feasible to change from the 2300-volt delta to a 4600-volt delta arrangement but in other cases the existing equipment represented too great an investment for a complete change of this character.

From studies of various methods of caring for the augmented load densities it was found that the existing equipment could largely be saved and the capacity of the distributing networks substantially increased by converting them to a 2300/4000-volt, star-connected, four-wire primary system. By about 1925 this system had extended to most of the larger cities and most power companies had found it economical for use in at least some parts of their territories.

In using the 2300-volt equipment on the 4000-volt, four-wire system it was necessary to stabilize the neutral conductor in some way. Most of the four-wire systems had the neutral conductor grounded at the

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substation only although sometimes low-voltage lightning arresters were placed on it at various points in the distribution network to aid in its stabilization in case of a break in it. In some instances, at the time of the installation of the four-wire system, the primary neutral was connected at various points in the network to driven ground rods thus resulting in a multi-grounded neutral system. In at least one instance the neutral conductor was not solidly grounded even at the substation, it being connected to ground through lightning arresters.

The experiences of the power companies with the multi-grounded neutral were generally favorable. It was found to be more reliable and to embrace some simplifications over other distribution methods. While the early multi-grounded neutral arrangements were obtained by making connections to ground along the primary neutral conductor and interconnecting it, at service transformers, to well-grounded secondary neutrals a further simplification in the arrangement was readily apparent.

It will be noted in Fig. 1 that this interconnection of the primary and secondary neutrals resulted in two grounded neutrals on the pole line in all sections where the secondary neutral existed. In extending the multi-grounded neutral arrangement or in reconstructing existing portions of the network, these two neutrals were combined into a single well-grounded conductor continuous in all portions of a feeder area and often continuous in all parts of a substation area or of several contiguous substation areas. This arrangement, called the "common-neutral," which was first extensively applied in Minneapolis * by Mr. S. B. Hood, resulted in certain savings in equipment and relief of congested pole heads and in a neutral network most effectively grounded since all secondary neutral grounds were thus made available, in addition to any driven grounds along the pole line.

The operation of this system in Minneapolis showed many advantages in the protection of secondary networks from the effects of voltage rises under abnormal conditions. In addition a paper presented in 1925 by Mr. Hood [1] pointed out that over a period of three years the rate of transformer failure was reduced to 8/10 of 1 per cent per annum. This excellent performance in transformers arose undoubtedly from the fact that with the "common-neutral" or interconnected neutral arrangements the lightning arresters are connected directly around the transformers. Later studies showed that the connection of the lightning arresters directly between the primary conductors and secondary neutral provides a degree of protection which cannot readily be obtained in any other way.[2, 3, 4, 5, 6, 7]

* Prior to applying this system in Minneapolis, Mr. Hood introduced it at Toronto, Canada.

In urban areas, the multi-grounded or common-neutral method of distribution introduced, in some instances, noise induction in nearby telephone circuits. In view of this fact an extensive cooperative investigation was undertaken by Project Committee No. 6 of the

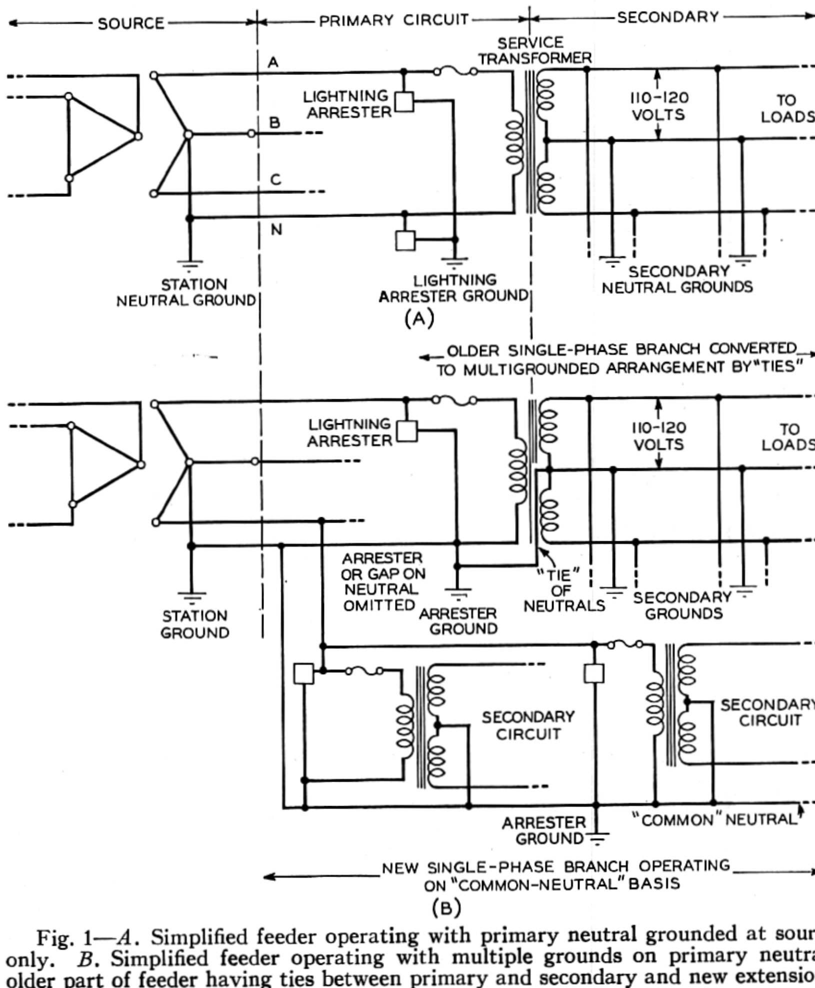


Fig. 1—*A*. Simplified feeder operating with primary neutral grounded at source only. *B*. Simplified feeder operating with multiple grounds on primary neutral-older part of feeder having ties between primary and secondary and new extensions being of common-neutral arrangement.

Joint Subcommittee on Development and Research of the National Electric Light Association and Bell Telephone System to determine the factors involved in the coordination of local power distribution systems and telephone systems. A study was carried out in Minneapolis during the years 1924 to 1926 having as its primary objective the determination of the factors involved where the telephone distribution was largely in aerial cable. The investigation was continued in Elmira, New York in 1926 to 1929 to embrace the factors introduced when the exchange telephone plant was of open-wire construction.[8] Supplementing these detailed technical studies, an investigation of certain economic features of various arrangements of power and telephone distributing methods and of their practical application under varying conditions was carried out in California in 1928 and 1929. As a result of these investigations the various factors involved in the coordination of multi-grounded or common-neutral power systems and telephone distribution systems were determined and certain practices developed for the coordination of these systems under various conditions in urban areas.[9]

The purpose of this paper is that of briefly outlining a few of the more important features of power and telephone circuits affecting noise coordination. Following such a review there is presented a list of measures which extended experience has shown will, where given proper consideration by both parties, enable multi-grounded or common-neutral power circuits and telephone circuits to live harmoniously. No attempt is made, however, to reiterate the extensive technical information obtained from the investigations outlined above as these are adequately covered in the references cited.

Recent Trends

During the past few years there has been extensive conversion from other types of urban power distribution to the multi-grounded or common-neutral system of primary distribution. Where there exists a three-phase, three-wire delta circuit the system is converted by making the secondary neutral network continuous, reinforcing it where necessary, and making the required changes in transformer connections. Where there is a three-phase, four-wire uni-grounded primary system the conversion is, as previously mentioned, made by interconnecting the primary and the secondary neutral at each load transformer generally removing the primary neutral only at the time of major rebuilding. In either case extensions are usually made using a single neutral in the secondary position.

In the urban areas most of the multi-grounded or common-neutral systems are of the 2300/4000-volt class, although there are a few instances where 4600-volt systems have been converted. At the present time there is being constructed a 6900/12,000-volt common-neutral distribution system at Wichita, Kansas.

The distinct trend in power distribution practice has been, in no small measure, influenced by the improved overall protection features readily obtained by the multi-grounded neutral arrangement as well as by certain equipment savings. The recent emphasis placed on the electrification of rural areas and the distinct need for maximum service continuity on rural power circuits has increased the interest in the use of the multi-grounded or common-neutral method of distribution in rural areas. The rural systems are generally of the 7600/13,200-volt class, although 4600/8000-volt circuits have been used to some extent.

The factors affecting inductive coordination involved in the use of the common-neutral method of distribution in rural areas, are somewhat different from those encountered in urban areas. This is largely due to the lower load densities, the greater lengths of circuits, higher operating voltages and to the somewhat different types of equipment employed in rural telephone distribution. These factors were investigated by the Joint Subcommittee on Development and Research during the summers of 1935 and 1936 and the more important considerations determined.[10]

Factors Influencing Inductive Coordination

In any problem of inductive coordination it is convenient to subdivide the factors influencing coordination into those relating to the inductive influence of the power circuit, the inductive susceptiveness of the telephone circuit and the inductive coupling between the two types of circuits. As far as urban distribution circuits are concerned the load current unbalance of the power circuit is usually the controlling influence factor. For rural distribution circuits the unbalanced charging currents are generally more important than the unbalanced load currents. Likewise, in an exchange telephone circuit the admittance and impedance unbalances of the two sides of the circuit are usually the controlling factors in its inductive susceptiveness. As far as coupling between the power and telephone circuits is concerned this is largely controlled by their relative positions and the lengths of the exposure. For urban areas their relative positions are largely fixed by the normal arrangement of conductors and cables on jointly-used poles. In rural areas power and telephone circuits are generally at roadway separation although some joint use exists. In urban areas considerable control can often be exercised over the coupling by planning the routes of the main feeds of the two services so as to avoid long sections of close exposure. In rural areas where there are no paralleling routes close together it is generally necessary for both services to use the same roads and therefore the opportunity to control the coupling by the cooperative planning of routes is much reduced.

Certain quantitative indications of the extent to which this measure of coordination is applicable in the two types of areas are shown in the illustrative examples in the Appendix.

Power Circuits

Power systems operate, for the most part, at frequencies of 60 cycles and below. Telephone circuits, on the other hand depend mainly upon frequencies above about 200 cycles for the transmission of speech. Ordinarily, therefore, the effects of induction from the fundamental frequency currents and voltages in neighboring power lines are negligible as far as telephone circuit noise is concerned. It is quite generally recognized, however, that it is impracticable commercially to build rotating machinery and transformers which are entirely free from harmonics. There are, therefore, harmonics present on all operating power systems and it is the harmonic-frequency components induced into telephone circuits from these power system harmonics that are of major importance from the noise standpoint.[11]

In any distribution circuit the harmonic currents present will fall within the following classes:—load currents, transformer-exciting currents and line-charging currents. With a uni-grounded neutral the load currents and the transformer-exciting currents are practically entirely confined to the wires of the circuit. Where the neutral is multi-grounded, the vector sum of the currents in the phase conductors (residual current) will divide between the neutral conductor and the paralleling earth path as determined by the relative impedances of these two paths. While there is some variation in the division of the return current between the neutral and ground paths, for most practical purposes this division may be assumed to be about half in each path at all the frequencies of interest.

As pointed out above, in the case of a line operating with uni-grounded neutral, the earth-return components of the load and transformer-exciting currents are ordinarily negligibly small. However, this is not true of the line-charging current which is chiefly a function of the magnitude and frequency of the impressed voltage, the circuit length, and, at non-triple harmonic frequencies, of the balance of the admittances to ground of the various phase conductors. While multi-grounding the neutral ordinarily increases the earth-return components of the load and transformer-exciting currents, it has been found, due to the parallel path provided by the neutral wire, on an average to decrease slightly the amount of charging current in the earth.

In an urban distribution system where the load density is relatively high, the load currents and transformer-exciting currents are relatively large and the line-charging currents are usually negligible. In such a system multi-grounding the neutral results in an increase in the current returning through the earth and a consequent increase in the inductive influence of the power distribution system.

In rural areas, however, where the load density is low and the load currents and transformer-exciting currents are relatively small, the line-charging currents become significant. In general, under such conditions the multi-grounding of the neutral does not increase the magnitude of the ground-return current at frequencies of interest from the noise induction viewpoint. Under certain conditions the magnitude of this ground-return current may actually be substantially decreased by the multi-grounding of the neutral. This effect is more marked for the higher voltage circuits.

The harmonics present in a distribution circuit may be divided into (1) triple harmonics, that is, the third harmonic and odd multiples of it, and (2) non-triple harmonics, that is, the odd harmonics, starting with and including the fifth, which are not multiples of three. The triple harmonics in a three-phase system are in phase in the three line conductors so that their residual value (vector sum) is the arithmetic sum of their magnitudes in the three-phase wires. The non-triple harmonics are spaced, in time phase, the same as the 60-cycle fundamental and the magnitude of the residual current (vector sum) for these harmonics is usually much less than their arithmetic sum. If these harmonics were perfectly balanced the residual current for these frequencies would be zero. In exposures involving three-phase sections of line the balance of the non-triple harmonics between phases is influenced by the degree of balance of the loads and single-phase branches and therefore has an important effect in reducing the overall influence of the power system. In exposures involving single-phase extensions, or extensions consisting only of two-phase wires and a neutral wire this advantage of the balancing of the non-triple harmonics is, of course, not obtainable.

The extent to which induction from the non-triple harmonic voltages and currents in power distribution circuits can be controlled by power circuit transpositions is ordinarily very limited. Usually, due to the large number of exposure discontinuities arising from changes in the power or telephone circuits, the power circuit transpositions are quite ineffective. This is particularly true in cases where the induction from the ground-return current is controlling. In specific cases where considerable wave shape distortion exists and the induction from the balanced voltages and currents may therefore be relatively important, transpositions in power distribution circuits may be found helpful.

Table *A* shows the average harmonics present on three-phase, four-wire industrial and residential feeders under light and heavy load conditions. The reduced magnitudes of the non-triple frequencies in the residual current (neutral and ground-return) are evident. The importance of this as regards noise induction is further indicated in the illustrative examples of the Appendix.

TABLE *A* *

AVERAGE CURRENT AND VOLTAGE WAVE SHAPES OF 2300/4000-VOLT, 3-PHASE, 4-WIRE DISTRIBUTION CIRCUITS

Frequency	Order of Harmonic	Phase-to-Neutral Voltage at Bus.	Current in Industrial Feeder (In Amperes)				Current in Residential Feeder (In Amperes)			
			Light Load		Heavy Load		Light Load		Heavy Load	
			Phase	Residual	Phase	Residual	Phase	Residual	Phase	Residual
60	—	2380	65.		130		53		99	
180	*3*	*16*	*1.1*	*2.6*	*1.1*	*2.9*	*1.8*	*5.2*	*1.9*	*6.0*
300	5	21	1.0	.15	1.3	.16	.43	.21	.75	.29
420	7	6.4	.3	.03	.3	.05	.13	.06	.17	.08
540	*9*	*1.7*	*.04*	*.08*	*.04*	*.13*	*.04*	*.09*	*.04*	*.09*
660	11	1.9	.07	.01	.09	.01	.04	.01	.06	.02
780	13	1.8	.08	.01	.05	.01	.02	.01	.04	.01
900	*15*	*.42*	*.01*	*.01*	*.01*	*.03*	*.01*	*.01*	*.01*	*.01*
1020	17	.90	.03	.01	.07	.01	.02	.01	.03	.01
1140	19	.87	.02	—	.04	—	.01	.01	.02	.01
1260	*21*	*.16*	—	—	—	*.01*	—	—	*.01*	*.01*
1380	23	1.4	.05	—	.06	—	.01	—	.03	.01
1500	25	2.1	.06	.01	.09	.01	.01	.01	.03	.01
1620	*27*	*.79*	—	*.01*	*.01*	*.02*	—	—	*.01*	*.01*
1740	29	1.5	.02	—	.03	.01	.01	—	.02	.01
1860	31	1.4	.01	—	.02	—	—	—	.01	—
TIF †		9.7	11.2	—	8.9	—	6.6	—	5.8	—
Kv. T or I.T.		23.2	733	193	1160	330	346	238	571	283

Note: Triple harmonics are italicized.
* Tables 31 & 32—pp. 235 & 236 of Vol. II of Eng'g Reports of Joint Subcommittee.
† New weighting—see Engineering Report No. 33 of Joint Subcommittee.

The triple-harmonic currents present on a feeder supplied from a delta-wye substation transformer bank are generally due to the exciting currents of the single-phase load transformers. Under this condition no excessive triples are impressed on the feeder at its source as is sometimes the case where the source is a wye-connected, grounded-neutral generator directly connected to the feeder. The exciting currents flow from the individual single-phase transformers toward the delta-wye transformer in the substation. The presence on the feeder of a large three-phase wye-delta load transformer with its neutral connected to the system neutral, provides a parallel path for supplying part of these triple-harmonic exciting currents as well as part of the unbalanced non-triple and fundamental currents and under certain conditions may substantially decrease the overall inductive influence of a feeder by reducing the ground-return current flowing through an exposure. The effect of such a connection in reducing the noise is dependent upon the location of the bank with respect to the exposure and its relative impedance to the various harmonics as compared to that of the path back to the substation. From the power operating standpoint such a bank tends to supply part of the unbalanced load and also, in case of the interruption of one phase between it and the substation, tends to supply the power to that portion of the phase still connected to it. Under certain conditions, the action of such a bank may prove detrimental to the operation of the power feeder due to its action in attempting to balance the voltages at the point of its connection to the feeder. Under other conditions the neutral of an existing bank can readily be connected to the feeder neutral with distinctly beneficial effects on the inductive influence and with little or no adverse effects on the power-system operation. The tendency of such banks toward noise reduction and towards unbalanced load supply is shown in two of the illustrative examples in the Appendix.

Telephone Circuits

The voltages induced into a telephone circuit may be divided into (1) metallic-circuit induction, that is, a voltage induced between the two sides of the circuit with a resultant current flowing around the circuit, and (2) longitudinal-circuit induction, that is, a voltage induced along the conductors such that the resultant current flows in a circuit having the telephone conductors as one side and the earth as the other. This latter voltage may also result in noise, due to its action upon telephone circuit unbalances, setting up currents in the voice channel (metallic-circuit). For either type of voltage, the induction may be "electric," that is, from the voltage on the power circuit, or "magnetic" from the current in the power circuit.

The local telephone circuit may be divided into three parts: (*a*) the central office equipment, (*b*) the line conductors and (*c*) the subscriber equipment. Inter-office circuits include only the first two items.

(*a*) *Central Offices Equipment*

The central office equipment associated with a subscriber circuit consists essentially of two elements: (1) line signaling equipment connected to the circuit for indicating to the operator, or to the dial equipment, the desire of a subscriber to start a call and (2) a linking or switching circuit or circuits for interconnecting two subscriber circuits either directly or through intervening trunk circuits and providing supervision during the call.

The line signaling equipment with its associated relay is either bridged across the line or arranged so that, when two subscriber circuits are interconnected, any ground connections on the line relays are automatically opened. The line signaling equipment is not, therefore, ordinarily a factor in noise considerations. Occasionally, however, the effect on noise of the ground connection on the line signaling equipment requires specific treatment when the longitudinal-circuit induction is sufficiently high. The noise in such instances occurs either during the pre-answering period before the line relay is "cut-off" or, in certain types of switchboards, on conversations between two persons on the same line (party-line) where the use of a switching circuit in the office is unnecessary.

The linking or switching equipment in the central office may consist of a pair of wires with bridged supervisory relays as in the case of a magneto office or may be a complicated arrangement of relays, repeating coils, condensers, etc., as in the case of common-battery offices of the manual or dial type. The necessary ground connections of the latter type of apparatus introduce the possibility of the unbalances in the equipment contributing to the overall noise when the longitudinal-circuit induction on the outside conductors is impressed on the switching circuits. Ordinarily in urban areas, due either to the frequency make-up of the longitudinal-circuit induction or to the relationships of the various impedances-to-ground, the amount of noise contributed by the central office equipment is relatively low. This is readily evident from Table B which shows, at 500 and 1000 cycles, the relative proportions of overall noise due to the action of induced voltages on station, cable and central office unbalances:

TABLE *B* *

RELATIVE IMPORTANCE OF CIRCUIT UNBALANCES

Type of Service	500 Cycles			1000 Cycles		
	Contribution from:			Contribution from:		
	Station	Cable	Office	Station	Cable	Office
Individual (bridged ringers)	Negligible	3	3	Negligible	20	20
Party-line (grounded 8-A ringers)	100	3	3	100	20	20

* See p. 72 of Vol. I of Eng'g Reports.

Cases arise, however, quite frequently where the relative circuit impedances or the frequency make-up of the induction or both are such that the noise contribution from the unbalances in the central office equipment becomes important. Such cases usually involve long subscriber or inter-office trunk circuits and particularly where sections of open-wire construction are present. Values of the unbalances in certain types of central office equipment are given on page 91 of Volume I of the Engineering Reports of the Joint Subcommittee on Development and Research.

(*b*) *Line Conductors*

Where the telephone line conductors are in open-wire, the induced voltage between conductors (metallic-circuit) as well as along these conductors (longitudinal-circuit) must be considered. The direct metallic-circuit induction can be greatly reduced by systematic transpositions in the telephone circuit. Due to the physical limitations in a practical layout of telephone transpositions, the reduction in metallic-circuit induction is, on the average, from 60 to 80 per cent on non-pole pairs and about 90 per cent on pole-pairs. Transpositions also tend to lessen the capacitance and inductance unbalances of the two sides to ground and to other circuits, thereby reducing the effect of the longitudinal-circuit induction on such unbalances. The improved balance of the mutual impedances between the various telephone conductors is, of course, distinctly beneficial in reducing crosstalk and transpositions are generally used for limiting the crosstalk where open-wire telephone circuits extend for substantial distances.

The construction of telephone cables is such that there is inherently very close spacing between the conductors and they are frequently transposed due to the continuous twisting of the pairs in manufacture. Due to this close spacing and frequent transposing there is practically no voltage induced between the wires of a cable pair or quad (group of four conductors). The unbalance to ground of the conductors of the present type of cable is so small that it is not ordinarily a contributing factor to noise induction. It may be noted, however, from Table *B* that in cases where the central office unbalances are of importance, the effect of shunt or series unbalances in the cables also needs consideration.

The lead sheath of a telephone cable provides practically perfect shielding against induction from power system voltages when it is grounded at one or more points. The sheath likewise provides substantial magnetic shielding when it is grounded more or less continuously as in underground construction or is grounded at both ends of the aerial section or near both ends of an exposure. The degree of magnetic shielding effected varies, depending on the size of the cable

TABLE *C*

MAGNETIC SHIELDING FOR VARIOUS FREQUENCIES
SIZES AND LENGTHS OF TELEPHONE CABLES AND VARIOUS GROUNDING RESISTANCES

(Calculated Values of e_r/e_i)
(e_r = Voltage remaining after shielding)
(e_i = Voltage present with sheath grounded at one point only)

Frequency	Full-Sized Cable (2.61″ Outside Dia.)						101 Pair 24 Ga. (0.85″ Outside Dia.)						51 Pair 24 Ga. (0.64″ Outside Dia.)					
	1 Mile*			3 Miles*			½ Mile*			1 Mile*			½ Mile*			1 Mile*		
	0ω †	5ω †	10ω †	0ω	5ω	10ω	0ω	5ω	10ω	0ω	5ω	10ω	0ω	5ω	10ω	0ω	5ω	10ω
180 Cycles.....	14%	82%	94%	14%	50%	71%	60%	95%	99%	60%	89%	95%	71%	96%	99%	71%	92%	96%
300 "	8.5	65	85	8.5	33	52	42	89	96	42	77	89	57	91	96.5	57	82	91
420 "	6	52	76	6	24	40	31.5	81	93	31.5	65	81	44.5	84	93.5	44.5	71	84
540 "	5	43.5	71	5	19	32	25	73	88	25	55.5	73	37	77	90	37	63	77
660 "	4	37	64	4	16	27	21	66	84	21	47.5	66	31	71	86	31	55	71
1000 "	3	25.5	44.5	3	11	18	15	51	72	15	35	51	22	56	74.5	22	41	56

* Refers to distances along cable sheath between the two grounding points.
† Refers to total grounding impedance (approx. d.c. resistance) of the two ground connections—expressed in ohms.

and the resistance of the ground connections, reaching optimum values of over 90 oer cent. Table *C* gives the magnitude of this shielding for various selected sizes and lengths of cable. Table *C* brings out distinctly the variation in the magnetic shielding due to the factors mentioned above. The effect of cable sheath shielding in several typical cases is further indicated in the Appendix.

TABLE *D*

RELATIVE SUSCEPTIVENESS OF SEVERAL TYPES OF STATION SETS

General Description of Station Set	Noise in Receiver Branch for 100 Noise Units to Ground—Average Power Wave Shape (*One Station on Line-Effect of Set Only*)
Class 1—Types of sets in most common use today	
a. Sidetone type of party-line set using 8A ringers or equivalents (one end of ringer grounded). (Common-battery talking and signaling)	350 Noise Units Approximately
b. Same type—local-battery talking	120 Noise Units Approximately
c. Magneto party-line set (52A Ringer or equivalent)	120 Noise Units Approximately
d. Individual-line set—any type	Negligible
Class 2—Types of sets frequently encountered	
a. Sidetone type of 4-party full-selective or 8-party semi-selective set (using relay or cathode tube to connect ringer to circuit during ringing period)	Negligible
b. Four-party selective or 8-party semi-selective sets employing high impedance ringers or relays connected to ground	About 30
c. Eight-party selective (harmonic ringing) sets employing ringers connected to ground and tuned to 4 different ringing frequencies	Limited data indicate that, depending on frequency for which ringer is tuned, noise will range from about 100 to about 400 units
d. Ground-return rural circuits (usually of magneto type and having code ringing)	3500 or more noise units
Class 3—Special types of sets	
a. Sidetone type of party-line set using split-condenser and higher impedance ringer (one end of ringer grounded)	About 20 noise units
b. Type of party-line set using split condenser arrangement with 8A ringer or equivalents (one end of ringer grounded).	About 90 noise units

(*c*) *Station Apparatus*

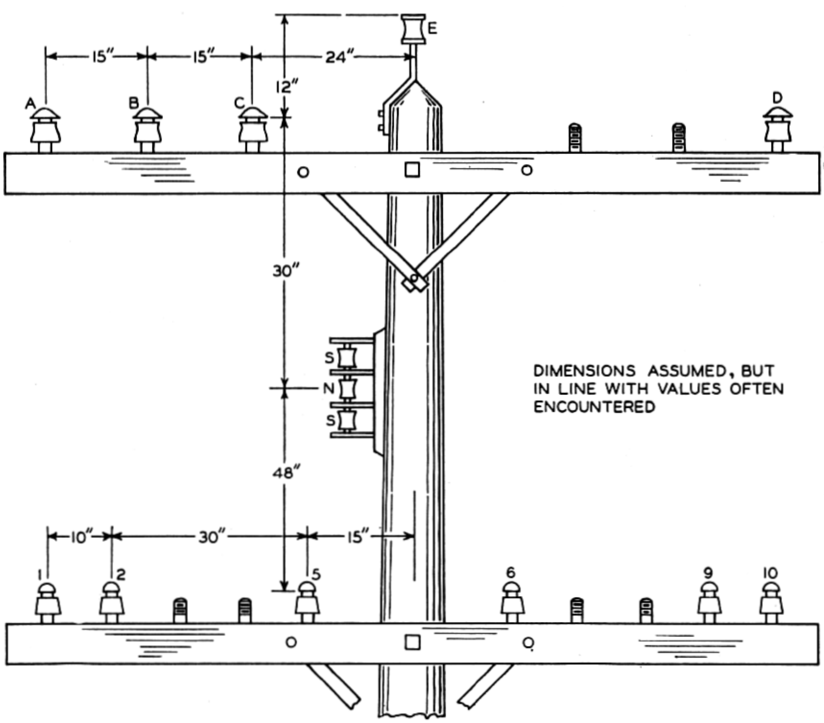
Individual-line stations employ a "bridged" ringer connection, i.e., the ringer is, in effect, connected between the two line conductors.

However, for selective signaling purposes party-line stations frequently have the ringer connected, in effect, between one of the line conductors and ground. The unbalance of the party-line station equipment is therefore affected by the impedance of the ringer and its point of connection in the station equipment. The relative susceptiveness of several types of station sets to noise-frequency induction is shown in Table *D*.

Table *D* shows that, with advance planning in areas where noise induction is or may likely become a matter of importance, much can be accomplished by the use of station sets of decreased inductive susceptiveness. Where such types of apparatus are substituted in existing plant, except in gradual replacements or in connection with general rearrangement programs, the expense is, naturally, increased.

Inductive Coupling

As stated above, the inductive coupling between exchange telephone plant and power distribution circuits in urban areas is largely controlled by such factors as the street layouts and the joint use of poles.



(See following page)

Direct Metallic Circuit Induction in Untransposed Telephone Circuits

Magnetic Induction, 1000 Cycles

Volts Metallic per Ampere of Power Circuit Current per 1000 Feet of Exposure

Type Power Circuit	Induction Component	Power Conductors*	Pair 1–2	Pair 5–6	Pair 9–10	Avg.
Single Phase	Residual	A & N	.021	.043	.0044	.022
" "	"	C & N	.0044	.018	.0053	.0092
" "	"	E & N	.0002	.023	.0013	.0082
Two Phase Wires & Neut.	Residual	A, C, & N	.013	.031	.005	.016
	"	A, D, & N	.008	.018	.009	.012
Three Phase	Residual	A, B, C, & N	.012	.033	.005	.017
	"	A, C, D, & N	.007	.01	.004	.007
Two Phase Wires & Neut.	Balanced	A, C, & N	.017	.026	.0009	.015
	"	A, D, & N	.026	.13	.026	.061
Three Phase	Balanced	A, B, C, & N	.015	.023	.012	.017
	"	A, C, D, & N	.023	.123	.026	.057

* In each case, conductor "N" is a multi-grounded neutral, the other wires being phase conductors. Assumed 50% of the residual current in the neutral and 50% in the ground.

Electric Induction

Volts per Kilovolt *Vm/Kv*

Type Power Circuit	Induction Component	Power Conductors†	Pair 1–2	Pair 5–6	Pair 9–10	Avg.
Single Phase	Residual	A & N	7	19	3	9.7
" "	"	C & N	2	7.3	2.3	3.9
" "	"	E & N	.4	9	.2	3.2
Two Phase Wires & Neut.	Residual	A, C, & N	5	13	2.6	6.9
	"	A, D, & N	2	7	2	3.7
Three Phase	Residual	A, B, C, & N	2.8	10	2	5.0
	"	A, C, D, & N	1.4	2.2	.7	1.4
Two Phase Wires & Neut.	Balanced	A, C, & N	3	7	.4	3.5
	"	A, D, & N	6	30	5	13.7
Three Phase	Balanced	A, B, C, & N	2.7	5.8	.4	3.0
	"	A, C, D, & N	5.6	27	5.4	12.7

† Wires S & S assumed continuous through exposure and grounded.

Fig. 2—Effect of relative positions on joint-use pole of power and telephone conductors on coefficients of induction for voltages and currents.

However, by cooperative planning of routes it is frequently practicable to secure lower coupling by avoiding long exposures between the main feeds of the two plants. As shown by the illustrative examples this procedure is, where applicable, very beneficial.

In rural areas where both distribution services must ordinarily be carried along the highways the opportunity for controlling the coupling between the two classes of circuits by cooperative planning of routes is much reduced.

Some benefit may be gained, however, in the case of open-wire construction particularly at joint-use separations, by arrangements of the conductors on the pole so as to avoid excessive spacings. As shown on Fig. 2 certain arrangements tend to minimize the amount of noise induction arising from the power circuit voltages and currents. This beneficial effect is, however, much less noticeable at roadway separations.

Summary and Conclusions

Since about 1915 there has been a continued increase in the use of the multi-grounded or common-neutral arrangement of power distribution in this country. At the present time, approximately half of the distribution is by 4000-volt multi-grounded or common-neutral circuits. A large part of the higher-voltage rural distribution is also operating with this arrangement.

In general it may be said that for the lower-voltage 2300/4000-volt distribution circuits, the use of the multi-grounded or common-neutral arrangement may be expected to increase the inductive influence of the power circuits. Unless attention is given to cooperative planning to secure features beneficial from the inductive coordination standpoint, noise problems may result either in restricted or extensive areas. With proper attention to the coordination features [9] such noise situations as develop are largely in the nature of isolated cases and can usually be cared for by relatively minor changes or adjustments in either or both plants.

For the higher voltage (11–13 kv.) rural distribution circuits, there seems to be little difference, from the noise induction standpoint, between the uni-grounded four-wire system and the multi-grounded or common-neutral arrangement.[10] Under many conditions the placing of multiple grounds on the neutral will result in noise reductions due to the effect, previously mentioned, of the multi-grounded neutral on the line charging currents. It is interesting to note that experience to date with the multi-grounded or common-neutral in rural areas has shown that many of the measures of coordination applicable in urban areas will prove similarly helpful in rural communities.

The measures of coordination which investigations and operating experience have shown to be practicable and effective include:

1. Cooperative planning by both parties to avoid not only severe exposure conditions but also types of equipment likely to aggravate the possible noise induction situation.

2. A reasonable degree of balance of the loads between the three phases of the power circuit. In the higher-voltage rural circuits this also includes the lengths of branches consisting of one or two phase wires and neutral.
3. The avoidance of unnecessarily heavily loaded branches consisting of one or two phase wires and neutral.
4. The prevention of excessive over-excitation of transformers.
5. The grounding, where necessary, of aerial telephone cables at or near both ends of an exposure to obtain the benefits of magnetic shielding.
6. The use of adequately coordinated telephone transpositions on open-wire extensions and the avoidance of severe unbalances in the open-wire conductors.
7. The correction of badly distorted voltage or current wave shape on the power system.
8. The connection of the neutral point of three-phase wye-delta load banks to the system neutral conductor.
9. The use of telephone station apparatus, on party-line service, of lower susceptiveness.
10. Occasionally the use of arrangements or apparatus to minimize the effects from unbalances in central office equipment.

It is, of course, essential in successfully coordinating the power distribution and telephone circuits that, as in other coordination situations, the power and telephone people view the matter as a mutual responsibility and fully cooperate in the application of the tools available. Experience over a period of years has now shown that where this is done adequate overall coordination can be readily secured.[12]

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Appendix

For the sake of brevity, the detailed calculations and some of the minor assumptions for the following examples have been omitted.

Illustrative Example 1

The purpose of this example is to show, for average power system wave shapes:

1. The noise induction problem that might be created by the exposure of a reasonably long aerial telephone cable in an urban area with a heavily loaded single-phase feeder. It features:
   - *a*. The relative importance of triple and non-triple harmonic induction, and
   - *b*. The extent to which planning of routes, grounding of cable sheaths, etc. might improve the situation.
2. The changes in the noise magnitudes for the same situation with the various single-phase loads well distributed among all three phases. Under this condition, attention is directed to:
   - *a*. The change in the relative importance of the triple and non-triple harmonic induction.
   - *b*. The amount of reduction obtained by the same remedial measures tried in 1-*b* above.

Figure 3 shows a possible method of supplying the single-phase loads in a rather extensive part of an urban area. The general layout shown on Fig. 3 is such that all of the current for the feeder area traverses a considerable part of the exposure. Under this quite extreme condition —essentially single-phase supply for a relatively large area—the noise at location C under heavy load conditions would be about as shown on Table I.

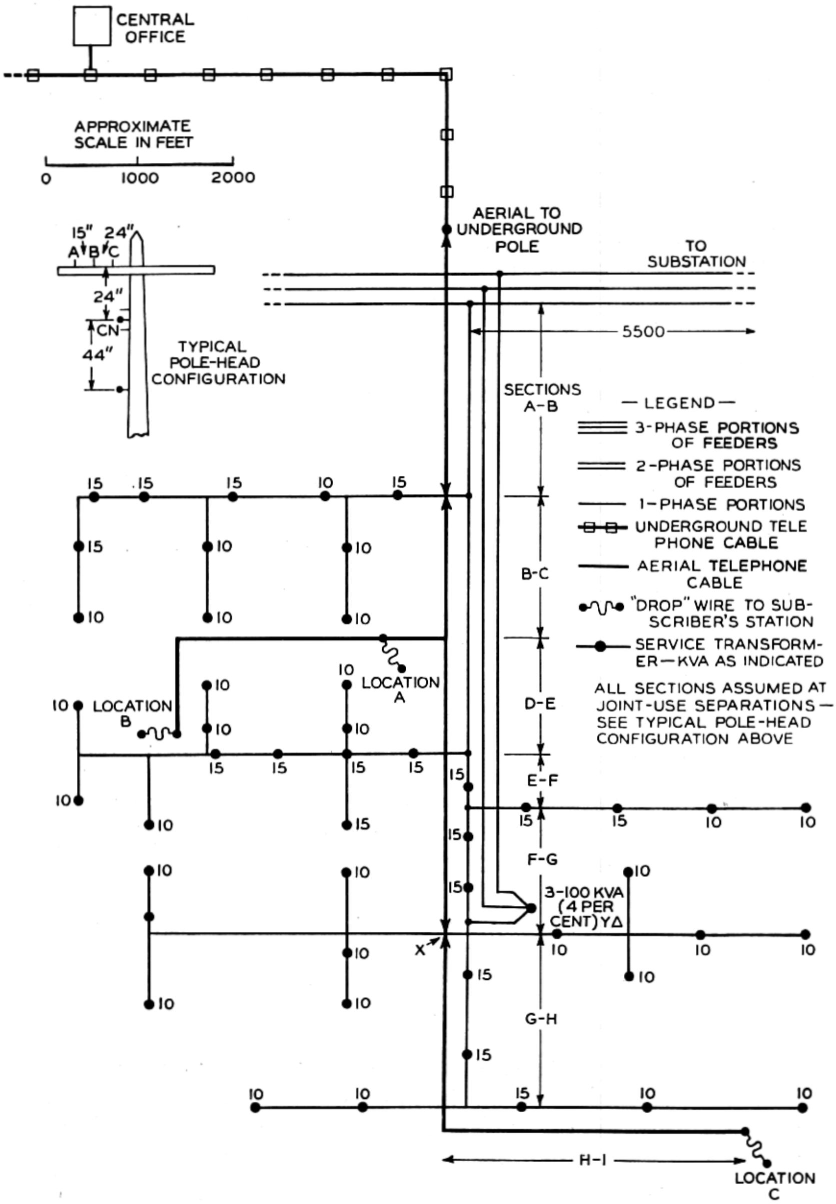

Fig. 3—Example of possible arrangement of feeder layout in an urban area where long aerial telephone cable is exposed to a heavily loaded one-phase feeder.

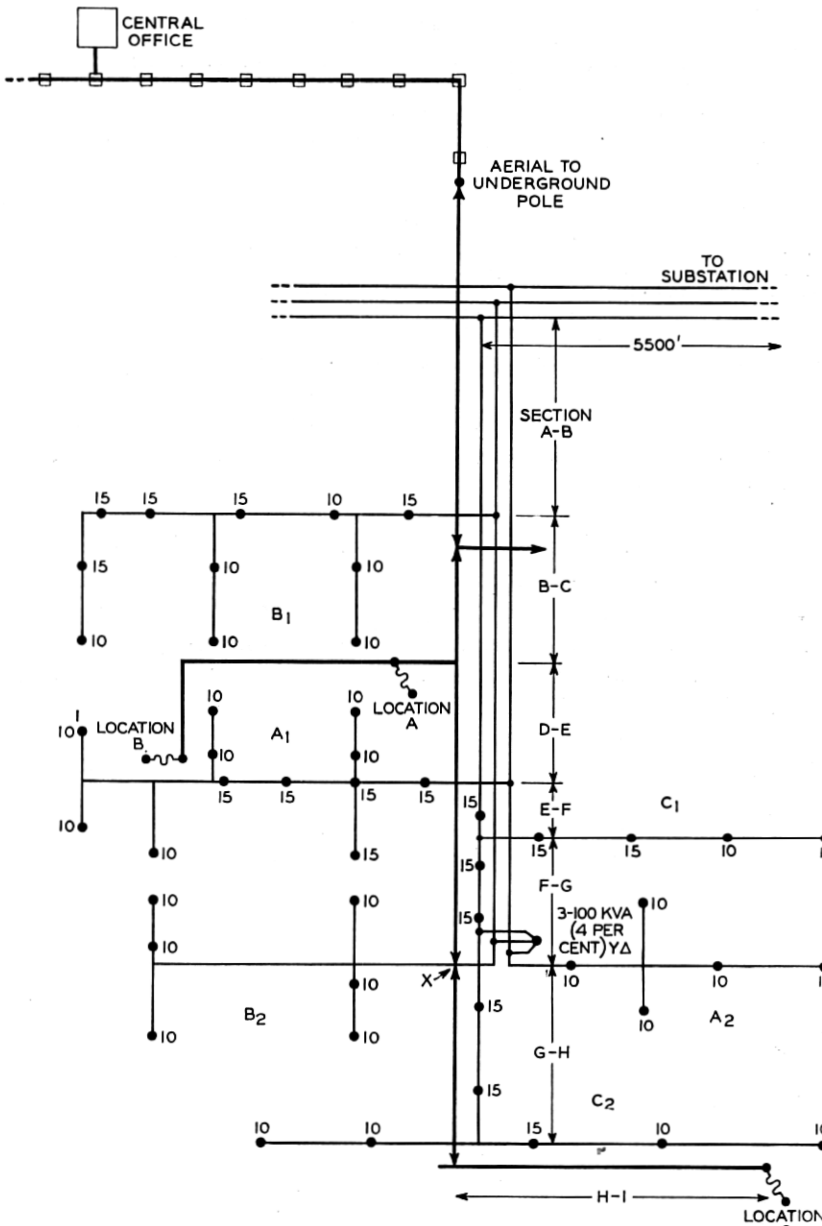

Fig. 4—Example of possible rearrangement of feeder layout shown in Fig. 3 to reduce magnitudes of "ground-return" currents.

TABLE I

NOISE CONTRIBUTIONS (FIG. 3) OF VARIOUS HARMONICS AND SECTIONS OF EXPOSURE

Section of Exposure	RMS Magnitude of Residual Current	Approximate Total Noise Contribution *	Approximate Noise Contribution From:	
			180 Cycles	300 Cycles and Higher Frequencies
A–B..........	210 amperes	1240 noise units	270 noise units	1215 noise units
B–E..........	157 "	1130 " "	250 " "	1100 " "
E–I..........	30–107 "	500 " "	100 " "	490 " "
	Total	2870 " "	620 " "	2800 " "

* Location *C*—For party-line service using 8A ringers, during heavy power loads.

It is evident from Table I that most of the party-line stations fed by the aerial telephone cable would need treatment. It will be noted from Table II that completely replacing the existing party-line stations with special station apparatus will, to a large extent, care for the situation since, in this case, the amount of noise contributed by the cable and central office unbalances would aggregate less than 150 units. Other measures either singly or in combination, probably more economical in their application, would provide substantial reductions in noise but would not be adequate for the more severely exposed stations.

TABLE II

COMPARISON OF EFFECTIVENESS OF VARIOUS REMEDIAL MEASURES (Fig. 3 Conditions)

Type of Remedial Measure	Approximate Noise on Party-Line Stations (Heavy Power Loads)	
	Location *A* or *B*	Location *C*
1. Before applying remedial measures..........................	1800 noise units	2870 noise units
2. Using special telephone station sets..........................	75 " "	125 " "
3. Avoiding exposure in section *A–B* by cooperative planning of routes..................	560 " "	1630 " "
4. Cable sheath shielding by tying aerial and underground telephone cables at junction pole and connecting aerial sheath to 1 ohm ground at point *X*.	1160 " "	1700 " "
5. Interconnecting 300 kva wye-delta bank with system neutral	1430 " "	1600 " " (170 kva of unbalanced load)
6. Combination of measures 3, 4, and 5......................	365 " "	420 " "

Assume, however, that instead of supplying the single-phase loads in the area shown on Fig. 3 from one phase only, the single-phase loads were distributed reasonably uniformly among the phases. This would be advantageous not only by the noise reduction possibilities, which will be more fully discussed but also by the improved regulation attainable on the feeder. Figure 4 shows a possible rearrangement of Fig. 3 along these lines and Table III shows the noise conditions with the feeder arrangements of Fig. 4.

TABLE III

NOISE CONTRIBUTIONS (FIG. 4) OF VARIOUS HARMONICS AND SECTIONS OF EXPOSURE

Section of Exposure	RMS Magnitude of Residual Current	Total Noise Contribution *	Noise Contribution From:	
			180 Cycles	300 Cycles and Higher
A–B..........	6 amperes	280 noise units	270 noise units	75 noise units
B–E..........	45 "	370 " "	250 " "	275 " "
E–I..........	5–45 "	150 " "	100 " "	115 " "
	Total	735 " "	620 " "	375 " "

* Location *C*—For party-line service using 8A ringers, during heavy power loads.

A comparison of Tables I and III shows that the noise from the non-triple harmonics has been very materially reduced by the balancing of loads made possible by the more favorable feeder arrangement of Fig.

TABLE IV

COMPARISON OF EFFECTIVENESS OF VARIOUS REMEDIAL MEASURES (Fig. 4)

Type of Remedial Measure	Approximate Noise on Party-Line Stations (Heavy Power Loads)		
	Location *A* or *B*	Location *C*	
1. Before applying remedial measures......................	480 noise units	735 noise units	
2. Using special telephone station sets......................	25–30 " "	40–50 " "	
3. Avoiding exposure in section *a–b* by cooperative planning of routes.....................	190 " "	460 " "	
4. Interconnecting 300 kva wye-delta bank with system neutral	330 " "	535 " "	(26 kv. of unbalanced load)
5. Cable sheath shielding—grounding at jct. pole and to 1 ohm ground at *X*...............	325 " "	420 " "	
6. Combinations of measure 3, 4, and 5.....................	85 " "	245 " "	

4, although that from the triple harmonics has been inappreciably changed. The net effect has been a reduction of nearly 75 per cent in the noise on the party line stations served by the telephone cable. The reductions afforded by various remedial measures are shown in Table IV.

It is evident from Table IV that, by the application of various of the measures of coordination, the need for an extensive rearrangement of either plant is avoided.

Illustrative Example 2

The purpose of this example is to show the extent to which remedial measures of the type generally applicable in urban areas (see Example 1), may be applied in a less thickly settled area where exposures to 2.3/4 kv. multi-grounded neutral arrangements are encountered under average conditions of power system wave shape. In detail the example covers:

a. The extent to which such measures as cooperative planning of routes and use of wye-delta load banks may be ineffective.

TABLE V

Noise at Various Locations (Fig. 5) and for Various Types of Telephone Service

Location	Type of Telephone Service	Total Noise	Contribution From:		Remarks
			Cable Exposures	Open Wire Exposures	
A	1. Common-Battery Party-line stations (Class 1-*a* Table *D*)	225–345	220–270	45–215	Open-wire noise dependent on effectiveness of telephone transpositions.
	2. Magneto party-lines (Class 1-*c* Table *D*)	85–225	75 app	40–215	
	3. Individual Line (Class 1-*d* Table *D*)	40–210	25–35*	About 10–210	Lower values of noise on circuits controlled by effects of station sets—higher values by effectiveness of telephone transpositions.
B	1.	170–1200	10–100	170–1190	
	2.	75–1175	20–35	70–1175	
	3.	60–1175	About 20*	55–1175	
C	1.	400–975	285–325	275–925	
	2.	150–870	110–125	110–860	
	3.	100–860	60*	75–860	*Noise in cable section due to office and cable unbalances.

b. The importance, particularly under joint-use conditions, of noise directly induced into the metallic circuit of open-wire telephone pairs and the importance, therefore, of suitable telephone circuit transpositions.

Figure 5 shows exposure conditions such as may be encountered in a small community serving a nearby rural area and Table V shows the noise conditions at several locations during heavy power loads.

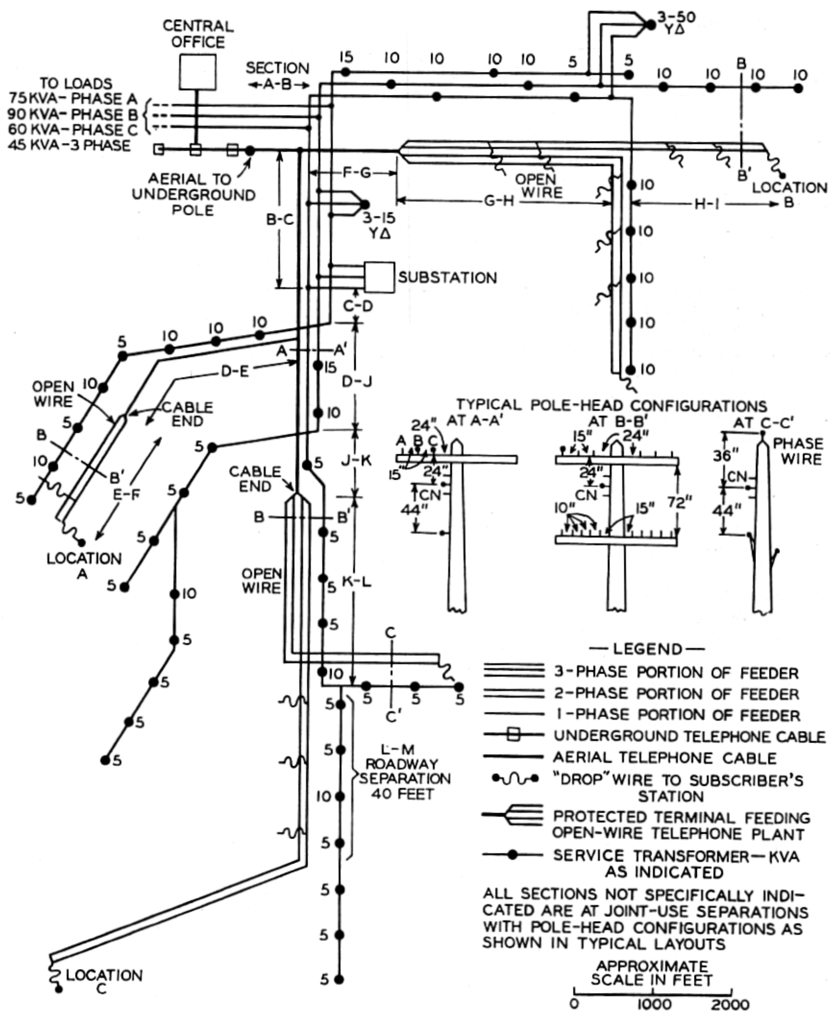

Fig. 5—Example of exposure conditions between 2300/4000-volt distribution feeder and exchange telephone plant in suburban and rural area.

The extent to which various measures of coordination could be applied to reduce the noise induction or to restrict the extent of special arrangements is shown in Table VI.

TABLE VI

Comparison of Effectiveness of Various Remedial Measures

Type of Remedial Measure	Approximate Noise at:								
	Location *A*			Location *B*			Location *C*		
	1 *	2	3	1	2	3	1	2	3
1. Before applying measures	225–345	85–225	40–210	170–1200	75–1175	60–1175	400–975	150–870	100–860
2. Using special tel. sets	40–210	40–210	Neg. Change	60–1175	60–1175	Neg. Change	100–860	100–860	Neg. Change
3. Avoiding exposure section *B–C* by cooperating planning	130–250	65–220	Neg. Change	Neg. Change			350–950	115–860	Neg. Change
4. Interconnecting neutral of 150 kva wye-delta bank	180–310	Neg. Change		150–1175	Neg. Change		370–950	Neg. Change	
5. Average degree of coordinated tel. transpositions	250	80	50	200	175	175	340	175	130
6. Tel. transpositions + cable sheath shielding †	210	70	50	180	175	175	320	165	130
7. Combination of 4, 5 and 6	185	65	50	160	155	155	310	160	125

* Type of station apparatus shown on Table V.

† Cable was assumed to be grounded at junction pole at end of Section F–G to 2.5 ohm ground; at other junction poles to grounds exceeding 10 ohms.

It is evident from this table that, for the conditions assumed, the use of reasonably coordinated telephone circuit transpositions will be necessary to care for the stations served by open-wire. Ordinarily the use of such transpositions in combination with such other measures as are reasonably effective would serve to take care of the stations served by telephone cable and would limit the extent to which special telephone station apparatus might be needed for the stations served by the longer open-wire extensions.