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POST OFFICE ELECTRICAL ENGINEERS

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A. MORRIS, A.R.C.Sc., M.I.E.E.

A PAPER

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TELEPHONE CABLE CIRCUIT INTERFERENCE.

Synopsis.—(i) Distinguishes between disturbance such as Singing, Echo and Morse flutter and thump, arising from the self energy of a circuit, and interference such as Cross-talk, Babble and Noise caused by the transfer to a circuit of energy from without. Differentiates between the degrading effect of noise interference upon the intelligibility of direct speech and the discomposing and annoying effects of cross-talk upon subscribers on account of apparent lack of secrecy of the system. (ii) Deals with the development of cable circuits from the interference immunity point of view. Single wire and looped circuits. Parallelism. Twin, Quad, Quad-pair and M.T. cable types. Loading and superposing. (iii) Describes the principles of the crossing and auxiliary apparatus methods of cable balancing. (iv) Enumerates the various kinds of electrical unbalance; explains how they arise in telephone cables. (v) Defines cross-talk attenuation. Gives the various measures for expressing cross-talk magnitudes. Expresses cross-talk attenuation in terms of currents and impedances of disturbed and disturbing circuits. Cross-talk level. Near-end and distant-end cross-talk. (vi) Gives the relation between percentage loss of articulation and voltage of various single and complex frequency noises. Noise voltage. Noise level/speech level difference. Explains how power circuit interference arises; discusses the degree of electrical balance necessary for freedom from same. (vii) Defines impedance interference characteristics and gives expressions for various capacity interference characteristics. Deduces the degrees of capacity balance necessary for various methods of circuit working. (viii) Shows how calculations may be effected for the prediction of cross-talk results. Applies the method to non-repeatered and repeatered circuits. Illustrates the manner in which the design of a circuit, so far as attenuation length of repeater section and repeater gain are concerned, is dependent upon the minimum cross-talk attenuation of the repeater sections. Compares the results of calculation with measurements. (ix) Describes methods adopted for the control of overall cross-talk and noise in telephone circuits. Switching tests. (x) Modern cable improvements. Grouping and screening. Control of unbalance in factory lengths. Star Quad type cable. Systematic jointing. (xi) Conclusion. (xii) References and bibliography.

(I). INTRODUCTION.

General.—Disturbances to a circuit may arise by reason of undesired interactions between the various elements constituting such a circuit. " Singing " and " echo " effect in repeatered circuits for example are types of this class of disturbance. Furthermore, in the case of a long-distance, loaded telephone circuit, upon the limbs of which, continuous current, earthed telegraph circuits have been composited, the telegraph current affects the permeability of the iron cores of the loading coils, varying their inductance and consequently the attenuation of the circuit, in such a way as to produce a waxing and waning in the strength of the speech currents in the telephone circuit. This form of disturbance is known as " Morse flutter " and has been considerably minimised in modern systems by the use of dust core loading coils. Again, in such a system, a disturbance may be heard in the receiving apparatus of the telephone circuit due to transient oscillations in the telegraph current. This is referred to as " Morse thump." Each of these forms is quite different from ordinary telegraphic induction. The various forms of circuit disturbance mentioned in this paragraph are maintained by reason of the energy of the circuit itself. They will not be further referred to, the class of disturbances to be dealt with subsequently being the interference caused by the transfer to a circuit of energy from without.

If a line is subject to interference, then in addition to the presence of a source of disturbance, the line must be in such a condition as to be affected by such a source. As a consequence of this it may be inferred that interference can be prevented either by removing the disturbing source or by so constructing and working the line that it is unaffected by external disturbances. In practice, absolute freedom from interference is seldom, if ever, experienced. It is rarely practicable to completely remove the disturbing source, although its effects may be considerably reduced; whilst at the same time perfect immunity from such disturbing effects as may exist is extremely difficult to attain in the construction and maintenance of lines.

The disturbance on a circuit will be due to the effects of its terminal and line apparatus, as well as to the actual line itself. Generally, the degree of interference existing in a circuit is dependent upon the magnitude of the disturbing current or/and voltage in the disturbing circuit or circuits, and upon the extent to which the disturbed circuit as a whole is liable or susceptible to such influence, *i.e.*, upon the extent of the resultant electrical coupling between the disturbed and the disturbing circuits.

The electrical couplings between the limbs of different circuits are, of course, inherent to the arrangement and cannot be eliminated. If, however, these couplings so neutralise each other that the resultant coupling between the complete circuits is zero, then there will be no disturbance between the circuits. The couplings referred to are electromagnetic, electrostatic and conductive in character, and the statement just made will generally require to apply separately to each type of coupling in order to secure absence of interference. Neutralisation of the couplings will not occur if unbalance of the electrical constants exists between the circuits.

Cross-talk and Noise.—The transfer of speech currents from one telephone circuit to another is sometimes referred to as " Secondary-Talking." In a certain classification of the various kinds of secondary-talking the term " Cross-talk " is applied to interference between any two independent telephone circuits, whilst " Overhearing " is restricted to interference between a phantom circuit and one or other of the physical circuits upon which it is formed. In what follows, the term cross-talk will be used in its most generally accepted sense, *i.e.*, it will include all classes of secondary-talking.

Present-day practice classifies all other forms of interference (from without) to telephone lines as " Noise." Such noise may be due to telegraphic induction, power circuit interference, or other causes and may be produced by the direct conduction or by magnetic or electric induction of single- or multi-frequency currents on to the telephone circuit.

In general, all the circuits of a telephone cable will " cross-talk " to one another. The total of such interference to any particular circuit will take the form of a sequence of confused unintelligible sounds, which is classified as noise and designated " Babble."

In the case of cross-talk and babble the energy is furnished to the disturbed circuit *via* the unbalanced couplings from the speech energy of associated or neighbouring telephone circuits. In the case of noise other than babble the source of energy is that of circuits transmitting any form of electrical energy other than that of speech.

Noise of sufficient intensity will seriously interfere with telephonic reception by reason of its degrading effect upon the intelligibility of direct speech on the circuit. Cross-talk, even of slight amount, is chiefly objectionable by reason of its discomposing and annoying effects upon subscribers on account of apparent lack of secrecy of the system. The freedom of a line from cross-talk and noise is as important as its transmitting efficiency to direct speech. The various factors affecting cross-talk and noise magnitudes will be dealt with later.

The numbers enclosed in parenthesis in the text refer to the appendix of " References and Bibliography."

(II). TELEPHONE CABLE CIRCUIT DEVELOPMENT.

Looped circuits, parallelism and the introduction of Twin type cable cores.—The use of looped or two-wire telephone circuits in place of the single wire lines was the result of one of the earliest attempts to produce a silent telephone circuit. These circuits were thereby not only freed from noise due to the effects of varying earth potentials at their terminals—giving rise to "earth currents," *i.e.*, to the direct conduction of extraneous currents—but they were not affected by electrical induction from such single-wire telegraph circuits as were in their vicinity, provided that the arrangement of the two types of line was so symmetrical as to ensure zero resultant magnetic and electric coupling, *i.e.*, equality of induction from the single-wire telegraphs on to each wire of the telephone loop.

Further improvements in the provision of silent telephone circuits were effected by equalising, as far as possible, the insulation resistances of the two wires of particular pairs.

Considering two independent two-wire circuits in the same plane, the wires of which do not cross each other at points intermediate to the circuit terminals, it is clear that one wire of one of the circuits will be at a greater average distance from the wires of the other circuit than is the remaining wire of the first-mentioned circuit. The result of this will be unequal induction on the wires of either circuit and consequently mutual interference between the circuits. This effect is known as " parallelism " and will exist between any two circuits which, running side by side along the same route, maintain similar general relative positions. (1) The twisting together of two wires considerably minimises this difficulty; the Twin cable pair was introduced in the year 1882 or thereabouts, for this purpose.

Unloaded Cable Circuits. Quad, Quad-pair, and Multiple Twin type cable cores.—The use of twisted (2) pairs for cable circuits having become the general practice by the year 1887, attention was next directed to the residual cross-talk which existed between such circuits.

During the period 1893 to 1894, the first commercial application of J. J. Carty's transposition schemes of 1891 (3) for the elimination of cross-talk was made in respect of twin cables drawn into Tremont Exchange, Boston, U.S.A. (4). The condenser balancing method (see later) was also used in this case, the condensers taking the form of twisted rubber-covered wires, connected between the wires of mutually interfering pairs.

The consideration of the systematic elimination of cross-talk in unloaded dry-core cables was undertaken in this country by the British Post Office, Messrs. F. Tremain and A. W. Martin presenting a report on the London-Birmingham (No. 1) telephone cable in 1899. Two types of cable were dealt with, namely, quad-core and twin-core types. The cross-talk existing between the diagonal pairs of the quad type was attributed to asymmetry, consequent upon the irregular mechanical distortion of the cores during manufacture of the cable, whilst the cross-talk between neighbouring pairs of the twin type was attributed to parallelism of the wires. Each of these features results in unequal electric induction on to the wires of the disturbed circuit, the former in an irregular manner, the latter in a regular and cumulative (with length) manner.

In order to eliminate the interference between two-wire circuits due to the above causes, crosses were inserted between the wires at the cable joints, the most suitable type of cross in any particular case being determined from the results of experimental trials. The eight possible ways of jointing together two quad type cores for the purpose of eliminating cross-talk whilst still maintaining the original relative positions of the wires, *i.e.*, without departing from the designed formation of such cores, was also described, a similar system of crossing for aerial lines being at the same time suggested.

Owing to the impossibility at the time of carrying out the above investigation, of manufacturing a quad core cable which would be free from mechanical distortion, and stable after installation, it was concluded that cross-talk was inherent to this type. The outcome of this and of the necessity for the working of phantom circuits in dry-core cables, was a change of cable design, the quad pair (42) type core being produced in 1901 and ultimately, the Dieselhorst-Martin, Multiple-Twin Cable of 1903 (5).

The working of earthed telegraph circuits in unloaded telephone cables resulted in interference to the telephone circuits. In the year 1902 or thereabouts " anti-induction " or " screened conductor " cables were introduced to overcome this difficulty. In these cables an earthed metal tape was lapped over the insulating paper of those single conductors intended for use as telegraph circuits. Such circuits were thereby efficiently screened electrostatically, but interference to the telephone circuits due to magnetic induction was still experienced. By ensuring continuity of the screen, removing the earth connection and working such concentric conductors as independent telegraph circuits the magnetic field of such circuits would thereby have been essentially confined within the insulated screen and it is probable that the magnetic component of the interference would have been eliminated.

The external electric field of such concentric conductors would of course have exercised a disturbing effect upon other circuits. Such effect would probably have been relatively feeble.

The " anti-induction " cable described above must not be confused with Patterson's anti-induction cable (6) which provided a large-gauge wire at the centre of the cable, or alternatively a number of bunched conductors, as a common return for other cable conductors, with the object of minimising the magnetic induction effects of such conductors. Circuits so arranged in the cable as to be remote from the field of such conductors and their common return will be freed to some extent from electro-magnetic interference. Such a cable was laid in 1885 between Birkenhead and Liverpool, the central bunched wires being earthed at each end (7).

Superposed and loaded cable circuits.—The introduction of inductance-loaded and of superposed circuits in underground cables raised a number of important questions in regard to disturbance features, and presented many difficulties.

Single-wire Wheatstone circuits and even looped Wheatstone circuits caused serious disturbance to loaded telephone circuits working in the same cable, although the placing of an impedance in the telegraph circuit in the former case—by reducing the current and so the strength of the magnetic field—considerably reduced the inductive disturbance. In some cases, however, the serious reduction of speed consequent upon the introduction of the necessary amount of inductance was inadmissible. For a time, therefore, and until the difficulties could be modified or overcome it was found necessary to provide separate cables for telegraph and telephone purposes, although such a total separation was in some instances uneconomical from a financial and traffic point of view.

After much experimental investigation and practical trial, sufficient data became available which showed that great care in manufacture and construction and a higher maintenance standard was required in the future, and that special testing operations were necessary at the jointing stage, when laying cables which were designed for superposing and loading. An outline of these proposals was made in a British Post Office Engineering memorandum dated December, 1912. The proposals were considerably developed as a result of the experience gained in the construction for joint telegraph and telephone working of a coil loaded, 48/70 M.T. + 6/100 M.T. cable between Leeds and Hull.

(III). CABLE BALANCING FOR INTERFERENCE IMMUNITY PURPOSES.

Crossing Method.—The work on the Leeds-Hull No. 1 cable was finished by November, 1913. The problem of the systematic elimination of cross-talk was dealt with by what is known as the " Crossing " method of cable balancing. The method was subsequently extended to deal with resistance and inductance unbalances, and was applied by the British Post Office to continuously loaded cables in the year 1922 (8). The method secures the neutralisation of the electrical unbalances of one cable length by those of other cable lengths which, for the sake of completeness of balance (over a frequency range) must not be very distant from one another and should preferably be consecutive lengths. Neutralisation of, for example, the whole of the capacity unbalances of every circuit is thereby effected, over as short a length as possible, by means of the insertion of suitable crosses between the wires at cable joints. Conductor resistance, electric capacity, inductance, etc., unbalances are separately dealt with by this method, the appropriate wire crosses for their elimination being suitably chosen. With cables of modern manufacture this method permits of practically perfect balance. In Pupinised cables, balance is effected within a length of cable equal to the spacing of the loading coils, *i.e.*, a loading section, the capacity balance being almost complete over each group of four factory lengths. Balance secured in this manner, at such relatively short intervals, is essentially uniform, and is accordingly independent of frequency.

In principle, the crossing method is the same as that devised by Tremain and Martin in 1899 for the elimination of cross-talk between the side circuits of quad type cables, although it is applied in a somewhat different manner. Whereas originally the best type of cross was determined by experimental trial involving measurements of disturbance, both before and after joining the cable lengths together, the present practice of measuring those electrical characteristics which are contributory to cross-talk (see " Interference Characteristics," later) enables the best mode of connection to be pre-determined and the final result accurately forecasted. This is rendered possible not only on account of the completeness of the knowledge of the effects of each and every type of cross, but also by virtue of the accuracy of the analysis and measurement of the electrical unbalances of cable cores. Upon this knowledge is based the systematic method of scheduling and selecting test results, which forms one of the important features of this method of balancing.

The crossing method is now in general use in the United Kingdom, the United States of America, and in most European countries excepting Germany. The details of application of the method differ in different countries. The principles of the method have been described elsewhere (9); complete details of the application of the method by the British Post Office being given in a Technical Instruction (10). The procedure adopted by the American Companies is described in Patent Specifications. References (11) to (14) apply.

The systematic balancing of cables in accordance with the crossing method was originally confined to within-core balancing, *i.e.*, to balance between each of the circuits of individual cores, control of the interference between the circuits of different cores being secured by reason of the separation resulting from the mixing of the cores during the crossing process. In normal cases such within-core balancing is usually adequate.

In those cases where the degree of core separation is limited, as for example, in small cables, or cables, in which the separate balancing groups contain relatively few cores, or in those cases where large unbalance exist between certain cores, or in those instances where a definite degree of core-to-core balance must be ensured, it is necessary to resort to between-core balancing in addition to the usual within-core balancing. The crossing method is applicable in this case, at least so far as the unbalances between adjacent cores in individual layers are concerned. Some details of a systematic method of procedure are dealt with in reference (15). The wires at each joint are connected together layer to layer and core to core in order of their stranding, cores adjacent in any particular factory length remaining adjacent throughout the length of each loading section. In this manner the core-to-core unbalances are confined to adjacent cores, and the extent of the balancing work is kept within reasonable limits. The wire crosses within each core are arranged to neutralise not only the core-to-(adjacent) core unbalances, but also, and at the same time, the within-core unbalances.

Systematic balancing between the cores of adjacent layers is impracticable in the general case, by reason of the prohibitive number of unbalance combinations involved. Fortunately the unbalances between the cores of adjacent layers can, by suitable design and careful manufacture, be restricted to very small values in factory lengths of high-grade telephone cable, and field-balancing operations are usually unnecessary. In the case of two-, three-, or four-core centre cables, however, the unbalances of the centre cores to the cores of the first layer may by inadvertence be so large as to require treatment during jointing. In such a case, by restricting the centre layer cores to the centre throughout the cable, as well as the first layer cores to the first layer, *i.e.*, by maintaining the centre and first layer cores intact, crossings within the first layer cores will effect the necessary neutralisation, although such balancing, if carried out on an extensive scale, is apt to become extremely intricate.

The connections between the wires, and the selecting and scheduling processes involved in the crossing method of balancing may be systematically dealt with by means of certain " Transformation Operators " (16). These operators are of great advantage in cases of multiple selecting for normal balancing, and are of especial utility for the selections involved in rebalancing during repair work.

Auxiliary Apparatus Method.—Another method of cable balancing which has been previously mentioned, will now be further referred to. It may be applied to each individual section of a circuit or to its overall length. In the former case it consists of the addition of suitable condensers, resistances, etc., as the case might warrant, at each of various points along the circuit, for the purpose of separately balancing each of the electrical inequalities. The procedure, generally, is to measure the unbalances of the circuits of loading sections of cable, and then insert the appropriate correcting apparatus in order to reduce the unbalanced couplings of the circuits to zero value. When these couplings are electrostatic in character, the method is known as the " Condenser " method of balancing. In the year 1890, Carty (17) described the connection of electric condensers between the wires of twin cables, at intervals along their length, for the purpose of balancing electric capacities. As already mentioned, this method was applied to twin cables in America in the year 1894. The first commercial application of the addition of condensers between the wires (and between the wires and earth) of cables of the four-wire core type, for the elimination of side-to-side and phantom-to-side interference respectively, appears (4) to have been made in the case of a quad core submarine cable between Eastport and Lubeck (Main, U.S.A.) in the year 1912. Although its use in America and in most European countries is restricted to those special cases where the crossing method cannot be conveniently applied, it constitutes the general method of cable balancing adopted in Germany, in which country a very complete technique in connection therewith has been developed.

Reference (18) relates to a description of the German method. After installation of the cable, the wires at each joint are connected together without crossings, layer-to-layer and core-to-core in the order of their stranding; cores adjacent in any particular factory length remaining adjacent throughout the length of each loading section. Core-to-(adjacent in the same layer) core balancing, in addition to within-core balancing, is necessary with this method of jointing, the former being undertaken prior to the latter. The magnitude of the capacity required in each case is determined directly by means of a special coupling meter, the residual cross-talk after balance, being measured on a specially arranged attenuation meter. In general, nine condensers per core are required for core-to-core balance, three condensers per core for within - core balance and three condensers per core for balance in respect of earthed power circuit interference. The condensers used are of a paper type, made up in convenient sizes and placed around the centre joint of the loading section beneath a special housing sleeve. Their capacity varies very little with temperature.

Reference (19) relates to a description of a particular mode of adding capacities to telephone circuits, by means of stub cables, for the above purposes, whilst reference (20) deals with a description of a method for the equalisation of the capacity couplings in factory lengths of cable by an alteration of the component capacities of the cores over a short portion of each such length.

When applied to long circuits complete from end to end, the auxiliary apparatus method consists of the addition of suitable impedance networks between the wires at the terminals of such circuits. The impedances of these networks are arranged to simulate the impedance interference characteristics (see later) of the circuits, over the audio frequency range. The method employed in the design of such networks was described (21) in the year 1921, and is based upon the reproduction of each " hump " of the interference characteristic, impedance-frequency curve by means of a resonating circuit, such circuits being subsequently connected in series.

(IV). UNBALANCES IN TELEPHONE CABLE CIRCUITS.

General.—A general reference to the unbalance of one circuit with respect to another as a governing feature of the interference between them has already been made. The electrical asymmetry between two circuits will give rise to unbalanced electric induction or/and magnetic induction effects. Interference will occur between the associated circuits of a four-wire core unless in each physical circuit the impedances of the two limbs between any two cross sections are equal to each other. Equality of these impedances in magnitude and phase angle, at all frequencies, will be secured if the distribution of the electrical constants is symmetrical for the associated limbs over the whole length of such circuits, *i.e.*, if there is electrical balance of conductor resistance, electric capacity, inductance and leakance.

Capacity Unbalance.—The mechanical distortion produced in the arrangement of the conductors of four-wire cores during the process of manufacture, which was pointed out by Tremain and Martin in the case of quad type cables, was greatly reduced in subsequent designs, particularly in the case of cables of the multiple-twin type. With the advent of inductance loading and especially when the principle of superposing over loaded circuits was adopted, cross-talk difficulties particularly between associated side and phantom circuits again arose, the main reason for which was traced to the above cause. In regard to the actual mode of production of cross-talk from this cause the following brief explanation is now given. Imperfect symmetry in the make-up of cables gives rise to inequalities in the electrostatic capacities between the wires of the different circuits formed on a two-pair core. Thus in the case of a single 176 yard length of high grade, multiple-twin cable these inequalities may average 14 parts in 1000, whilst they may exist to the extent of as much as 90 parts in 1000, in some cores which have been badly crushed during cable stranding operations. These inequalities are referred to as capacity unbalances; they give rise to unequal electric induction between the wires of different circuits, the direct result of which is cross-talk.

The interference due to capacity unbalance depends not only upon the magnitude of the unbalance, but also upon the voltage of the disturbing circuit. The impedance of an inductance loaded telephone circuit being much greater and its attenuation being much smaller than that of a similar but unloaded circuit, the average voltage over its length is correspondingly greater. With the same distribution of capacity unbalance, therefore, loaded lines will be subject to a greater cross-talk disturbance than similar unloaded lines, and hence the capacity balance of a loaded line will require to be very much better for a given degree of cross-talk immunity than that of an unloaded line.

The capacity unbalance of telephone cables of modern manufacture has a preponderating effect upon the total disturbance resulting from the combined effects of all the different classes of electrical unbalance.

With the usual nomenclature (22) for the direct capacity network of an individual four-wire unit of a multi-core cable (the conductors of all other cores assumed disconnected from each other and from the lead sheath), see Fig. 1, the quantities $(w - x)$, $(z - y)$, $(w - z)$ and $(x - y)$ are the direct wire-to-wire capacity unbalances of the core; they are represented by p, q, r and s respectively. The quantities $(a - b)$ and $(c - d)$ are the direct pair-to-earth capacity unbalance of the core; they are represented by u and v respectively. The quantity $[(a + b) - (c + d)]$ is the direct phantom to earth capacity unbalance and may be represented by f. The whole of the capacity unbalances so defined are invariable for any particular cable core. Representative values of each of the

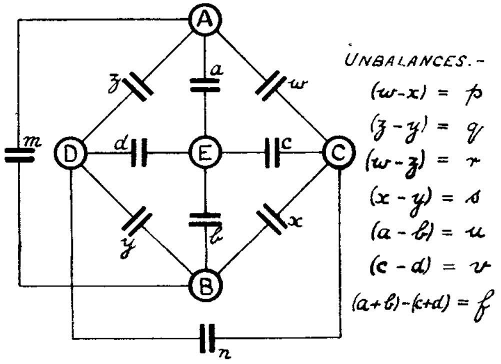


FIG. 1.—DIRECT CAPACITY NETWORK OF A FOUR-WIRE CORE OF MULTI-CORE CABLE.

above-mentioned unbalances for 176 yard factory lengths of modern multiple-twin and star quad cables are given in table No. 1.

Conductor Resistance Unbalance.—Exact equality of conductor resistance between the associated wires of cable circuits is seldom if ever secured in practice. The chief reasons for this are to be found in the asymmetry of twinning and the non-uniform electrical and physical character of the copper wires from which such circuits are constructed. In view of the differences in conductivity consequent upon variations in the annealing processes, or the presence of traces of impurities in the material, the electrical unbalances due to these causes are limited in the manufacturing stage by arranging for the two wires of a pair to be made up of consecutive lengths of the same reel of wire. Owing to the very great attention which is given to these matters in modern manufacturing processes the resulting inequalities from these causes are generally very small, averaging about one part in a thousand of the loop resistance per standard length of cable. Inequalities of this magnitude, especially when distributed, would not give rise to serious disturbances; it is the maximum values, of the order of two or more parts in a hundred, which are a source of difficulty in the construction and working of cable circuits.

Resistance unbalances of such a magnitude are rarely met with on the side circuits and but seldom on the phantom circuits of factory lengths of modern Pupinised telephone cables.

So far as mutual interference between the side and phantom circuits of a four-wire core is concerned, resistance unbalance of either side circuit will cause cross-talk only between the phantom circuit and the particular side circuit containing the unbalance. The interference so caused is most pronounced when the circuits are terminated. Furthermore, in a long circuit, the nearer the unbalance is to the disturbing end of the line the greater will be the resulting interference.

Resistance unbalances of side circuits are neutralised by similar unbalances in immediately succeeding lengths of cable in order to eliminate the cross-talk to (and from) their associated superposed circuits. Resistance unbalance of a phantom circuit will not cause interference to the other circuits.

of the same core, such unbalances are however maintained at a low value in practice in order to limit the interfering effects of exposure from power systems.

Insulation Resistance Unbalance.—Under normal conditions the magnitude of the current flowing from one conductor to another, between which an alternating potential exists, depends to a very limited extent only, upon the magnitude of the insulation resistance between such conductors. Furthermore, since in the case of modern trunk cables the magnitude of the insulation resistance attained in manufacture, and the standard of constructional and maintenance work attained in practice is so high and uniform, little or no cross-talk difficulty is experienced from this cause. An equivalent average uniform insulation resistance of 10,000 megohms per mile is the minimum figure aimed at, but it frequently happens that the actual cable itself between loading coils reaches an average uniform value of 50,000 megohms per mile. When the insulation resistance of particular wires is lowered from some cause such as, for example, a defect in the cable sheathing, trouble may arise owing to the unequal conduction of current to the limbs of other circuits, with consequent interference, before even the efficiency of transmission is effectively impaired. In such a case, in order to get rid of the resulting cross-talk or ringing induction, the fault must be removed by restoring the normal insulation resistance of the cable circuits.

Leakance Unbalance.—Owing to the uniform and high-grade electrical properties of the materials composing the insulating medium in dry-core cables, interference between the circuits of such cables due to unequal dielectric losses, *i.e.*, leakance unbalances, is negligibly small. Extreme care in the choice and treatment during cable manufacture of these materials is required in order to secure this result. Moreover, such precautions are the more necessary because any inequalities which would otherwise be introduced might have a far greater effect in originating interference based upon capacity unbalance than upon leakance unbalance.

Mutual and Self Inductance Unbalances.—The current from the disturbing circuit enters the disturbed circuit *via* the inductance unbalance, *i.e.*, *via* the unbalanced magnetic coupling between the circuits. The magnitude of the resulting interference is proportional not only to the extent of the unbalance but also to the current strength of the disturbing circuit. As in the case of resistance unbalance, the effect is more pronounced when the circuit is terminated. If inductance unbalance exists at a cross section close to an open-ended line, no disturbance from that source will be apparent at the sending end.

Unbalance of mutual induction in the cable sections of Pupinised cables and also in continuously loaded cables is attributable to unsymmetricality of make-up. Crosses introduced for the purpose of eliminating side-to-side interference due to capacity unbalance will in general remove any unbalance of mutual induction arising from dissymmetry of make-up. The effect of such mutual inductance unbalance is, however, very much smaller than that of capacity unbalance due to the same cause.

Up to the present and in modern dry-core, multiple-twin telephone cables, no great difficulty has been experienced from mutual inductance unbalance. In the case of non-loaded Gutta Percha or Balata submarine cables of quad formation, where the individual wires are electrostatically screened from each other, owing to the presence of water within the spaces separating the insulated wires, the cross-talk which exists between side circuits is, to a considerable extent, due to mutual inductance unbalance. Special care during manufacture will eliminate this trouble (23).

The self inductance of the loading section lengths of Pupinised cables is very small, averaging one milli-henry per mile, in the case of the side circuits of multiple-twin cables. The inductance unbalances of such circuits are extremely small, the cross-talk resulting therefrom being generally inappreciable.

In Krarup-loaded cables, differences of self inductance of the associated wires of a pair may average 10 parts in 1000 and may reach a maximum value of 70 parts in 1000, for 0.65 mile lengths of cable, loaded to the extent of 20 to 30 millihenries per mile. The effective resistance unbalances in such cables are also appreciable. Such unbalances give rise to cross-talk between associated pair and phantom circuits of superposed cores. Each of these electrical unbalances requires to be dealt with in continuously loaded cables. The method of treatment for balancing purposes is analogous to that already described for resistance unbalance. Recent work in connection with interference between the circuits of continuously loaded cables is dealt with in reference (23).

(V). CROSS-TALK IN TELEPHONE CABLE CIRCUITS.

General.—The extent to which a conversation in one circuit can be overheard in another will depend fundamentally upon their unbalanced couplings, and upon their respective transmission characteristics (24). The amount of amplification or gain of any repeaters which may be included in the circuits will also influence the result.

Cross-talk is introduced into a circuit at many points along its length. As the length of a circuit is increased a greater number of points at which unbalance exists are introduced, and so the extent of the cross-talk will depend upon the length of the circuit, being generally greater for long than for shorter ones.

Some of the cross-talk current is dependent upon the voltage of the disturbing circuit, some to the magnitude of the current flowing in the disturbing circuit. The magnitude of the cross-talk current at any point due to an unbalance existing at that point is proportional to that unbalance. As a result of the propagation effects in a telephone circuit, however, similar but non-adjacent couplings will produce cross-talk currents at a circuit terminal which will differ in magnitude and phase, in a manner depending upon the distances between them and also upon the frequency of the source.

The cross-talk current caused by unbalanced electric coupling, flows from the point at which the electrostatic capacity unbalance exists, in opposite directions around the two ends of the disturbed circuit in parallel, whilst the cross-talk current caused by unbalanced magnetic couplings flows from the point of origin around the two ends of the disturbed circuit in series. If cross-talk currents of these two kinds, introduced at the same point, are in phase at one end of the circuit they will not necessarily be in phase at the remote end. Furthermore, since there is attenuation along the line of the current and voltage of the disturbing circuit as well as attenuation of the cross-talk current along the disturbed circuit, the cross-talk in a long line, for this and the previous reason, will generally be different at one end from what it is at the other, as well as being different according to the particular end of the disturbing circuit to which the source is connected.

The attenuation of the lines and of their couplings will vary in a regular manner with frequency, but since as a result of propagation effect there is a change along the disturbing line of the phase of the current and of the voltage, compared with their respective values at the sending end, and similarly for the phase of the cross-talk currents in the disturbed line, the magnitude of such changes with length being dependent upon frequency, it follows that the magnitude of the total cross-talk in a circuit due to the various classes of unbalanced couplings will vary in an irregular manner with the frequency of the interfering source. It is for this reason that the result of a cross-talk test taken at a single frequency is of rather limited value, particularly so far as near-end cross-talk on a long line is concerned. Voice tests are of course the only true criteria, but the results of such tests are liable to considerable variations according to the types of transmitters and receivers employed. Furthermore, their execution entails considerable time, since the mean of a number of different voices is necessary to ensure reliable average results, and such tests are not very conveniently made. Accordingly, in practice, cross-talk tests are made at a number of single frequencies covering the audio range, or alternatively, by means of a complex tone giving results comparable with those obtained from the voice tests. An important practical difficulty arising from the use of speech, or of a complex tone, is the marked difference in tone of the cross-talk and disturbing currents which at times occurs when the cross-talk between two circuits at a particular frequency is very much greater than at any of the other frequencies comprised in the voice or in the complex tone.

In the determination of the cross-talk between two circuits, each should, in the general case, be terminated by its own characteristic impedance. This is particularly necessary for short circuits where open or non-suitably terminated ends may give rise to such voltage or current distribution along the circuit, or to such end reflections as will accentuate the disturbance due to the existing unbalances. There are, of course, occasions when such effects are desired, *e.g.*, when obtaining a measure of the cross-talk in loading sections of cable due to (i) capacity unbalance between the circuits, or (ii) resistance unbalance of a circuit. In the former case the test would be taken with the circuits open, in the latter case the circuits would be short circuited. In the general case, however, such effects must be avoided, and this applies not only to reflections from terminating apparatus but also from the measuring apparatus except the disturbing source at the testing end of the circuit.

Both the method of defining and the measure for expressing cross-talk magnitudes should be of universal application. The desirability of this will be evident not only from the purely scientific point of view, but also from the standpoint of practical convenience, such as the ensuring of results obtained on cables of different line constants being strictly comparable, and also for the purpose of facilitating the setting up of a definite constructional and maintenance cross-talk standard, particularly for those cases of long-distance telephone circuits, the various sections of which are operated and maintained by different Administrations.

Furthermore, in those cases where cross-talk results for the circuits of repeater sections of cable are available, it is of great convenience if the methods of expression are such as to render it easily possible to predict the overall cross-talk on the circuit (see " Cross-talk level," later) after the insertion of the telephonic repeaters. Conversely, with a knowledge of the tolerable overall cross-talk on a repeatered circuit (see minimum cross-talk level, later), it should be possible to determine the greatest allowable cross-talk (see minimum " Cross-talk attenuation," later) and hence the permissible limits for the magnitudes of the unbalanced couplings in the repeater sections of cable.

Cross-talk Attenuation.—The modern definition and mode of quantitative expression of cross-talk were arrived at and recommended for general adoption in June, 1925, by the 3rd Commission of Rapporteurs of the International Long-Distance Telephone Consultative Committee (C.C.I.). Cross-talk was thereby defined in relation to the ratio of the electrical power available at the receiving end of a circuit R to the electrical power input at the sending end of a circuit S and was expressed quantitatively as the coefficient of attenuation of current and/or voltage necessary to produce the same attenuation of power as is represented by this power ratio. This is generally known as, and will be referred to subsequently as the " Cross-talk Attenuation " between two circuits. It is the current or voltage attenuation of the quadripole formed by the sending end of the disturbing line and the receiving end of the disturbed line, the lines being terminated at their other ends by their characteristic impedances.

In accordance with the foregoing, if the powers are P and p for the circuits S and R respectively, expressed say in micro-watts or any other suitable electrical power unit, then the cross-talk attenuation will be represented numerically in either the fractional or the logarithmic (natural) telephone transmission attenuation measures thus:—

(i) N millionths, where.........$N = 10^6 \sqrt{p/P}$.

(ii) B nepers, where

$$B = -\log_e \sqrt{p/P},\ i.e.,\ B = 2.3 \log_{10} \sqrt{P/p}.$$

Expressed as an attenuation of power, cross-talk may be represented numerically in logarithmic (common) measure thus:—

(iii) X decibels, where..............$X = 20 \log_{10} \sqrt{P/p}$.

The following relations between the various telephonic transmission attenuation measures are of frequent use in cross-talk calculations, namely:—

(*a*) $N = 10^6 e^{-B}$, or $B = 2.3\,(6 - \log_{10} N)$.

(*b*) $N = 10^{(6 - X/20)}$, or $X = 20\,(6 - \log_{10} N)$.

Table No. II. gives corresponding current and/or voltage attenuation magnitudes expressed fractionally in millionths and logarithmically in nepers. Fig. 2 expresses these relations in the form of curves. The table has been compiled from equations (*a*) and (*b*) given above. Examination of this table shows that an amount of cross-talk represented by the larger of the numbers expressing cross-talk in millionths is represented by the smaller of the numbers expressing cross-talk in nepers. Thus loud cross-talk represented by 10,000 millionths is equivalent to 4.6 nepers, whereas faint cross-talk represented by 10 millionths is equivalent to 11.5 nepers. Table No. II. also gives corresponding power attenuation magnitudes expressed logarithmically in decibels.

The cross-talk attenuation between any two circuits as just defined, may be written down in terms of the sent current for the disturbing circuit, the received current for the disturbed

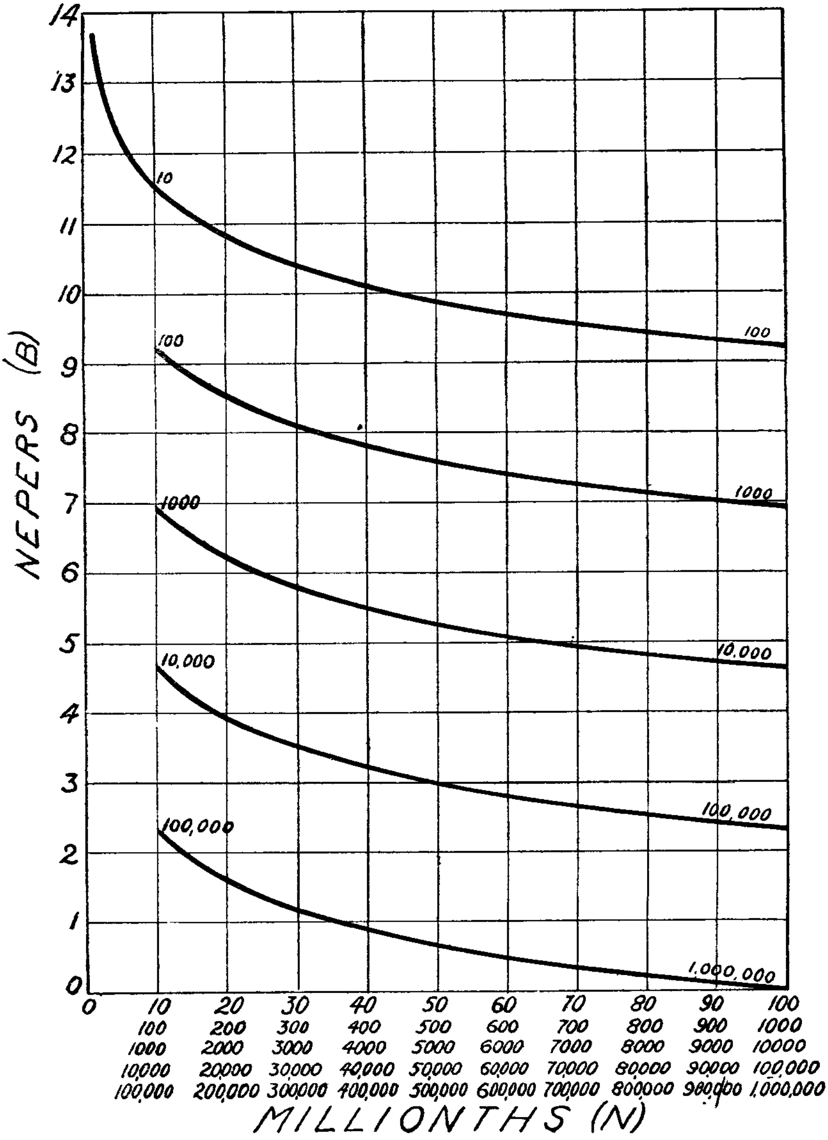
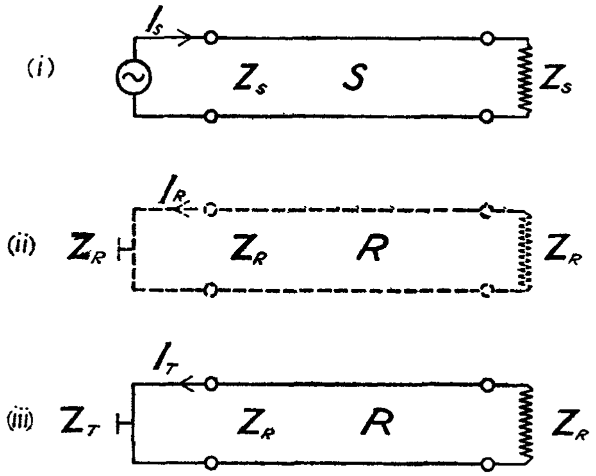


FIG. 2.—RELATION BETWEEN ATTENUATION MAGNITUDES EXPRESSED IN MILLIONTHS AND IN NEPERS.

NOTE.—Multiply current or voltage attenuation expressed in Nepers, by 8.69 to obtain corresponding power attenuations expressed in Decibels.

circuit and the impedance of the circuits and the receiving instrument, thus (see Fig. 2A):—



$$\text{B nepers} = \log_e \frac{I_S}{I_R} + \tfrac{1}{2}\log_e \frac{Z_S}{Z_R}$$

$$\doteqdot \log_e \frac{I_S}{I_T} + \log_e \frac{2Z_R}{Z_R + Z_T} + \tfrac{1}{2}\log_e \frac{Z_S}{Z_R}$$

NOTE:— $\frac{I_R}{I_T} = \frac{Z_R \sinh Pl + Z_T \cosh Pl}{Z_R(\sinh Pl + \cosh Pl)} \doteqdot \frac{Z_R + Z_T}{2Z_R}$, if the lines are of such a length that sinh Pl and cosh Pl have approximately the same value.

FIG. 2A.—CROSS-TALK ATTENUATION IN TERMS OF SENT AND RECEIVED CURRENTS AND THE IMPEDANCES OF THE CIRCUITS AND OF THE RECEIVING INSTRUMENT.

Let the vectors Z_S and Z_R be the characteristic impedances of the disturbing and disturbed circuits, S and R respectively. Let each circuit be terminated by an impedance equal to its own characteristic impedance. Let a generator furnish a current I_S at the sending end of the disturbing circuit and let I_T be the current caused to flow through a telephone, of impedance represented by the vector Z_T, placed across the listening terminals of the disturbed circuit, by reason of the cross-talk couplings between the two circuits. Then:—

Power input to circuit S.................................... = $I_S^2 Z_S$

Power available at listening terminals of circuit R ... = $I_R^2 Z_R$

Now $$\frac{I_R}{I_T} = \frac{Z_R \sinh Pl + Z_T \cosh Pl}{Z_R (\sinh Pl + \cosh Pl)}.$$ (See ii and iii of Fig. 2A).

$$\fallingdotseq \frac{Z_R + Z_T}{2Z_R}$$, if the lines are of such length that sinh Pl and cosh Pl have approximately the same value.

$$e^{-B} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots = \frac{I_T (Z_R + Z_T)}{2I_S Z_R} \sqrt{\frac{Z_R}{Z_S}}$$

Hence cross-talk attenuation B nepers $= \log_e \dfrac{2I_S Z_R}{I_T (Z_R + Z_T)} \sqrt{\dfrac{Z_S}{Z_R}}$

Writing this in the form :—

$$B = \log_e \frac{I_S}{I_T} + \log_e \frac{2Z_R}{2Z_R + Z_T} + \tfrac{1}{2} \log_e \frac{Z_S}{Z_R},$$

the various corrections to be applied to a cross-talk current attenuation measurement, made under unmatched impedance conditions will be evident.

If the telephone impedance is equal to Z_R (as in ii of Fig. 2A) then :—

$$\text{Cross-talk attenuation, B nepers} = \log_e \frac{I_S}{I_R} + \tfrac{1}{2} \log_e \frac{Z_S}{Z_R}$$

Cross-talk level.—The actual amount or volume of cross-talk between two circuits will depend not only upon the cross-talk attenuation between the circuits, but also upon the power available in the disturbing circuit. The magnitude of the cross-talk in a circuit can be expressed in terms of the transmission level of such cross-talk, the prefixing of a negative sign representing, as usual, a level below Reference Transmission Volume. The term " Cross-talk Level " (of the disturbed circuit) will be used subsequently when referring to this quantity. It is the accepted cross-talk criterion for a circuit, since its magnitude in any particular case will determine whether or not the cross-talk disturbance can be heard as intelligible speech. In this connection it should be observed that apparent lack of secrecy of the system, with its adverse psychological effect upon subscribers, will in general occur at a much lower cross-talk level than that at which degradation of the quality (*e.g.*, articulation) of the normally transmitted speech occurs. Symbolically if :—

Transmission level of input to disturbing circuit = + W nepers.
Cross-talk attenuation between the circuits........... = B nepers
Then transmission level of the cross-talk, *i.e.*,
Cross-talk level.......................... = − (B − W) nepers.

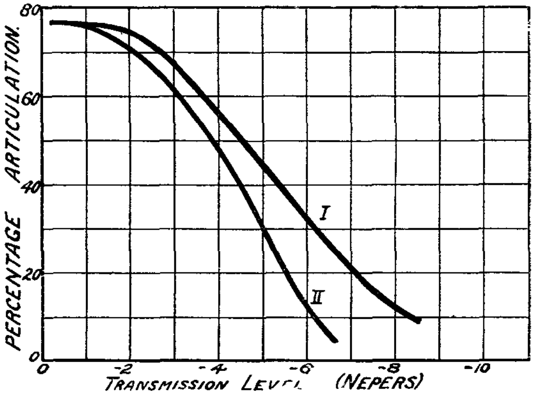


FIG. 3.—DEPENDENCE OF SYLLABIC INTELLIGIBILITY (ARTICULATION) UPON TRANSMISSION LEVEL.

Tests made with Distortionless Line free from Disturbance and with ordinary C.B. Apparatus.

I. Receiver in Silence Cabinet.
II. Receiver subject to ordinary room noise.

From Fig. 3, which has been copied from an article quoted in reference (49), it is seen that speech at a level of about −7 nepers is quite unintelligible, from which it follows that the cross-talk level on a circuit should not be higher than −7 nepers. The C.C.I. recommend a minimum value of −7.5 nepers, hence the following condition may be written down, namely :—

$$(B - W) = \text{or} > 7.5.$$

The interpretation of the above general equation for particular cases will be dealt with later. It will be shown that the minimum permissible cross-talk attenuation between the various circuits in a cable depends upon the types of circuit concerned. Thus the use of amplifiers on some circuits by raising their transmission level above that of other circuits (*e.g.*, the limits of level for two-wire circuits are +0.6 to −1.6; for four-wire circuits +1.1 to −3.0) makes it necessary to provide for a much higher cross-talk attenuation per repeater section, than would otherwise be adequate.

Near-end and Distant-end Cross-talk.—The cross-talk in a long line will depend upon the terminal for which the cross-talk is considered. By this is meant the terminal or particular end of the disturbing circuit to which the source of disturbing power energy is connected. Furthermore, cross-talk considered for a particular terminal will generally be different according to which terminal is selected for listening purposes. Cross-talk obtained by listening at that terminal adjacent the source is termed near-end cross-talk. Cross-talk obtained by listening at that terminal remote from the source is termed distant-end cross-talk. Obviously four cross-talk values may be determined for a circuit, namely, near- and distant-end cross-talk considered for one circuit terminal and near- and distant-end cross-talk considered for the other circuit terminal. For two circuits S and R each having terminals X and Y, the four cross-talk values for the circuit R from the circuit S, are defined in table No. III.

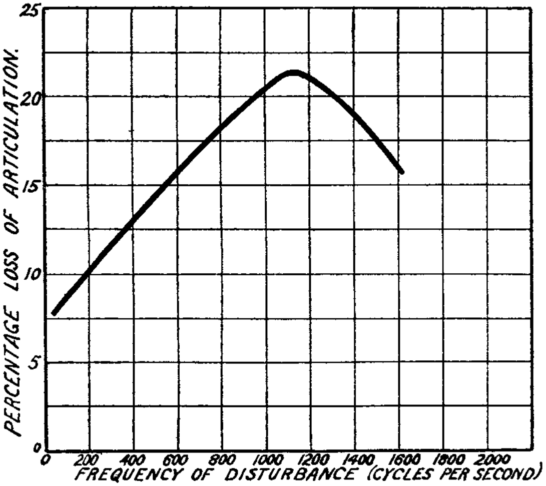


FIG. 4.—DEPENDENCE OF ARTICULATION UPON FREQUENCY OF DISTURBING CURRENT.

(Constant Disturbance of one *m*V on Receiver).

(VI). NOISE IN TELEPHONE CABLE CIRCUITS.

General.—The effect of noise upon a circuit is to degrade the articulation of the individual speech sounds normally transmitted over the circuit.

Recent work, see references (25) and (28), has shown that the percentage loss of articulation on a circuit due to the disturbing effect of currents of single—or multi—frequency, depends (for articulation losses up to 60%) upon the voltage and frequency of the disturbance and upon the transmission level of the received speech. The dependence of articulation upon frequency of the disturbing current is given (25) in Fig. 4 for a line (of 3 nepers attenuation, with Standard C.B. terminals and 300 ohm local line) subject to one millivolt disturbance across the receiver terminals. This curve shows that the percentage loss of articulation increases practically uniformly with frequency from a value of 7.8 at 50 cycles to 21.8 at 1150 cycles (the resonant frequency of the receiver in this case was 1150 cycles), after which it decreases fairly steadily to a value of 16.2 at 1600 cycles.

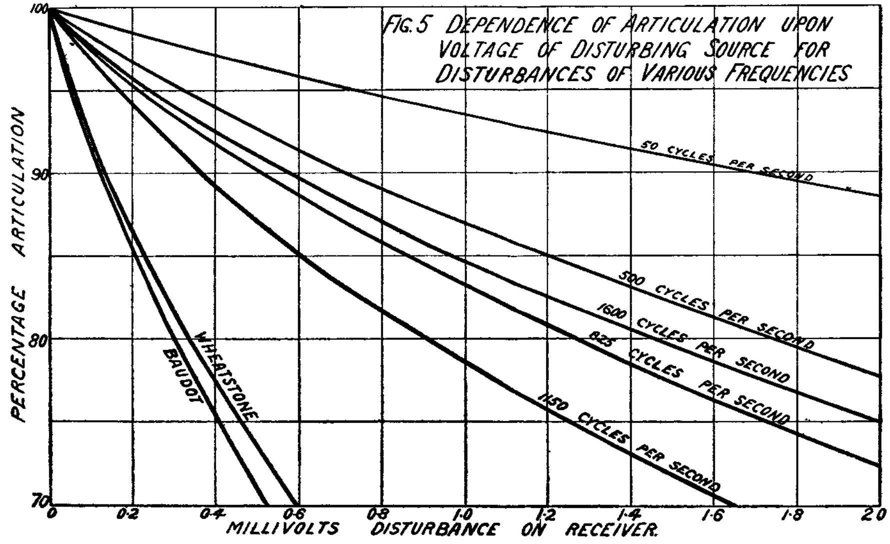


FIG. 5 DEPENDENCE OF ARTICULATION UPON VOLTAGE OF DISTURBING SOURCE FOR DISTURBANCES OF VARIOUS FREQUENCIES

For a given disturbing voltage, Wheatstone and Baudot (working at 100 words per minute) telegraphic disturbances have a much greater interfering effect than any single frequency. For the circuit referred to above, the percentage loss of articulation for one millivolt (across the receiver terminals) of such disturbances is 43.5 and 47 respectively.

The percentage loss of articulation (100 – A) for any partcular frequency can be expressed in terms of the disturbing voltage (V millivolts) across the terminals of a standard C.B. receiver as follows :—

$$(100 - A) = kV^{0 \cdot 6}$$

where k is a constant for any particular frequency or type of telegraphic (or power circuit) induction. It will be seen that k is numerically equal to the percentage loss of articulation, at that frequency, for one millivolt disturbance. Each of the curves of Fig. 5 gives (25) a plot of the above equation for the circuit referred to above, for a particular frequency disturbing source.

There is a definite relation between the percentage articulation and the percentage general intelligibility on a circuit subject to noise, such relation being independent of the type of disturbance, *e.g.*, whether from a single-frequency source, or complex as in the case of speech babble, telegraphic induction, tramway or other forms of power induction. Fig. 6 gives (25) this relation in graphical form.

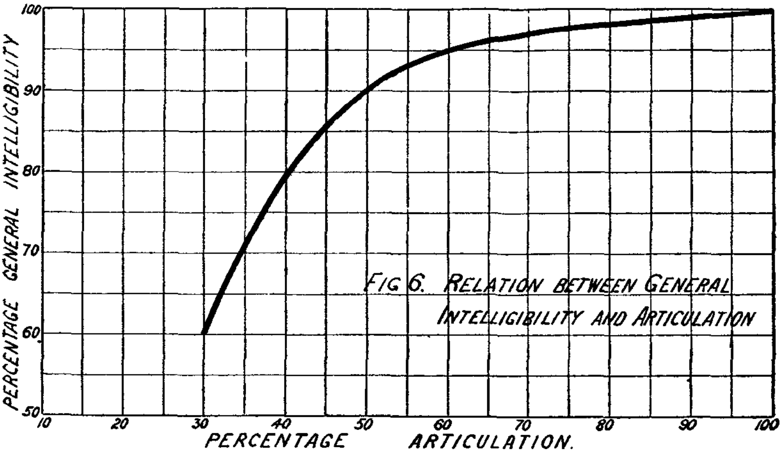


FIG 6. RELATION BETWEEN GENERAL INTELLIGIBILITY AND ARTICULATION

Noise voltage.—Noise on a telephone circuit is most rationally expressed in reference to the loss of articulation which it produces. Since, however, the determination of such loss, except in a laboratory, presents many difficulties, and the interpretation of the results obtained are frequently quite personal and therefore generally unsatisfactory, noise on a circuit is best expressed in terms of the voltage across its conductors which produces it.

The difference between the electromotive forces induced in the associated limbs of a circuit by a disturbing source is known as the " Noise voltage " on the circuit; it can be related to articulation loss in any particular case by means of the foregoing data. Table No. IV. gives the magnitude of the voltage (across the line terminals of the particular circuit previously referred to) of disturbing sources of various frequency, necessary to produce articulation losses of 5, 10 and 12.5 per cent. respectively. The table has been prepared from Fig. 5 on the assumption that the line voltage is five times the voltage across the telephone receiver. The corresponding noise voltages may be readily calculated from a knowledge of the electrical features of the circuit.

The maximum permissible reduction of articulation due to noise on an International circuit has not yet been definitely fixed by the C.C.I., but a provisional figure of 5%, corresponding to a reduction of general intelligibility of 1%, has been suggested.

Noise level/speech level difference.—If the transmission level of normally received speech on a circuit is $-U$ nepers in accordance with the usual definition and if $-Y$ nepers is the level of the disturbing noise, then $(Y-U)$ nepers is the difference between the noise and speech levels of the disturbed circuit. This difference has been used to express the interfering effect of noise for the purpose of arriving at a value for the maximum permissible noise voltage on a telephone circuit. It may be referred to as the " Noise level/speech level difference " for the circuit. Experience shows that if this quantity has a value equal to or greater than 2.5 nepers, then the interfering effect of the noise is essentially nil (48). On this basis the permissible noise voltage may be calculated. Thus for a circuit of overall (subscriber to subscriber) attenuation equal to 3.3 nepers (see C.C.I. recommendations, reference (30)), on the assumption that the average outgoing speech voltage is 1 volt, the disturbing voltage across the receiving instrument should not exceed 3 millivolts. This will correspond generally to a noise voltage of 6 millivolts.

In passing, it should be observed that the necessity for ensuring that the magnitude of the noise level/speech level difference does not fall below the above-mentioned value of 2.5 nepers is particularly important in repeatered circuits. Speech currents if allowed to attenuate to such a point that the noise currents constitute an unduly large proportion of the total line current will be indistinguishable from noise on the output side of the repeater. The maintenance of the voice level above a certain value, say -1.6 nepers for two-wire circuits and -3 nepers for four-wire circuits [as per C.C.I. recommendations (30)], at all points in the system, by correct location of the repeaters and the amount of their gain, will generally secure the desired result.

Power circuit interference.—Disturbances to telephone circuits from power systems are generally caused by the higher harmonics of the fundamental frequency of the interfering currents and voltages. Power installations employing earthed returns, either wholly or partially, or earthed neutral points, are particularly troublesome from the interference point of view. High-tension systems give rise in general to electric induction effects, heavy-current systems to magnetically induced disturbances.

By careful design (47) of the power plant in ensuring that currents of undesirable frequency, wave-form and amplitude are not transmitted—and this applies to nominal direct current as well as to alternating current systems—and by suitable lay-out in regard to proximity and length of exposure as well as by equalisation of the load on the phases in polyphase systems, much can be done by way of preventing the currents flowing in the power system from exerting a disturbing effect upon communication lines.

Little general disturbance to the telephone system from power systems has occurred in this country to-date, the telephone cable network particularly, being as yet, practically immune. Recent and proposed extensions of the electrical power system are however likely to give importance to this question in the near future. A considerable amount of work has been done on the subject of power circuit interference in America and in Germany. An International Committee (C.M.I.) is at present engaged in formulating rules for the control of power circuit interference. For an extensive bibliography relating to this subject see reference (26).

Telephone cable circuits located in the neighbourhood of power systems are in general much less liable to interference than overhead circuits. Cable circuits contained in efficiently earthed sheaths are essentially free from electric induction effects. Furthermore, for armoured telephone cables laid directly in the ground, by suitable design of the sheathing and armouring, magnetic induction effects upon the cable circuits (especially from currents of low frequency but also from the upper harmonics if special forms of construction are adopted) can be considerably minimised by reason of the counter inductive effect of sheath currents. Such neutralising effect increases as the self induction of the sheath and armouring increases and its resistance decreases (27). Nevertheless considerable magnetically induced disturbance from the upper harmonics of the source is at times experienced in those cases where telephone cables are run alongside earthed, heavy-current systems, such as for example electrically operated railways.

Degree of electrical balance of the circuits of a telephone cable for interference immunity from external power circuit interference.—The alternating magnetic field produced by the power system induces an electro-motive force in each of the cable conductors. This E.M.F. gives rise to a potential difference to the sheath upon each of the wires of the cable, the value of such P.D. to sheath for any particular conductor being dependent upon the magnitude of its impedance to sheath, under the existent conditions. The interfering voltage in the circuit is the P.D. between the conductors, the magnitude of which will be equal to the difference between their P.D.'s to the sheath.

Considering the case of a cable containing a single four-wire core, if at all cross-sections along the length of the cable and for each circuit separately the two limbs of such circuit have :—

(i) The same impedance to the sheath and (ii) the same propagation constant, and if (iii) the two limbs being at the same average distance from the disturbing source, the E.M.F. induced in each is the same, then at all cross-sections the P.D. to earth of the limbs will be equal, and there will accordingly be no P.D. between the limbs and therefore no disturbance to the circuit. Since, as already explained, the conductor resistance, dielectric leakance and the inductance of the associated wires of telephone cable circuits are essentially equal to each other, then (i) and (ii) will be satisfied if the direct electric capacity of each limb to the cable sheath has the same magnitude. The capacity to earth interference characteristics in this case will accordingly be u, v and f. [See Section (iv)].

In the case of a multi-core cable containing a circuit which is completely enveloped by an insulated metallic screen, an E.M.F. will be set up in the screen by induction from the disturbing source, as well as in each of the conductors beneath it. On the assumption that the wires are at the same average distance from the disturbing source, if the direct capacities to the screen of the associated wires of such a circuit are equal to each other, then the P.D. between such wires will be zero.

Referring to the non-screened cores, E.M.F's are set up in the wires of all such cores. The resulting P.D. to sheath (so far as current of the disturbing frequency is concerned) of a wire of any particular circuit will be dependent upon the resulting P.D.'s to sheath of the various other wires of the cable, since the existence of such potentials will affect the magnitude of the impedance to sheath of the wire in question. In the case of cables in which cross-jointing of the cores is general over the whole cable cross-section, the impedances to sheath (under the existent conditions of potential of all the cable conductors) of the wires of each core will, except for their unbalances, be of the same magnitude. Similarly for their P.D.'s to sheath; the disturbing P.D. in any particular circuit being equal to the unbalance of P.D. resulting from its impedance unbalance. For cable cores grouped and cross-jointed in layers the P.D. to sheath of all the wires of the outer layer will be essentially the same, and will depend upon their impedance to sheath. The unbalance of such impedance will give rise to a disturbing P.D. in each circuit of the layer. The P.D. to the outer layer of all the wires of the next inner layer will also be essentially the same, and will depend upon their impedance to such layer. The unbalance of such impedances will give rise to a disturbing P.D. in each circuit of the layer. Similarly for the other inner layers. The total disturbing P.D. in any particular circuit will of course depend upon its unbalances to the layer (or sheath) above, and to the layer below.

The unbalances giving rise to noise P.D's, referred to above, are difficult to express in terms of the capacity system of a multi-core cable, and expressions analagous to those of Section (VII) are not available. The main difficulty lies in the fact that unlike the cross-talk case, the whole of the cores in any particular layer, being at essentially the same potential, contribute no capacity unbalance to any core in the same layer. A recent Patent (14) deals with this effect by specifying certain capacity interference characteristics of a cable pair to the layer of conductors (or to the sheath) above, and to the layer of conductors below. The Patent does not disclose a systematic method of handling such characteristics when applied to the elimination of power circuit interference in a multi-core cable.

Noise ratio.—In order to obviate the complexities of dealing in detail with unbalances relevant to noise, the use of a quantity called " Noise ratio " as a measure of the balance of a cable from the noise point of view has been suggested (50).

The noise ratio of a circuit may be defined as the ratio of the voltage induced to earth at the end of the circuit and the voltage produced in the metallic circuit. This ratio may be expressed logarithmically in nepers. If measured as near-end noise ratio, with tone applied only to the layer under test, the results obtained are approximately constant for different lengths of cable, and since they are affected only by those unbalances which produce noise in practice they can be utilised as criteria of the noise balance of cable circuits. As in the case of cross-talk attenuation, noise ratio varies in an irregular manner with the frequency of the disturbing source. Measurements should therefore be made with a complex tone, or alternatively noise ratio/frequency characteristics should be determined.

(VII). INTERFERENCE CHARACTERISTICS.

Impedance Interference Characteristics. — The interference between any two circuits may be eliminated by means of a suitable impedance placed at one of the terminals, and connecting one wire of one circuit and one wire of the other circuit (29). In general an impedance network will be necessary for the purpose, the frequency response of which, over the frequency range of the disturbing current, will require to vary in an irregular manner. Furthermore the impedance network suitable for near-end cross-talk elimination will be different from that for distant-end cross-talk purposes, and each will depend upon the particular terminal for which the cross-talk is considered. In the case of side-to-phantom cross-talk, elimination may be alternatively effected by a suitable impedance network placed between one wire of the side circuit and earth. Fig. 7 gives particulars of an impedance network, together with a curve showing its frequency response over a frequency range of 300 to 1750 cycles per second. This net-

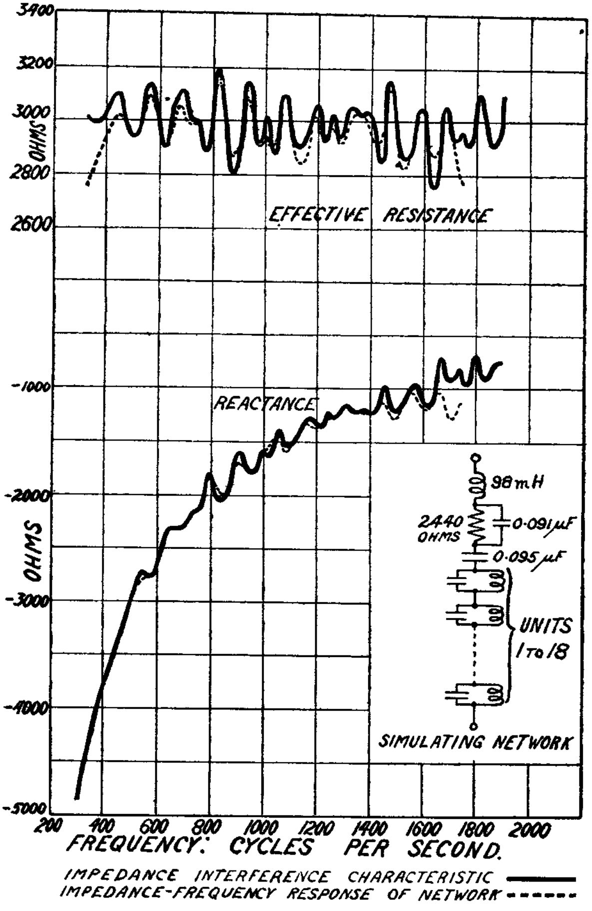


FIG. 7.—SIMULATION OF IMPEDANCE INTERFERENCE CHARACTERISTIC BY MEANS OF AN IMPEDANCE NETWORK.

work when connected between one wire of one core and one wire of another core was used to reduce the cross-talk between the phantom circuits formed on each core.

In the case of short lengths of cable, instead of a complicated impedance network, simple capacities, resistances or mutual inductances only will be required for cross-talk elimination purposes, as already explained in the paragraph dealing with the Auxiliary Apparatus method of cable balancing.

Capacity Interference Characteristics. — In Pupinised cables, electric capacity unbalance has a preponderating effect upon the total disturbance resulting from the combined effects of all the different classes of electrical unbalance. The extent of the electrostatic interference between any two circuits of a multi-core cable can be related to their wire-to-wire and wire-to-earth capacity unbalances by means of an expression known as a wire-to-wire "Capacity Interference Characteristic" (16). In any particular case this characteristic represents the magnitude of a single capacity, which, when placed between one wire of one circuit and one wire of the other circuit, produces immunity from electric interference between the two circuits in question. A capacity placed between one wire of one circuit and earth, in order to produce the same result, is known as a wire-to-earth capacity interference characteristic. In the following paragraphs wire-to-wire characteristics will be implied, except in those cases where a definite statement is made to the contrary.

In the C.C.I. specifications certain quantities defined in a similar manner to the interference characteristics quoted above are referred to as capacity unbalances.

An interference characteristic, unlike a capacity unbalance (under definite potential conditions for the other cable cores), is not an invariable quantity for two circuits, since the magnitude of the characteristic in any particular case will in general be dependent upon which wires of the circuits in question are chosen for connection to the single capacity referred to above. For within-core interference characteristics, however, the discrepancy thereby introduced will be relatively unimportant, not exceeding 1% of the measured value for a core in a factory length of cable (176 yards), or 0.1% of the measured value for a 2000 yard loading section of cable. For between-core interference characteristics the percentage discrepancy may be much larger.

The values (approximate in some instances) of the capacity interference characteristics for certain cases may be written down in terms of the capacity unbalances. The earthed side circuits referred to below represent the condition of a normal speaking circuit during signalling operations, whereby one limb of the circuit (in some signalling systems) is earth connected.

(1) For side-to-side (within the same core) interference:—
(i) ...... $(p - q)$ or $(r - s)$

(2) For side-to-phantom (within the same core) interference:
(i) ...... $(p + q) + \delta_1 u$ .... (for AB side circuit)
(ii) ...... $(r + s) + \delta_1 v$ .... (for CD side circuit)

where $\delta_1 \fallingdotseq (c + d)/(a + b + c + d) \fallingdotseq (a + b)/(a + b + c + d)$, and has a value of approximately 0.5 for any type of four-wire core.

(3) For side to earthed-side (within the same core) interference:—
(i) ...... $p - \delta_2 (q + u)$ .... (for AB side to CD side with D wire earthed)
(ii) ...... $q - \delta_2 (p + u)$ .... (for AB side to CD side with C wire earthed)
(iii) ...... $r - \delta_2 (s + v)$ .... (for CD side to AB side with B wire earthed)
(iv) ...... $s - \delta_2 (r + v)$ .... (for CD side to AB side with A wire earthed)

where $\delta_2 \div w/(z + a) \div z/(w + a) \div w/(x + c) \div x/(w + c)$, etc., and has a value of about 0.16 for a M.T type and about 0.30 for a quad type core.

The magnitude of the characteristics quoted above can be determined by a direct capacity measurement. A check of the accuracy of the four measurements made upon a core for the determination of side to earthed-side characteristics is afforded by the circumstance that the difference between (i) and (ii), or between (iii) and (iv), is very nearly equal to $(1 + \delta_2)$ times the side-to-side interference characteristic $(p - q)$ of the core.

If Ke is the capacity to earth required to be connected to one wire (say A) of a side circuit (say AB) in order to neutralise the interference from the other side circuit (say CD) of the same core, one wire (say D) of which is earthed, it can be shown that $K = \delta_2 Ke$, where K is the capacity required to be connected between B and C to produce the same effect, *i.e.*, where K and Ke are the side (AB) to earthed-side (CD with D earthed) wire-to-wire, and wire-to-earth interference characteristics respectively of the core.

By using for the capacity network between any two circuits of a multi-core cable—the remaining conductors of the cable assumed disconnected from each other and from the lead sheath—an analogous nomenclature (but written in capitals) to that employed for the capacity network within a core, the values of the capacity unbalances and of the interference characteristics for such circuits may be written down. The interference characteristics in certain cases are as follows:—

(4) For pair-to-pair (in different cores) interference:—
(i) ...... $(P - Q)$ or $(R - S)$.

(5) For pair-to-phantom (in different cores) interference:—
(i) ...... $(P' - Q')$ or $(R' - S')$.

(6) For phantom-to-phantom (in different cores) interference:
(i) ...... $(P'' - Q'')$ or $(R'' - S'')$.

(7) For pair to earthed-pair (in different cores) interference:
(i) ...... $P - \delta_3 (Q + U)$
(ii) ...... $Q - \delta_3 (P + U)$
(iii) ...... $R - \delta_3 (S + V)$
(iv) ...... $S - \delta_3 (R + V)$

where $\delta_3 \doteqdot W/(Z + A) \doteqdot Z/(W + A) \doteqdot W/(X + C)$, etc., and has a value of the order of 0.06 for M.T. and quad type cores.

As before, the magnitude of each of the characteristics quoted above can be determined by a direct capacity measurement. A check of the accuracy of the four measurements made for the determination of pair to earthed-pair (in different cores) characteristics is afforded by the circumstance that the difference between (i) and (ii), or between (iii) and (iv), is very nearly equal to $(1 + \delta_3)$ times the interference characteristic $(P - Q)$ of the two pairs in question.

If K*e* is the capacity to earth required to be connected to one wire (say A) of a pair (say AB) in order to neutralise the interference from another pair (say A^1B^1), one wire (say B^1) of which is earthed, it can be shown that $K = \delta_3 Ke$, where K is the capacity required to be connected between B and A^1 to produce the same effect, *i.e.*, where K and K*e* are the pair (AB) to earthed-pair (A^1B^1 with B^1 earthed) wire-to-wire and wire-to-earth interference characteristics respectively of the two pairs.

In further reference to the foregoing, it is observed that each of the characteristics enumerated under (7) involves a quantity, U or V, which is practically the same as the quantity known as the "Resultant earth capacity unbalance" of

either pair of a two-pair core. Thus for any two-pair core :—
(8) The resultant earth capacity unbalances of the pairs are :—

$$\text{(i)} \ldots\ldots\ u + \delta_4 (p + q)$$
$$\text{(ii)} \ldots\ldots\ v + \delta_4 (r + s)$$

where $\delta_4 \fallingdotseq [c(z+y+d)+n(c+d)] \;/\; [(w+x+n+c)(z+y+n+d) - n^2]$,

$$\fallingdotseq [d(w+x+c)+n(c+d)] \;/\; [w+x+n+c)(z+y+n+d) - n^2],$$
$$\fallingdotseq [a(x+y+b)+m(a+b)] \;/\; [(w+z+m+a)(x+y+m+b) - m^2],$$
$$\fallingdotseq [b(w+z+a)+m(a+b)] \;/\; [w+z+m+a)(x+y+m+b) - m^2],$$

$\div\ c/(z+y+d) \div a/(x+y+b) \div$ etc., and has a value of about 0.72 for a M.T. type core and about 0.53 for a quad type core.

Representative values of each of the above-mentioned capacity interference characteristics for 176 yard factory lengths of modern multiple twin and star quad cables are given in table No. V.

Degree of capacity balance for immunity from electrostatic interference between the working circuits of a telephone cable.—Perfect capacity balance of a four-wire core is represented by the equations :—

(9) $\text{(i)} \ldots\ldots\ w = x = y = z$
$\text{(ii)} \ldots\ldots\ a = b = c = d$

which are equivalent to :—

(10) $\text{(i)} \ldots\ldots\ (p - q) = 0$
$\text{(ii)} \ldots\ldots\ (p + q) = 0$
$\text{(iii)} \ldots\ldots\ (r + s) = 0$
$\text{(iv)} \ldots\ldots\ u = 0$
$\text{(v)} \ldots\ldots\ v = 0$
$\text{(vi)} \ldots\ldots\ f = 0$

With a perfectly balanced core, each of the capacity interference characteristics numbered (1) to (3) would have zero value and such a core would accordingly be free from all of the within-core interferences so far considered.

For many of the methods adopted in practice of working a multi-core cable, a degree of balance falling short of the perfect is however sufficient to ensure immunity from electrostatic interference between the circuits. Thus :—

(11) For the working of pair circuits only, it is sufficient if :—

(i) ...... $(p - q) = 0$ .... within each core.
(ii) ...... $(P - Q) = 0$ .... between different cores.

In such a case the within-core requirements would be ensured by capacity balancing each core to the degree represented by (i), whilst the between-core requirement would be approximately ensured by appropriate design and manufacture, together with either special core-to-core balancing or (15) systematic core separation, or by the core separation resulting from the balancing operations involved in (i).

(12) For pair and phantom circuit working, additional degrees of within- and between-core balance, as represented by the conditions stated below, are necessary thus :—

$$\left.\begin{array}{ll} \text{(i)} \ldots\ldots (p - q) \ldots\ldots\ldots & = 0 \\ \text{(ii)} \ldots\ldots (p + q) + \delta_1 u & = 0 \\ \text{(iii)} \ldots\ldots (r + s) + \delta_1 v & = 0 \end{array}\right\} \text{ within each core.}$$

$$\left.\begin{array}{ll} \text{(iv)} \ldots\ldots (P - Q) \ldots\ldots & = 0 \\ \text{(v)} \ldots\ldots (P' - Q') \ldots\ldots & = 0 \\ \text{(vi)} \ldots\ldots (P'' - Q'') \ldots\ldots & = 0 \end{array}\right\} \text{ between different cores.}$$

In such a case the within-core requirements would be ensured by capacity balancing each core to the degree represented by (i), (ii) and (iii), whilst the between-core requirements would be secured in a manner similar to that for (11).

In connection with the within-core requirements of this case it will be obvious that (ii) and (iii) may be satisfied with quite large values of $(p + q)$ and u, and $(r + s)$ and v respectively, provided $(p + q)$ and $\delta_1 u$ and also $(r + s)$ and $\delta_1 v$ are of opposite sign and of equal magnitude, *i.e.*, immunity from side-to-phantom (within core) interference may be secured by compensating wire-to-wire unbalances by wire-to-earth unbalances. This process is, however, objectionable, since the exact prediction of the residual interference characteristics referred to in (2) for two cable lengths jointed together in any particular manner is not possible if the characteristics are very unsymmetrical in respect of their earth components—the arithmetic sum of two such mutual capacities being different from the resultant mutual capacity of the two mutual capacities connected in parallel. Furthermore, a cable in which such compensation has been made will in general be imperfectly balanced in respect of its separate wire-to-wire and wire-to-earth capacity components. In order to avoid these objections it is the practice of the

British Post Office when balancing cables required for pair and phantom circuit working to comply as far as possible not only with equations (i) to (vi), but also with the equations :—

$$\left.\begin{array}{ll}\text{(vii)} \ldots\ldots & u = 0 \\ \text{(viii)} \ldots\ldots & v = 0\end{array}\right\} \text{ within each core.}$$

It will be seen from the next paragraph that such a degree of balance is desirable in order to ensure immunity from earthed-pair interference.

(13) For pair and earthed-pair working, a greater degree of within-core balance than is required for (12), as well as a greater degree of between-core balance than is required for (11), is necessary. The degree of balance required is represented by the conditions stated below, thus :—

$$\left.\begin{array}{lll}\text{(i)} \ldots\ldots & (p - q) & = 0 \\ \text{(ii)} \ldots\ldots & (p + q) & = 0 \\ \text{(iii)} \ldots\ldots & (r + s) & = 0 \\ \text{(iv)} \ldots\ldots & u & = 0 \\ \text{(v)} \ldots\ldots & v & = 0\end{array}\right\} \text{ within each core.}$$

$$\text{(vi)} \ldots\ldots \ P, Q, R, S, = 0 \text{ between cores.}$$

In such a case the within-core requirements would be ensured by capacity balancing each core to the degree represented by (i), (ii), (iii), (iv) and (v), whilst the between-core requirement would be approximated to in the same manner as for (11). It will be observed that the degree of within-core balance required in this case is little short of perfect. A cable of modern design and manufacture, field balanced within-core to this degree could accordingly be used in addition for phantom working, since the order of the balance is the same as would be achieved by compliance with equations (i), (ii), (iii), (vii) and (viii) of (12).

The degree of electrical balance of the circuits of a telephone cable for interference immunity from external power circuit interference is dealt with in Section (VI).

Representative values of each of the previously mentioned capacity interference characteristics for loading sections of modern multiple twin and star quad cables, which have been capacity balanced to various degrees, are given in table No. VI.

(VIII). PREDICTION OF CROSS-TALK RESULTS.

General.—When considering the effects of special couplings or of telephonic repeaters, it is sometimes necessary, for the purpose of predicting the limiting values of cross-talk attenuation arising between two circuits, to have recourse to a method of cross-talk calculation. Such a method, which has been found to give results substantially in agreement with subsequent direct measurements, will now be described. The effects of reflection at points at which changes of impedance occur are neglected. The method is approximate and has not the same order of precision as that obtained, for example, in ordinary telephonic transmission calculations. It has, however, a rational basis, and gives sufficiently exact results to warrant its application in practice to all cases where a more rigid mathematical analysis would be unjustified, not only by reason of complexity, but also because in the practical application and interpretation of any cross-talk attenuation determination, due account must be taken of the somewhat divergent views respecting the permissible minimum cross-talk level.

The method (31) will now be illustrated in reference to its application to a number of typical cases:—

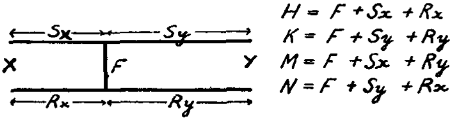


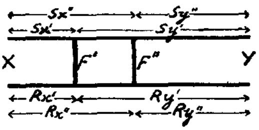
FIG. 8.—SINGLE COUPLING BETWEEN TWO NON-REPEATERED CIRCUITS.

Case of a single coupling between two non-repeatered circuits. Fig. 8.—Consider two circuits S and R, which are coupled together at one point only; S being the disturbing circuit and R the disturbed circuit. Let the point be situated at a distance x from the X terminals of the circuits and y from their Y terminals. Let the attenuations of the two portions of the S line be Sx and Sy nepers respectively and of the two portions of the R line, Rx and Ry nepers respectively. Let the extent of the coupling be such that there is an attenuation equivalent to F nepers across it. Then the magnitude of the near-end cross-talk attenuation, X being the listening terminal of circuit R, will be represented by (F + Sx + Rx) nepers.

Near-end cross-talk, listening at the Y terminal of circuit R, as well as distant-end cross-talk, considered for each terminal, can be similarly computed. The results are given in table No. VII.

Consideration of the results shown on table No. VII. that the minimum cross-talk attenuation is F nepers. This occurs in the case of near-end cross-talk, when the coupling is situated at that end of the circuits for which the cross-talk is considered. When the coupling is at the centre of the circuits, near- and distant-end cross-talk attenuation, considered for the same or for opposite terminals, are of the same value. When the circuits have exactly the same attenuation, the distant-end cross-talk attenuation has the same value for each terminal and is independent of the position of the coupling.

Case of two couplings between two non-repeatered circuits. Fig. 9.—Let S and R be the two circuits as before, F′ and F″ nepers the extent of the couplings situated x' and x'' respectively from the X terminal of the circuits and y' and y'' respectively from the Y terminal, whilst Sx', Sx'', Sy'. Sy'', Rx', Rx'', Ry' and Ry'' nepers are the respective attenuations of the several portions of the circuits. Let the quantities H′, K′,.........H″, K″,...... etc., have an exactly similar meaning to that of the quantities H, K......etc., of the table No. VII.



$$H' = F' + Sx' + Rx'$$
$$K' = F' + Sy' + Ry'$$
$$M' = F' + Sx' + Ry'$$
$$N' = F' + Sy' + Rx'$$
$$H'' = F'' + Sx'' + Rx''$$
$$K'' = F'' + Sy'' + Ry''$$
$$M'' = F'' + Sx'' + Ry''$$
$$N'' = F'' + Sy'' + Rx''$$

FIG. 9.—TWO COUPLINGS BETWEEN TWO NON-REPEATERED CIRCUITS.

For the purposes of addition or subtraction, in computing the resultant value, it will be convenient to express the separate cross-talk attenuations fractionally, *e.g.*, by converting from nepers to millionths. If the final result is required to be expressed logarithmically, *e.g.*, in nepers, reconversion from millionths can readily be effected. Table No. VIII. gives the limiting values (*i.e.*, minimum and maximum) of the cross-talk attenuation.

The minimum cross-talk attenuation obviously occurs when the cross-talk currents, in any particular case, are in phase at the listening terminal. Consideration of the above results will make this clear, since in these circumstances the terms in each of the above expressions are additive.

Case of a single coupling between two repeatered circuits, such coupling being situated at the Repeater Station. Fig. 10.—With similar notation to that employed heretofore for the two circuits S and R, with the repeaters located at the centre of each circuit and reckoning the repeater gain in each circuit to be G nepers, the various values of the cross-talk attenuation are given in table No. IX. Since the coupling may be situated either on one side or the other of the repeater, each position of the coupling has been considered, and results given in accordance therewith.

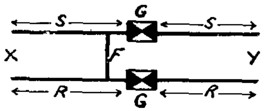


FIG. 10.—SINGLE COUPLING BETWEEN TWO REPEATERED CIRCUITS.

Consideration of the above results shows that the near-end cross-talk attenuation considered for one circuit terminal is less than when considered for the other circuit terminal if the position of the coupling is on that side of the repeater remote from the terminal for which the cross-talk is considered. Distant-end cross-talk has the same value considered for either circuit terminal and is unaffected by the position of the coupling.

When the circuits have the same attenuation (b) then :—

(i) The minimum value of cross-talk attenuation is $(F + b - 2G)$ and occurs in the case of near-end cross-talk considered for either circuit terminal, when the coupling is on that side of the repeater remote from the terminal for which the cross-talk is considered. Writing the expression for the attenuation in the form $[F + (b - G) - G]$ and regarding the value of $(b - G)$, which is the residual attenuation of the circuit, as fixed in value (say, 1.0 neper), it will be seen how the cross-talk attenuation in this case depends upon the repeater gain.

(ii) The maximum value of cross-talk attenuation is (F + *b*) and occurs in the case of near-end cross-talk considered for either terminal, when the coupling is on the same side of the repeater as the terminal for which the cross-talk is considered.

(iii) The intermediate value of cross-talk attenuation is [F + (*b* − G)] and occurs in the case of distant-end cross-talk; it has the same value considered for either terminal and for either position of the coupling.

Case of two couplings between two repeatered circuits, such couplings being situated at the repeater station, one on either side of the repeaters. Fig. 11.—With similar notation to that employed heretofore for the two circuits S and R, with the repeaters, each of gain G nepers, located at the centre of each circuit and with the coupling on the X side of the repeater represented by F*x* and that on the Y side by F*y*, the limiting values (*i.e.*, minimum and maximum) of the cross-talk attenuation are given in table No. X.

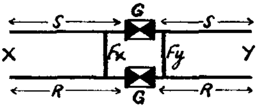


FIG. 11.—TWO COUPLINGS BETWEEN TWO REPEATERED CIRCUITS.

The cross-talk attenuation is a minimum when the cross-talk currents due to the two couplings are additive.

From the above results it is seen that since $e^{-(Fy - 2G)}$ and $e^{-(Fx - 2G)}$ will generally be much greater than e^{-Fx} and e^{-Fy} respectively (each of these quantities is less than unity) most of the near-end cross-talk considered for one circuit terminal will be due to the coupling on that side of the repeater station remote from that terminal, the cross-talk from the other coupling diminishing or increasing the value of the resultant cross-talk attenuation due to both.

Near-end cross-talk attenuation will be increased if the repeater gains are reduced, since in these circumstances the expression inside each of the square brackets is decreased. Distant-end cross-talk attenuation in such a case will also be increased by the amount of reduction of repeater gain. Where normal repeater gains and lengths of cable are concerned, distant-end cross-talk attenuation will never be less than the near-end value. For equal values of the two couplings, the minimum and maximum limits will be wide in the case of distant-end and narrow for near-end cross-talk attenuation. Thus if $Fx = Fy = F$, then for distant-end cross-talk the limits will be ∞ to $(F + S + R - G - 0.69)$, whilst for near-end cross-talk they will be :—

$$[F+S+R-2.3 \log_{10} (e^{2G}-1)] \text{ to } [F+S+R-2.3 \log_{10} (e^{2G}+1)]$$

Near-end cross-talk in circuit R with circuit S as the disturbing source will be the same as that in circuit S with circuit R as the disturbing source, independently of the position of the repeaters in the circuits. So far as distant-end cross-talk is concerned, however, if S and R are, for example, associated side and phantom circuits of a multiple-twin cable, side to phantom (distant-end) cross-talk may be greater or less than phantom to side (distant-end) cross-talk if the repeaters are not located at the centre of each circuit.

Consideration of distributed couplings in the line portion of telephone circuits.—The various cases so far considered have dealt with localised couplings only, the normal cross-talk in the cable portion of the circuits having been disregarded. For the purposes of calculation according to the method already indicated, the normal cross-talk in the line portions of the circuits due to distributed couplings may be treated as follows :—

The normal cross-talk between the line portions of any two circuits may be regarded as due to a single coupling situated at the listening terminal appropriate to that for which the cross-talk is being considered. The attenuation of such coupling will be the cross-talk attenuation obtained by listening at that terminal; near-end values being taken when overall near-end cross-talk is being computed, and distant-end values for overall distant-end cross-talk.

If a coupling, additional to the normal couplings, occurs at the repeater station between the lines on the X side, the resultant near-end cross-talk may be considered as due to a single coupling situated at the X terminal, the attenuation of this coupling being such as to give rise to the same cross-talk attenuation as would be obtained by an actual measurement from the X end of the circuits.

When listening at X to cross-talk caused by the lines on the Y side of the repeater station, such cross-talk may be considered as due to a single coupling situated at the repeater station on the Y side, the attenuation of this coupling being such as to give rise to the same cross-talk attenuation as would be obtained by an actual measurement on the Y side lines, taken from the repeater station.

In the case of distant-end cross-talk X to Y, *i.e.*, speaking at X and listening at Y, the cross-talk in the length X to the repeater station may be represented by a single coupling at the repeater station on the X side, of attenuation equivalent to that obtained by measurement when speaking at X and listening at the repeater station.

The cross-talk in the length situated between the repeater station and Y may be represented by a single coupling, at the Y terminal, of attenuation equivalent to that obtained by measurement when speaking at the repeater station and listening at Y.

The minimum cross-talk attenuation values obtained by test on some repeater sections of modern cable are given in table No. XI.

Effect of cross-talk upon the design of repeatered circuits.—The foregoing may be applied to the case of long repeatered circuits for the purpose of determining the effect upon the overall cross-talk attenuation, of the normal cross-talk couplings in the repeater sections.

Considering the case of two two-wire circuits each consisting of five repeater sections of attenuation b nepers per section and four repeaters each of gain G nepers, F nepers being the near-end cross-talk attenuation per repeater section, the minimum overall near-end cross-talk attenuation is given by :—

$$F - 2.3 \log_{10} \left[1 + e^{-2(b-G)} + e^{-4(b-G)} + e^{-6(b-G)} + e^{-8(b-G)} \right]$$

Taking the numerical value of the repeater section attenuation (b) as 1.5 nepers and the gain of each repeater (G) as 1.6 nepers—these figures give an overall transmission attenuation for the circuit of 1.1 nepers—then the minimum overall cross-talk attenuation is given by :—

$$F - 2.04$$

Assuming the input level at the terminals of the portion of the circuit under consideration to be -1 neper, the cross-talk level will be $-(F - 1.04)$ nepers. If this is not to be lower than -7.5 nepers (See Section V), then F should not be less than 8.54 nepers. An average value for the near-end cross-talk attenuation between side circuits in a repeater section of cable is 9.5 nepers.

In the case of the respective Go and Return elements of two four-wire circuits each consisting of ten repeater sections of attenuation b nepers per section and nine repeaters each of gain G nepers, F nepers being the near-end cross-talk attenuation per repeater section, the minimum overall near-end cross-talk attenuation is given by :—

$$F - 2.3 \log_{10} \left[1 + e^{-2(b-G)} + e^{-4(b-G)} + \ldots\ldots + e^{-18(b-G)}\right]$$

Taking the numerical value of the repeater section attenuation (b) as 2.9 nepers and the gain of each repeater (G) as 3.1 nepers—these figures give an overall transmission attenuation for either element of the circuit, of 1.1 nepers—then the minimum cross-talk attenuation is given by :—

$$F - 4.68$$

With assumptions similar to the foregoing the cross-talk level in this case will be − (F − 3.68) nepers, and if the cross-talk level standard is achieved then F should not be less than 11.18 nepers. By the careful separation of Go and Return elements of four-wire circuits working in the same cable (see later), the near-end cross-talk attenuation between such circuits in a repeater section of cable can be limited to 10.82, or even 11.51 nepers.

The minimum overall distant-end cross-talk attenuation between Go elements (or between Return elements) of the two four-wire circuits just referred to will be given by :—

$$F + 10b - 9G - 2.3 \log_{10} 10$$

Writing ($10b - 9G$), the overall transmission attenuation of either element of the circuit, as 1.1 nepers, the minimum overall distant-end cross-talk attenuation becomes :—

$$F - 1.2$$

With assumptions similar to the foregoing, the cross-talk level in this case will be − (F − 0.2) nepers, and if the cross-talk level standard is achieved then F should not be less than 7.7 nepers. An average value for the distant-end cross-talk attenuation between side circuits in a repeater section of cable is 9 nepers.

The above examples illustrate, in perhaps a somewhat exaggerated degree, the manner in which the normal cross-talk couplings of the repeater sections tend progressively to decrease the overall cross-talk attenuation in a circuit, as the number of repeaters, *i.e.*, as the length of the circuit is increased. Conversely the design of the circuit, so far as attenuation length of repeater section and repeater gain are concerned, is seen to be dependent upon the average minimum cross-talk attenuation which occurs in the completed repeater sections of cable.

Comparison of calculated with overall measured cross-talk in repeatered circuits.—Provided the repeater gains and repeater section transmission attenuation are of normal value there is usually good agreement between the calculated and measured results. When very large repeater gains are used or when one of the repeater sections is very short, the overall cross-talk attenuation will be very small, particularly in the case of distant-end cross-talk; the discrepancy between calculated and measured values being correspondingly great. Discrepancies will also occur in some cases owing to effects which are indeterminate and which cannot therefore be precisely included in the calculations. Such effects as unbalances in terminal transformers, alteration of overall conditions as between the passive and energised state of the repeaters, and either the cumulative or cancellation effects of cross-talk currents due to different sources, are amongst the chief causes which give rise to predicted results too widely different in their upper and lower limits to be of practical value.

(IX). CONTROL OF OVERALL CROSS-TALK AND NOISE IN TELEPHONE CIRCUITS.

The residual cross-talk and noise at the terminals of a circuit in a well-designed system is due to the small resultant deviations from perfect construction, rather than to dissymmetries in design. The unbalances of the short lengths of cable, individual loading coils and apparatus items are maintained as small as is economically possible during manufacture, whilst the balancing of loading sections of cable ensures the systematic reduction of interference in the early stages of the field construction of long-distance circuits. Difficulties arise, however, in the further application of normal balancing methods to the later and final stages of the work, since the unbalances of relatively long lengths of circuit consisting of cable and loading coils, or of continuously loaded cable, are complex quantities (32), difficult to measure and analyse into their components, and giving rise to much complication when attempts are made to utilise them for the purpose of selecting suitable connections at joints for further cross-talk elimination purposes. In order to control the amount of the residual interference in repeater sections, other means are therefore desirable, the most direct of which entails a determination of the actual magnitude of the interference.

In Pupinised cables it is the practice, as already indicated, to balance the sections of cable, situated between loading coils for capacity and (if necessary) conductor resistance, thus ensuring a considerable degree of interference immunity in each loading section. The loading coils, which are manufactured to a high standard of interference freedom, both in respect of the elements of individual coil units and the encased or assembled units, are then inserted at the various loading points along the route, in such a manner that the repeater section of cable is thus subdivided into a number of groups of cable and coils. In this country the groups generally consist of three loading sections (cable and coils). Adjacent groups are then jointed together, on the results of "group tests," into further groups of six loading sections (cable and coils). These operations are repeated until the final groups consist only of the two halves of the repeater section. The group tests consist principally of cross-talk and noise tests, although other tests for the purpose of checking the correctness of the loading, the maintenance of the insulation resistance and the absence of spurious conductor resistance and other faults are also regularly included. As a result of the noise and cross-talk tests, the jointing together of the groups is arranged so as to prevent noise and cross-talk from building up to excessive values. Such tests are particularly useful for the control of noise in circuits not specially balanced to earth, or of disturbances from other causes in respect of which no balancing operations have been undertaken in the loading section stage of the construction work. In order to facilitate the selection of circuits for jointing purposes, switches are inserted between the groups, the best connections being determined on the results of repeated trial. Such tests are frequently referred to as "Switching tests."

In the case of cross-talk, the tests should be made with voice currents obtained from an ordinary telephone. Alternatively, a complex tone simulating speech, or a number of separate tones taken over the audio frequency range should be used. Furthermore, near- and distant-end tests are taken with a view to the achievement of the best possible all-round result. As the work proceeds and the groups become longer, *i.e.*, as the groups consist of a greater number of cable sections and coils the effects of phase become more pronounced and accordingly (i) greater differences will be observed between tests taken at different frequencies and (ii) there will generally be a greater diversity between near- and distant-end cross-talk. In dealing with (i), special consideration is given, in determining the best mode of connection, to those tones which give rise to the greatest total disturbing effect—as judged by their magnitude and frequency—specially disturbing tones being given sole consideration at selected switching points. In regard to (ii), attention is directed to the question as to whether a given circuit will, when working, be more susceptable to the one form of cross-talk than to the other. Thus since in four-wire repeatered circuits, distant-end cross-talk between circuits transmitting in the same direction is of relatively greater importance than near-end cross-talk, consideration is given to this feature when determining the best mode of connection to be adopted as the result of the tests. If special care is taken in the primary groups to secure good all-round results, the perplexities introduced into the determination of the best modes of connection, in the later stages of the work, will be considerably minimised. Great care is taken with those primary groups which are adjacent the repeater stations.

American practice in regard to tests for cross-talk elimination purposes is similar to the above, although differing in detail. The tests are referred to as " Cross-talk Polling Tests."

Reference (33) relates to the Dutch Administration's method of jointing lengths of modern, paper-insulated, multi-quad, Krarup cables together, with the object of minimising cross-talk due to electrostatic capacity, inductance and effective resistance unbalances. The cross-talk tests are taken from one end of the cable, the remote end being suitably terminated. One or more frequencies are used, the results being expressed in nepers. The jointing proceeds under control, the best connections being found by trial on systematic switching. Every third joint may be made on the results of a two or more frequency tests, and at regular intervals cross-talk/frequency curves (over the audio range) may be plotted for the purpose of detecting unfavourable frequencies; jointing to suit the results of such tests being subsequently carried out. In order to minimise the testing work involved in the very large number of possible jointing combinations, a definite, determined order of manipulation is adopted. Furthermore, by measuring distant-end instead of near-end cross-talk a further diminution of the testing work is effected by reason of the fact that distant-end cross-talk measurements show a certain degree of independence with respect to the frequency of the testing current.

Reference (34) relates to the American method of jointing groups of loading coil sections and coils together (to form a complete repeater section of cable) in such a manner as to secure maximum immunity of the circuits from noise. The desired result is obtained by a noise measurement in which the circuits concerned are connected together at one end and fed at that end from an earthed generator. At the remote end a telephone is connected across one of the circuits, for the purpose of determining—as evinced by minimum sound in the telephone—the best mode of connection of the circuits at a joint intermediate between the two ends. A specially careful application of the method for the joints in cable lengths situated at places along a cable route where inductive exposure to power systems is heaviest should have beneficial effects in minimising noise at the cable terminals.

(X). MODERN IMPROVEMENTS IN THE DESIGN AND CONSTRUCTION OF TELEPHONE CABLE CIRCUITS FROM THE INTERFERENCE IMMUNITY POINT OF VIEW.

Grouping of circuits.—The use of telephonic repeater circuits has rendered the conditions in respect of interference particularly severe. It has previously been shown that unbalanced couplings of such a magnitude as to be considered quite satisfactory when repeaters are not employed, may give rise to considerable cross-talk under repeatered conditions. In order to secure a sufficiently high attenuation value for the normal cross-talk coupling between four-wire repeatered circuits it has been found necessary to isolate the Go from the Return elements of such circuits in cables designed for four-wire repeater working. By suitable grouping of the cable cores during balancing operations in the field, considerable separation can thereby be ensured. Furthermore if groups of Goes and Returns are separated by another group of circuits which are working on some other system, additional immunity will be secured by reason of the electric shielding effect of the intervening group. The separation may be effected by means of an intermediate layer or by two groups of diametrically opposite circuits in the same layer or by an electrostatic screen, either complete or partial. These principles are embodied in one form or another in the construction of all modern long-distance telephone cables.

If two cable cores are stranded in a layer with at least two other cores between them, there will be practically no electric coupling between them owing to the electric shielding effect of the two separating cores and of the other cores in the layers above and below the layer in question. Use has recently been made of this, as an alternative to the use of special screening tapes for four quads of a 160/40 quad cable, which are required to be specially free from interference with each other. The four special cores were chosen from the outer layer and are situated at the ends of two diameters at right angles to each other. They have been balanced for within-core interference immunity as a separate group, the remaining cores in the layer having been similarly balanced as another group. The pair-to-pair (adjacent cores) interference characteristic for factory lengths of the cable having a mean and maximum value of 7 m.m.f. and 32 m.m.f. respectively and the pair-to-pair (adjacent layer) interference characteristic having a mean and maximum value of 1.8 m.m.f. and 9 m.m.f. respectively, the special cores, in addition to being immune from interference with each other, suffer little interference from the other cores of the cable.

Such a result will always be possible of achievement provided the number of cable cores is not so small as to give rise to :—

(i) Relatively large core-to-core capacity unbalances between adjacent cores of the manufacturing lengths.

(ii) Relatively large core-to-core capacity unbalances between cores in adjacent layers of the manufacturing lengths.

(iii) Excessive augmentation of the effects of (i) and (ii) in complete cables due to the impossibility of extensive mixing of the cores during the jointing together of the manufacturing lengths.

Screening of cable circuits.—The screening or shielding, in the year 1902 or thereabouts, of single wire telegraph circuits working in unloaded telephone cables has already been referred to. Screening appears first to have been devised in the year 1881 by John Imray who described the arrangement in a cable of a thin metal sheet of highly conducting material so as to almost completely envelop each of the cable cores. This metal sheet was connected to the cable sheath at frequent intervals.

A design for a 160 pr. 40 lb. P.C.M.T. cable, consisting of four layers about a centre layer of four cores was prepared by the B.P.O. Engineering Department in 1919. The third layer was completely enveloped by a metal tape and one core in the fourth layer was also screened. The screen of this core was in contact with the lead sheath and with the screen of the third layer, which was thereby maintained at earth potential. The fourth layer cores were intended for telegraph working. The cost of such a make-up was, at the time, rather heavy and manufacture was not proceeded with. 12, 1.3 m.m. conductor cores, forming the centre and first layer of the Paris-Strasbourg cable, are shielded from the remaining 82 cores by means of a metallic screen wrapped around the first layer. This cable was completed in 1926; the screened group being used for telegraphic purposes.

Some of the standard types of trunk cables manufactured in Germany are provided with a central, lead-sheathed core. The main reason for such provision is believed to lie in the facility thus furnished for fault localisation purposes in cases of equally low insulation resistance on all cores other than the centre core. In addition, however, such provision makes available a completely screened core, whilst at the same time, by reason of decreased electric couplings and propinquity, interferences between the first layer cores are considerably minimised.

If a circuit AB is completely surrounded by either an insulated or earthed shield S of electrically conducting material, the electrostatic field set up by an alternating E.M.F. impressed across the terminals of any other circuit A′B′ will be wholly external to the shield. There will be no direct electric coupling between the circuits and accordingly no E.M.F. induced between the wires A and B, and therefore no disturbance to the circuit AB from electrostatic effects of the circuit A′B′. The electromagnetic effects of the circuit A′B′ upon the circuit AB will be practically unaffected by the presence of the shield; such effects are however very small if the circuits consist of twinned conductors and if the current magnitudes are not excessive.

The advent of broadcasting and the provision of interference-free telephone lines for its various distribution schemes has revived the question of shielding in relation to the electrostatic screening of telephone circuits working at relatively high speech levels, and a number of cables of recent construction have been provided with a few screened cores for the transmission of music. In such cases the cores are completely enveloped with a metal or metallised paper tape, insulated from the cable sheath and from earth. The circuits of such cores are completely free from electric interference from the other cable cores. The standard make-ups of the non-screened type cables, which are necessarily, to a large extent the outcome of their general design, cannot be exactly reproduced in the screened type and the latter are somewhat less economical from the space point of view. Furthermore they are, at present, rather more difficult and costly to construct. Sufficient experience has not yet been obtained in regard to the effectiveness of ordinary desiccating methods for the maintenance of insulation resistance, nor to the likelihood of trouble arising from the abrasion of metal dust and splinters from the screens. Unless the screening is carried over at the joints the pair-to-pair interference characteristics of such cores to other cores may reach a value of 7 to 10 M.M.F. per 2000 yard loading section.

References (35) to (39) deal with the screening of cable circuits. Reference (40) deals with the method of designing a screen to ensure the same propagation constant for the screen and the conductors beneath it. Reference (41) deals with the electric separation of Go and Return cable conductors and leads to loading coils, as well as the magnetic shielding of loading coils and of single-way telephonic repeaters.

The screens hitherto described, completely envelop the cores and are applied during the usual quadding operations. If, however, a single core is shielded from another single core by means of a separator of conducting material, fixed in position during cable stranding operations and partially enveloping either or both cores, then a very high degree of immunity from electrostatic interference between such cores can be secured. Groups of cores may be similarly shielded from one another. Although this method is not so perfect as complete screening, it is much more economical in the utilisation of space for screening purposes. It has been used in place of the usual "separator cores" between the oppositely transmitting groups of four-wire circuits.

Control of unbalance in factory lengths of cable.—Although the twinning of wires was devised to overcome disturbance due to parallelism, interference may still arise between cable circuits, more especially in the case of adjacent circuits, if the respective lengths of lay of the pairs are such as to cause the wires of one circuit to take up exactly the same relative position with respect to the wires of the other circuit, either entirely or at frequent intervals throughout their length.

Tremain in the year 1901 (42) and Dieselhorst and Martin in 1903 (5) pointed out the necessity for the use of different lays in the various cores of a cable, in order to obviate this difficulty. Considerable attention has of late been given to this matter and such effects are now almost entirely eliminated in practice by the employment of suitable lays. In modern cables the twinning, quadding and stranding lays, for the various pairs, cores and layers respectively, are of such relative length in the finished cable that not only the average and maximum capacity unbalances within individual cores, but also and particularly those between adjacent cores in the same layer, and between cores in adjacent layers are of very small value. Table No. XII. gives core-to-core (adjacent in same layer and in adjacent layers) interference characteristics for 176 yard factory lengths of multiple twin and star quad cable respectively.

In general a definite number of different classes of core are used in the manufacture of telephone cables, the classification being made in respect of the twinning and quadding lays previously referred to. The number of such classes used in any particular case will depend upon the make up of the cable as regards the total number of cores. The modern tendency is to restrict the number to two main classes of core per layer, additional classes being added either for inclusion in layers where the two-class arrangement would result in the adjacency of cores of the same class, or for use as centre-layer cores, where the interference difficulties, which always exist in the case of layers containing a few cores only, owing to their excessive adjacency or propinquity, would otherwise be increased.

The developments in cable manufacture referred to above have rendered within-core balancing by the crossing method adequate in all cases except in those instances of small cables or of balancing groups containing relatively few cores. In such latter cases the greatest degree of core mixing possible for the reduction of the within core unbalances may not secure the necessary degree of core-to-core balance. In these circumstances additional balancing will be necessary, namely, between adjacent cores in individual layers (15). For adequate balance under these conditions the unbalances between cores in adjacent layers will require to be small.

Re-introduction of Quad Type cable.—Reference has been made to the interference difficulties experienced from imperfect symmetry of formation of the early quad type core when applied to dry core cables. With modern methods of manufacture, quad cables have been revived in Germany under the general title of " Star " or " Spiral-four " cables (43). In the modern design, a stiffening of the paper tubes has resulted in the accurate and permanent centralisation therein of the conductors, whilst a central string upon which the covered conductors are bedded is used for the purpose of ensuring symmetry of the cores. This extremely important feature of centralisation of the conductors within the paper tubes may be secured either by the use of specially creased or corrugated surfaced paper wrappings or by a spiral whipping of string directly next the conductor over which the insulating paper is tightly wrapped. A.S.P.C. quad cable was re-introduced into the British telephone system in 1925 (44). So far as experience to date is concerned the unbalances between the associated pairs of the cores of star quad cable are greater than between adjacent pairs of twin cables and much greater, particularly in respect of maximum values, than in M.T. cables. This circumstance is explainable since with equal pair circuit mutual capacity in the M.T. and star quad types, the direct capacities (w) upon which the side-to-side interference characteristics depend are about two and one-third times those of the M.T. type core (45). The earth unbalance of the pairs is also greater in the star quad cables than in those of M.T. type, and this may be accounted for to some extent by the somewhat greater direct earth capacity. The unbalance between pairs not in the same quad is much smaller than between pairs associated in the same quad. Furthermore, the unbalances between non-associated pairs are, on the average, smaller in star quad than in M.T. cables. Extended experience of quad cables will undoubtedly result in improved within-core capacity balance by reason of the inherent symmetry of this type as compared with the M.T. type.

Quad type cable as originally designed for gutta-percha telegraph cables is still employed in the manufacture of modern, balata, submarine telephone cables. The cores of modern, continuously loaded, paper insulated, submarine cables are also of this type. The air space in such cables is relatively small, the dielectric consisting almost wholly of paper.

Systematic Jointing.—In order to control interference between the circuits of telephone cables, several systems of jointing cable conductors have been adopted during recent years. These systems have been used separately and in combination, and have been applied to short cables, for which the interference immunity requirements are not so exacting as for trunk cables. Systematic jointing is not a substitute for the test-selected jointing of normal cable balancing processes. Cable balancing effects a neutralisation and therefore an overall reduction of the interferences in a cable and may be used to produce any desired degree of freedom from interference, whereas the systematic jointing schemes described below, except in the case of "Cross-whipped" jointing (see later), only control the overall result by preventing the building-up of large interference between any two particular circuits and thereby distributing the total interference amongst all the circuits, *i.e.*, by substituting cross-talk babble on all circuits for loud cross-talk on some circuits and faint cross-talk on others.

In the case of twin cable the cross-talk on any particular circuit, at least from circuits in the same layer, is mainly due to the cross-talk from the circuits on either side and immediately adjacent to it. If the distance over which any two circuits are adjacent is limited, then the cross-talk between them will be restricted to the cross-talk resulting from such limited adjacency. In order best to impose such limitation on all the circuits of a group a systematic method of connecting the wires at each joint must be adopted. Various methods have been employed and degrees of adjacency not exceeding one length in five lengths for a 20 pair group, one length in seven lengths for a 28 pair group, one length in ten lengths for a 40 pair group and one length in thirteen lengths for a 53 pair group have been secured. The method is particularly advantageous in the case of cables containing a large number of pairs. It furnishes no control of the capacity unbalance to earth of the circuits.

In the case of cables of the two-pair core type, *e.g.*, M.T. and star quad, the side circuits of each two-pair core will require to remain associated throughout the whole length of such circuits if phantom circuit working is desired. The above-described method of controlling cross-talk between cable pairs cannot therefore be applied, so far as interference between associated side circuits or associated side and phantom circuits is concerned, and test-selected jointing, either wholly or in part, is necessary. Systematic jointing has, however, been applied to the pair circuits of different two-pair cores, by jointing the cores in such a manner as to secure minimum adjacency of any two cable cores throughout the circuit length.

If phantom circuits are not required, then the two-pair core formation need not be maintained and control of the cross-talk between any two cable pairs may be secured by separating the pairs of the cores and applying a suitable scheme for limiting their subsequent adjacency. The economic advantages of star quad cable over twin cable may be fully utilised by the use of this method of jointing since the alternative to the method is test-selected jointing for side-to-side balance. An electrical advantage in respect of the superior capacity balance to earth of quad cable is also secured although of course this method of jointing does not control this feature.

The contrast between the main principles underlying test-selected jointing for the neutralisation of cross-talk by balancing processes and systematic jointing for the control of cross-talk, is emphasised by the preceding paragraphs. In the former case the adjacency of the circuits between which balance is desired is maintained, *e.g.*, the two pairs of two-pair cores in the case of within-core balancing and consecutive two-pair cores in the case of core-to-core balancing, whereas in the latter case, minimum adjacency of the circuits whose mutual cross-talk is being controlled is provided for.

If a single factory length of cable of the two-pair core type is cut into two equal lengths, it frequently happens that the capacity unbalances of similar cores in the two halves are similar to each other in magnitude and sign, particularly in the case of cores of relatively large unbalance. If therefore the two half sections are connected together, core-to-core and pair-to-pair, but with a cross in the wires of each pair, then a reduction in the phantom-to-side capacity interference characteristics and in the side-to-earth capacity unbalances will result, the side-to-side capacity interference characteristic remaining of the same value as before the cut. Practical use is made of this in the jointing together in the field of consecutive lengths of cable, such consecutive lengths being successive lengths during manufacture. This method of jointing is referred to as "Cross-Whipped" jointing. Reference (46) applies. In addition to securing a reduction of the capacity unbalances referred to, it effects a reduction in the conductor resistance unbalance of the side circuits. The side-to-side capacity interference characteristics of course increase and at the same time the increased adjacency of the pairs of consecutive two-pair cores results in an increase in the pair-to-pair interferences. The method is ineffective in practice unless the consecutively jointed lengths are cut from a single manufactured length.

The practicability of applying systematic jointing, the determination of the particular scheme, or combination of schemes, to be used and the extent to which part systematic and part test-selected jointing will be adopted in any individual case is arrived at on the result of capacity unbalance measurements on a few representative cable lengths and a knowledge of the overall results required.

(XI). CONCLUSION.

In the elimination of disturbance in communication lines it has been necessary from time to time to improve the general design of the system and to change the standards of manufacture, construction and maintenance of the plant, in order to accommodate changes in the conditions of working. Hitherto lower standards could be safely adopted, whereas at the present time, when the use of telephonic repeater circuits has rendered the conditions in respect of interference particularly severe, much higher standards are necessary.

The modern practice is to eliminate interference in each of the different portions of the system; the line (cable), line plant (loading coils) and terminals apparatus (repeater station and exchange equipments) being separately treated and maintained in an efficient state of electrical balance. The line and line plant are generally separated from the terminal apparatus by means of suitable well-balanced transformers interposed between the line and local sides of the circuit terminals. Too much importance cannot be given to this feature, since an otherwise well-balanced circuit may be considerably degraded in this respect by exchange or repeater station equipment.

Great improvements have been effected during recent years in the manufacture of telephone plant and in telephone constructional work, particularly in regard to the elimination of electrical unbalances and non-uniformities. It seems that a limit is being approached in these respects and it is highly improbable that any very considerable improvement will be economically possible in this connection, at least so far as the cable is concerned. Manufacturing irregularities cannot be entirely eliminated in the commercial product and if greater freedom from interference is called for in the future, a review of the methods of circuit working, especially a complete economic study of the conditions under which extra facilities are being obtained in telephone cables, *e.g.*, telegraph working, superposing, etc., would seem to be inevitable, since balancing in the field to a finer degree than is accomplished at present would appear to be prohibitive. The technical difficulties are surmountable, it is entirely a question of cost and of the practical difficulties involved in the construction and maintenance of such a system.

Various sources of information which have been consulted during the writing of the paper are referred to in the attached bibliography. The author tenders thanks to his colleagues who have carried out and prepared in suitable form the large number of tests neecssary for the publication of the tables. Grateful acknowledgement is also made for other assistance, particularly that derived from their suggestions and criticisms. The author is much indebted to Mr. L. C. Voss for the preparation of the illustrations.

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Table No. I.

AVERAGE WIRE-TO-WIRE AND WIRE-TO-EARTH CAPACITY UNBALANCES OF 176 YARD FACTORY LENGTHS OF MULTIPLE TWIN AND STAR QUAD CABLE.

CAPACITY UNBALANCES.		M.T. Cable.	Star Quad Cable.
		M.M.F.	M.M.F.
Wire-to-wire (*p*, *q*, *r*, *s*)	Mean Max.	15 100	45 150
Pair-to-earth (*u*, *v*)	Mean Max.	40 150	70 330
Pair-to-earth (resultant)	Mean Max.	55 300	80 350
Phantom-to-earth (*f*)	Mean Max.	125 440	100 250

TABLE No. II.

CORRESPONDING TELEPHONIC TRANSMISSION ATTENUATION MAGNITUDES EXPRESSED VARIOUSLY IN MILLIONTHS, NEPERS AND DECIBELS.

Current or Voltage attenuation expressed in :—		Power attenuation expressed in :—	Current or Voltage attenuation expressed in :—		Power attenuation expressed in :—
Millionths N	Nepers B	Decibels X	Millionths N	Nepers B	Decibels X
1	13.82	120	3500	5.66	49.1
10	11.51	100	4000	5.52	48
20	10.82	94	4500	5.40	46.9
30	10.41	90.5	5000	5.30	46
40	10.13	88	6000	5.12	44.4
50	9.90	86	7000	4.96	43.1
60	9.72	84.4	8000	4.83	41.9
70	9.57	83.1	9000	4.71	40.9
80	9.43	81.9	10000	4.61	40
90	9.32	80.9	11000	4.51	39.2
100	9.21	80	12000	4.42	38.4
110	9.12	79.2	13000	4.34	37.7
120	9.03	78.4	14000	4.27	37.1
130	8.95	77.7	15000	4.20	36.5
140	8.87	77.1	16000	4.14	35.9
150	8.80	76.5	17000	4.07	35.4
160	8.74	75.9	18000	4.02	34.9
170	8.68	75.4	19000	3.96	34.4
180	8.62	74.9	20000	3.91	34
190	8.57	74.4	21000	3.86	33.6
200	8.52	74	22000	3.82	33.2
210	8.47	73.6	23000	3.77	32.8
220	8.42	73.2	24000	3.73	32.4
230	8.38	72.8	25000	3.69	32
240	8.33	72.4	26000	3.65	31.7
250	8.29	72	27000	3.61	31.4
260	8.25	71.7	28000	3.58	31.1
270	8.22	71.4	29000	3.54	30.8
280	8.18	71.1	30000	3.51	30.5
290	8.15	70.8	31000	3.47	30.2
300	8.11	70.5	32000	3.44	29.9
350	7.96	69.1	33000	3.41	29.6
400	7.82	68	34000	3.38	29.4
450	7.71	66.9	35000	3.35	29.1
500	7.60	66	40000	3.22	28
550	7.51	65.2	45000	3.10	26.9
600	7.42	64.4	50000	3.00	26
650	7.34	63.7	55000	2.90	25.2
700	7.26	63.1	60000	2.81	24.4
750	7.20	62.5	65000	2.73	23.7
800	7.13	61.9	70000	2.66	23.1
850	7.07	61.4	75000	2.59	22.5
900	7.02	60.9	80000	2.53	21.9
950	6.96	60.4	85000	2.47	21.4
1000	6.91	60	90000	2.41	20.9
1100	6.81	59.2	95000	2.35	20.4
1200	6.73	58.4	100000	2.30	20
1300	6.65	57.7	200000	1.61	14
1400	6.57	57.1	300000	1.20	10.5
1500	6.50	56.5	400000	0.92	8
1600	6.44	55.9	500000	0.69	6
1700	6.38	55.4	600000	0.51	4.4
1800	6.32	54.9	700000	0.36	3.1
1900	6.27	54.4	800000	0.22	1.9
2000	6.21	54	900000	0.11	0.9
2500	5.99	52	1000000	0	0
3000	5.81	50.5			

Table No. III.

DEFINITIONS OF NEAR-END AND DISTANT-END CROSS-TALK.

Cross-talk in circuit R from circuit S, considered for terminal :—	Near-end or Distant - end cross-talk.	Disturb on circuit S at terminal :—	Listen on Circuit R at terminal :—
X	Near-end	X	X
X	Distant-end	X	Y
Y	Near-end	Y	Y
Y	Distant-end	Y	X

Table No. IV.

THE VOLTAGE (ACROSS THE LINE TERMINALS OF A CIRCUIT CONSISTING OF A 3 NEPER LINE WITH STANDARD C.B. TERMINALS AND 300 OHM LOCAL LINE) OF DISTURBING SOURCES OF VARIOUS FREQUENCIES NECESSARY TO PRODUCE CERTAIN ARTICULATION LOSSES.

Percentage Articulation loss.	Millivolts disturbance.					
	Frequency in cycles per second.					Telegraphic disturbance
	50	500	825	1150	1600	
5	4	1.7	1.0	0.8	1.2	0.3
10	8.3	3.7	3.4	1.9	2.8	0.7
12.5	10.7	4.7	3.2	2.5	3.8	0.9

TABLE NO. V.

CAPACITY INTERFERANCE CHARACTERISTICS FOR 176 YARD FACTORY LENGTHS OF MULTIPLE TWIN AND STAR QUAD CABLE.

Cable Type.		Capacity Interference Characteristics (M.M.F.)						
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
		S/S	S/Ph.	S E.S	Pr/Pr	Pr/Ph	Ph/Ph	Pr/E.Pr
Multiple Twin	Mean	9·5	58	24	16.5	12.4	16.2	22.2
	Max.	35	225	59	65	140	65	60
Star Quad	Mean	18	163	50	5	5	5	16
	Max.	35	485	115	20	30	15	110

TABLE NO. VI.

CAPACITY INTERFERENCE CHARACTERISTICS AND CAPACITY TO EARTH UNBALANCES IN MICRO-MICRO-FARADS FOR LOADING SECTIONS OF MULTIPLE TWIN AND STAR QUAD CABLE WHICH HAVE BEEN CAPACITY BALANCED TO VARIOUS DEGREES.

Cable Type	Length Yards	Capacity Interference Characteristics.							Capacity Unbalances.		
		S/S	S/Ph	S/E.S	Pr/Pr	Pr/Ph	Ph/Ph	Pr/E.Pr.	Dirc. Pr/E	Res. Pr/E	Ph/E.
Balanced for Side and Phantom circuit working, and for direct earth unbalance of side circuits.											
60/70 M.T.	2000	$\frac{15}{50}$	$\frac{37}{90}$	$\frac{25}{64}$	$\frac{31}{165}$	$\frac{27}{125}$	$\frac{36}{85}$	$\frac{29}{87}$	$\frac{50}{165}$	$\frac{37}{105}$	$\frac{616}{1410}$
Balanced for Side circuit working and for direct earth unbalance of side circuits.											
38/70 Q.	2540	$\frac{6}{20}$	$\frac{391}{935}$	$\frac{54}{165}$	$\frac{15}{155}$	$\frac{15}{180}$	$\frac{16}{40}$	$\frac{13}{54}$	$\frac{18}{45}$	$\frac{108}{280}$	$\frac{394}{920}$
Balanced for side circuit working and for direct earth unbalance of side circuits; also a measure of side to phantom balancing.											
200/40 Q.	2000	$\frac{11}{30}$	$\frac{46}{250}$	$\frac{55}{110}$	$\frac{9}{40}$	$\frac{8}{50}$	$\frac{8}{30}$	$\frac{37}{125}$	$\frac{54}{210}$	$\frac{45}{140}$	$\frac{300}{1235}$
No capacity balancing whatever. Systematic jointing for side circuit working. Quads split.											
254/40 Q.	2007	$\frac{32}{120}$	$\frac{364}{1200}$	$\frac{55}{165}$	$\frac{13}{130}$	$\frac{47}{320}$	—	—	$\frac{221}{650}$	$\frac{256}{870}$	—

TABLE No. VII.

CROSS-TALK ATTENUATION DUE TO A SINGLE COUPLING BETWEEN TWO NON-REPEATERED CIRCUITS.

Near-end or distant-end Cross-talk.	Cross-talk attenuation.	
	Listening at the circuit terminal :	Magnitude in nepers; circuit S being the disturbing source.
Near-end	X	$F + Sx + Rx = H$
do. do.	Y	$F + Sy + Ry = K$
Distant-end	Y	$F + Sx + Ry = M$
do. do.	X	$F + Sy + Rx = N$

TABLE No. VIII.

LIMITING VAULTS OF CROSS-TALK ATTENUATION DUE TO TWO COUPLINGS BETWEEN TWO NON-REPEATERED CIRCUITS.

Near-end or distant-end Cross-talk.	Cross-Talk Attenuation.	
	Listening at the circuit terminal :	Magnitude in nepers; circuit S being the disturbing source.
Near-end	X	$-2.3 \log_{10} [e^{-H'} \pm e^{-H''}]$
do. do.	Y	$-2.3 \log_{10} [e^{-K'} \pm e^{-K''}]$
Distant-end	Y	$-2.3 \log_{10} [e^{-M'} \pm e^{-M''}]$
do. do.	X	$-2.3 \log_{10} [e^{-N'} \pm e^{-N''}]$

TABLE NO. IX.

CROSS-TALK ATTENUATION DUE TO A SINGLE COUPLING BETWEEN TWO REPEATERED CIRCUITS.

Side of repeater on which the coupling is situated.	Near-end or distant-end Cross-talk.	Cross-talk attenuation.	
		Listening at the circuit terminal :—	Magnitude in nepers; circuit S being the disturbing source.
X	Near-end	X	$F + S + R$
X	do. do.	Y	$F + S + R - 2G$
X	Distant-end	Y	$F + S + R - G$
X	do. do.	X	$F + S + R - G$
Y	Near-end	X	$F + S + R - 2G$
Y	do. do.	Y	$F + S + R$
Y	Distant-end	Y	$F + S + R - G$
Y	do. do.	X	$F + S + R - G$

TABLE NO. X.

LIMITING VALUES OF CROSS-TALK ATTENUATION DUE TO TWO COUPLINGS BETWEEN TWO REPEATERED CIRCUITS.

Near-end or distant-end cross-talk.	CROSS-TALK ATTENUATION.	
	Listening at the circuit terminal :—	Magnitude in nepers; circuit S being the disturbing source.
Near-end	X	$S+R-2.3\log_{10}[e^{-Fx} \pm e^{-(Fy-2G)}]$
do. do.	Y	$S+R-2.3\log_{10}[e^{-Fy} \pm e^{-(Fx-2G)}]$
Distant-end	Y	$S+R-G-2.3\log_{10}[e^{-Fx} \pm e^{-Fy}]$
do. do.	X	$S+R-G-2.3\log_{10}[e^{-Fy} \pm e^{-Fx}]$

TABLE NO. XI.

MINIMUM CROSS-TALK ATTENUATION (NEPERS) FOR REPRESENTATIVE REPEATER SECTIONS OF TELEPHONE CABLES.

CIRCUITS.	2-WIRE CIRCUITS.	4-WIRE CIRCUITS.	
	—	BETWEEN GROUPS	WITHIN GROUPS
	NEAR END	NEAR END.	DISTANT END
MULTIPLE TWIN UNDERGROUND CABLE, COIL LOADED (SIDE 177 mH. Phantom 107 mH.) Length—62 miles.			
Side to Side	8.52	—	8.1
Phantom to Side	8.52	—	7.6
Phantom to Phantom	7.82	10.82	7.82
STAR QUAD UNDERGROUND CABLE, COIL LOADED (SIDE 177 mH. for 2-wire circuits, 44 mH. for 4-wire circuits). Length—32 miles.			
Side to Side	9.21	—	9.32
Pair to Pair	9.21	10.82	9.03
STAR QUAD UNDERGROUND CABLE, NON-LOADED. Length—32 miles.			
Side to Side	10.6		
Pair to Pair	9.43		
P.C. QUAD CABLE, CONTINUOUSLY-LOADED (12 mH per naut) SUBMARINE TYPE. Length—69 nauts.			
Side to Side	9.4		
Phantom to Side	8.6		
Phantom to Phantom	11.4		
Pair to Pair	11.4		
BALATA QUAD CABLE, NON-LOADED, Length—32 nauts.			
Side to Side	10.9		
Phantom to Side	9.4		

TABLE NO. XII.

WIRE-TO-WIRE CAPACITY INTERFERENCE CHARACTERISTICS, BETWEEN CORES FOR 176 YARD FACTORY LENGTHS OF CABLE.

Wire-to-wire capacity interference characteristics between cores.		Micro-micro-farads.			
		Multiple Twin.		Star Quad.	
		Average and max. Mean.	Average and max. Max.	Average and max. Mean.	Average and max. Max.
Pair to Pair	For adjacent cores in the same layer	13/24	42/62	7/9	32/73
Phantom to Pair		16/27	44/56	—	—
Phantom to Phantom		21/28	70/120	—	—
Pair to Pair	For Cores in a centre layer (of 4 cores) to cores in the next layer.	5/8	13/20	4/5	17/18
Phantom to Pair		12/18	31/46	—	—
Phantom to Phantom		15/19	58/101	—	—
Pair to Pair	For cores in an outermost layer to cores in the layer beneath.	3/4	8/15	2/3	9/15
Phantom to Pair		4/6	12/35	—	—
Phantom to Phantom		5/6	23/69	—	—