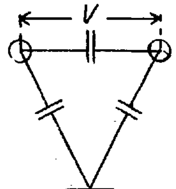

Fig. 1

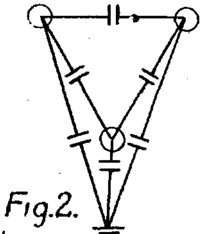

Fig. 2.

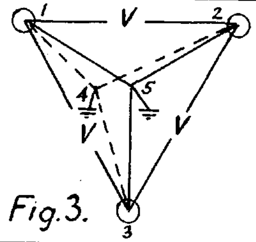

Fig. 3.

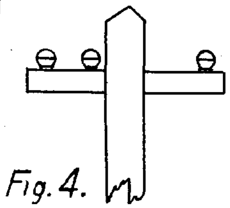

Fig. 4.

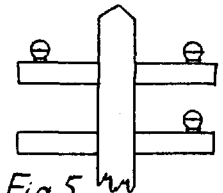

Fig. 5.

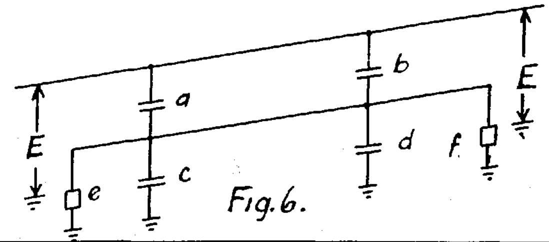

Fig. 6.

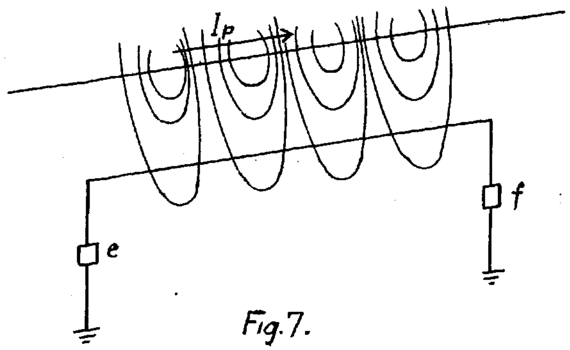

Fig. 7.

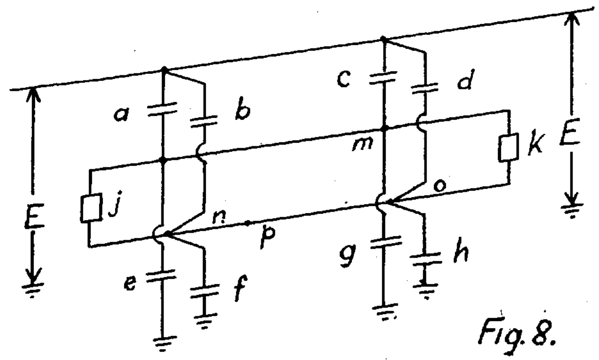

Fig. 8.

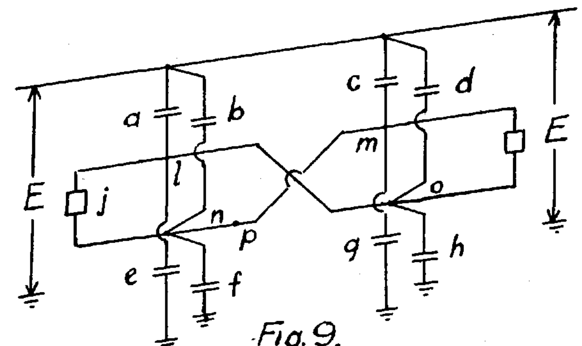

Fig. 9.

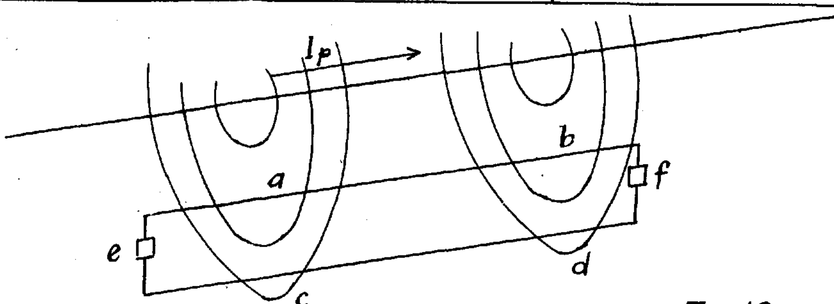

Fig. 10

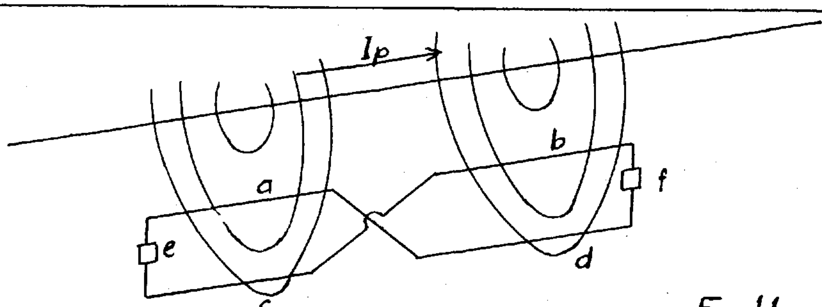

Fig. 11.

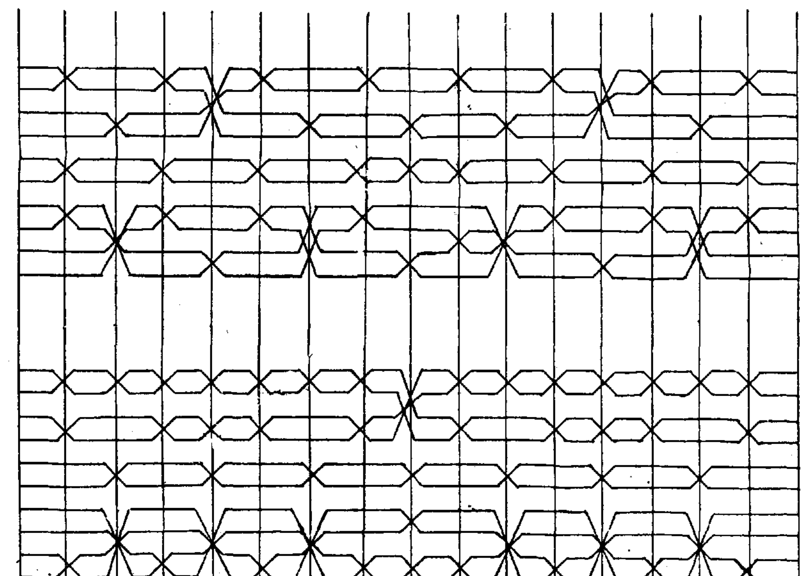

Fig. 12

Cross Talk and Inductive Interference

C. A. WRIGHT, *Profesor of Electrical Engineering*

The reduction of interference of telephone circuits with each other, and of power circuits with telephone circuits is one of the most important and sometimes one of the most difficult problems the telephone and electric power and lighting companies have to solve. This article discusses the theory applying to the above conditions, and the principal methods of reducing or eliminating disturbances.

If two or more resistances are connected in series to the terminals of a battery, there will be a drop of potential across each resistance. These potentials will be directly proportional to the resistances. If two or more condensers are connected in series to a source of alternating electromotive force and if I is the current which flows through the circuit, f, the frequency, and E_1, E_2, E_3, the potentials across the condensers of capacity C_1, C_2, C_3;

$$E_1 = \frac{I}{2\pi f C_1},\quad E_2 = \frac{I}{2\pi f C_2},\quad E_3 = \frac{I}{2\pi f C_3},\ \text{and}$$

$$\frac{E_1}{E_2} = \frac{C_2}{C_1},\quad \frac{E_2}{E_3} = \frac{C_3}{C_2},\quad \frac{E_3}{E_1} = \frac{C_1}{C_3},$$

or the potentials are inversely proportional to the capacities of the condensers. This is to be expected because capacity is a measure of admittance rather than, as is resistance, a measure of impedance. It should be noted from this equation when put in the form,

$$I = 2\pi f C E$$

that, for a given potential impressed upon the circuit, the current is directly proportional to the frequency.

If an alternating current of frequency, f, flows through a circuit containing resistance R, and inductance, L, part of the applied electromotive force, RI, will be used up in forcing the current through the resistance, and part will be used up in overcoming the electromotive force of self-induction, $2\pi fLI$, where L is the self-inductance of the circuit. The self-inductance is defined as the linkages of magnetic flux with the circuit per ampere of current in the circuit. It varies with the dimensions of the circuit, the number of turns of conductor in the circuit, and the material of the magnetic circuit. Where the magnetic circuit is in air, as it is in the cases which we will consider, L may be computed.

If an alternating current I flows in one of two adjacent parallel circuits, some of the magnetic flux links with the other circuit and an electromotive force, $2\pi fMI$ will be induced in the second circuit. The mutual inductance of the circuits, M, is defined as the number of linkages of magnetic flux with the second circuit per ampere of current in the first circuit. As in the case of self-inductance, the mutual inductance may be computed. The current which will flow in the second circuit will be the induced electromtive force, $2\pi fMI$, divided by the impedance of the circuit. For a given value of current, in the first circuit the electromotive force in the second circuit is directly proportional to the frequency.

Every electric circuit has, distributed throughout its length, resistance, leakance, inductance, and capacity. Each circuit has distributed mutual inductance with each circuit in its vicinity, and between each pair of adjacent wires, and between each wire and the ground, there is distributed leakance and capacity. In the cases which will be considered in this discussion the effects of leakance may be disregarded. In the accompanying diagrams distributed resistance inductance, and capacity, are shown "lumped."

There must be considered the distributing effects of power, telegraph and telephone circuits, and the degree to which telephone circuits may be disturbed by other circuits.

The balanced voltages of an electric circuit or the unbalanced or residual voltage may disturb a communication circuit. Disturbance from such a cause is known as electrostatic inductive interference. Cross talk between telephone circuits, as well as interference from power circuits may be due to such a cause. The magnitude of the disturbing voltages is small, but the proximity of the disturbed and disturbing circuits makes the disturbance in many cases serious.

The balanced currents or the unbalanced or residual current of an electric circuit may also disturb a communication circuit. Disturbance from such a cause is known as electromagnetic inductive interference. Cross talk may be electromagnetic.

Most cases of inductive interference are electrostatic rather than electromagnetic.

The capacities between the two conductors of a single-phase power line and between the conductors and ground are as shown in Fig. 1. If the two capacities to ground are equal and if we imagine the two conductors as shown to be replaced by a conductor made up of two conductors very close together the voltage between this hypothetical conductor and ground will be zero. If the two capacities to ground are not equal the ground potential will not be midway between the potentials of the two conductors. If the two conductors as before are replaced by the hypothetical conductor, there will be a potential between the hypothetical conductor and ground. This potential is the residual voltage. We will have the exact equivalent of a single-phase ground return power line, but with an electromotive force equal to the residual voltage, instead of the electromotive force between the two conductors.

In Fig. 2 are shown the capacities between the conductors of a three-phase power line, and between the conductors and ground. If the capacities to ground are all the same, the voltages to ground may be represented by the dotted lines of Fig. 3. If we were to replace the three conductors by a single hypothetical conductor as in the case of the single-phase line, there would be no potential between this line and ground and no residual voltage. If the capacities to ground are not the same, the voltages to ground might be represented by the full lines of Fig. 3. If a hypothetical conductor were substituted for the three conductors there would be a residual voltage between the hypothetical conductor and ground. Again we would have the equivalent of a single-phase power line with a ground return. The voltage of this single-phase line would be the residual voltage.

The following table taken from the "Final Report of the Joint Committee on Inductive Interference to the Railroad Commission of the State of California," gives characteristic residual voltage in per cent of balanced three-phase voltage between conductors for various configurations of single circuit power lines. It is assumed that the power circuits are untransposed.

Equilateral triangle	0.5 to 4
Vertical	6 to 11
Horizontal	....
Symmetrical	5 to 9
Unsymmetrical	7 to 11
Isosceles triangle	....
Base horizontal	0 to 8
Base vertical	0.5 to 9
"L"	2 to 6
Inverted "L"	4 to 7

Fig. 4 and Fig. 5 show configurations of three-phase lines which would cause unbalanced capacities and voltages to ground, and therefore residual voltages.

It is not possible to balance out the effect of the residual voltage on a telephone line by transposing the conductors of the power line, but transposition will often greatly decrease the residual voltage, because it tends to equalize the capacities between the power conductors and ground.

Grounding one conductor of a power transmission line greatly increases the residual voltage and the interference with adjacent communication circuits. If the line is a single-phase line the residual voltage becomes the voltage between conductors. If it is a three-phase line the residual voltage becomes the vector sum of the voltages, between the two ungrounded conductors and the other one.

Residual currents are the unbalanced currents which flow in the line. It may be readily seen that the effect of these unbalanced currents on communication circuits is the same as if a hypothetical conductor carrying the residual current were substituted for the conductors of the power line, forming a single-phase power line with a ground return.

Electromotive forces and currents which are balanced in the power lines, may cause interference with telephone or telegraph circuits, because they are located at different distances from the latter circuits. The voltage or current which is nearest a communication circuit has the greatest effect on it. Transposition of the power conductors will reduce or eliminate the interference due to balanced voltage and current.

Interference between telephone circuits, or cross-talk, is essentially like that between a power line and a telephone circuit, except that the disturbing voltages and currents are much smaller and the circuits are closer together.

In cases of electrostatic interference alternating current flows from the power line through the distributed capacity between the power line and the telephone line and through the distributed capacity between the telephone line and ground to ground. The voltage in this circuit is the residual voltage, E, between the hypothetical conductor, which represents the combination of all of the power conductors, and ground. A grounded telephone line is shown in Fig. 6. As the telephone substation sets shown at "e" and "f" have a very small impedance, compared with that of the capacity between the telephone line and ground, it may be assumed without much error that all of the current from the power line flows through them. It may be assumed also that their impedance is negligible in comparison with that of the distributed capacity between the power line and the telephone line. Then the total current which will flow to the telephone line will be $I = 2\pi f\ (a+b)E$ where "a+b" is this distributed capacity, and the current through each substation set is $\pi f\ (a+b)E$. Under this condition, there will be a "noise" in the telephone sets at "e" and "f".

If the receivers are on the switch hooks the circuit is open at the substation sets. The voltages across the capacities "a+b" and "c+d" will be inversely proportional to these capacities and their sum will equal E. If E is large touching the telephone line endanger life in extreme cases. However, the capacity "a+b" may be so small, and its impedance so high that an extremely small current flowing through the body will decrease the potential of the telephone line to a small value.

A residual current in the power line would affect a grounded telephone line as shown in Fig. 7. If M is the mutual inductance between the power line and the telephone line the voltage which will be induced in the telephone line by a current Ip in the power line will be $E = 2\pi fMIp$, and if R and L are the resistance and self-inductance of the telephone line the current which will flow in the telephone line will $It = 2\pi fMIp \div \sqrt{R2 + 2\pi fL}$.

In Fig. 8 a metallic telephone line is shown exposed to electrostatic inductive interference from a power line. As the capacities "a" and "c" are greater than "b" and "d" and as "e", "f", "g" and "h" are equal, assuming that the two conductors of the telephone circuit are in a horizontal plane, the points "l" and "m", and "n" and "o", are at different potentials and current will flow from the conductor of high potential to that of low potential through the substation sets at the ends of the line. If the telephone line is transposed as in Fig. 9 less current will flow through the substation sets. There will be a flow of current between "l" and "o" and between "m" and "n" which will redistribute the current in the distributed capacities and make the potentials of the two sides of the telephone circuit more nearly equal. The transpositions must not be too far apart as the impedance of the paths "l-o" and "m-n", which may be considered as shunting the substation sets, might be large enough to prevent effective equalization of the potentials. Even if the transpositions occur at very frequent intervals there will always be a slight flow of current through the substation sets in cases of electrostatic interference.

In some cases metallic telephone circuits may be transposed so that there is very little "noise" in the telephone substation sets, and there may at the same time be sufficient voltage between the two sides of the telephone circuit and ground to give any one who touches the circuit a painful shock.

If the interference is electromagnetic as in Fig. 10, there is greater electromotive force induced in the side "a-b" than in "c-d" because more lines of force which encircle the power line link with the side "a-b" than with the other side of the telephone circuit. The electromotive forces in both sides of the circuit are in the same direction with respect to the power line and it is their difference which forces current through the telephone circuit. Transposing the telephone circuit, as in Fig. 11, equalizes the electromotive forces and makes their sum zero with respect to the substation sets.

Interference is generally both electrostatic and electromagnetic although one or the other may predominate. In most cases electrostatic interference greatly predominates.

It is not difficult to determine to which kind of interference the disturbance is due. In Figures 6, 8 and 9 if the switch hook of the substation set at one end of the telephone line were operated to open the line the current through the other substation set would increase and the "noise" would become louder. Under the conditions shown in Figures 7, 10 and 11 if the telephone line were opened at one end, no current would flow through the other substation set and the noise would disappear. If, therefore, when the telephone line is opened at one end the noise of the interference in the substation set at the other end of the line increases it may be assumed that the interference is electrostatic. If the noise of the interference decreases or disappears it may be assumed that the interference is electromagnetic.

Where the interference is from power lines which carry a lighting load the interference will increase greatly at dusk when the load in increasing if the interference is electromagnetic. If the interference is electrostatic the interference will not increase. Quantitative measurements of interference taken at this time will indicate what kind of interference predominates.

The methods of computing the amount of induced voltage and current in the disturbed line described above are approximate, but give practically accurate results for short lines and lines of medium length. For long lines it may be best in many cases to solve the differential equations of current and electromotive force in the parallel lines.

If there is a ground or leak at the point "p" of the telephone line the current which flows through the capacities "a", "b", "c", and "d" will flow to ground through this leak or ground rather than through the capacities "e", "f" "g", and "h", and in doing so must flow through the substation sets, causing noise. A lumped resistance or impedance in the circuit, may also cause a redistribution of current through the distributed capacities, and of current through the substation sets and thereby cause "noise." The connection of a grounded to a metallic circuit is an extreme case of a ground on one side of the line. Sometimes such a line may be "noisy" where neither line used alone would be "noisy." Connecting the grounded and the metallic lines through repeating coils will frequently correct the trouble.

The sensitivity of the ear to sound varies with the pitch, and there is a frequency at which the diaphragm of a telephone receiver is resonant. It was found by the American Telephone and Telegraph Company that if interfering currents of constant amplitude but of varying frequency are superimposed on the talking current in the standard substation receiver used by the Bell Telephone Companies, interfering current of 1100 cycles a second gives the maximum interference. Currents of frequencies less than 100 cycles cause practically no interference. The interference decreases as the frequency is increased above 1100 cycles per second.

If all of the voltages and currents in distribution systems varied according to a sine wave, no interference of a serious nature would occur. In all distribution systems, however, there are found in addition to the currents and voltages of fundamental frequency, harmonics, or currents and voltages of frequencies which are multiples of the fundamental frequency. Odd harmonics up to the 19th frequently occur and those as high as the 35th have been observed. The even harmonics are balanced out in the generator windings and do not occur in commercial wave forms. Harmonics may be caused by irregularities in the magnetic circuit of generators, by the distortion and voltage wave forms due to the magnetizing currents in transformers, or by other conditions which may exist. As harmonics in the current and voltage wave forms of distribution systems serve no useful purpose and as they are responsible for interference of power circuits with telephone circuits, manufacturers are making every effort to reduce their magnitude in the wave forms of power apparatus.

The harmonics in wave forms may be emphasized by some methods of connecting transformers and other apparatus, and interference may result from transient or abnormal conditions such as those caused by failure of all of the switches in a three-phase circuit to open at the same instant.

In the above discussion the effect of one sine wave, current or voltage only has been considered. If, as is generally the case, the interference is due to currents and voltages of several frequencies, the combined interfering effect equals the square root of the sum of the squares of the individual effects. That is if a, b, c, etc., represent the interfering effects of currents of as many frequencies in a circuit, the combined effect of all of them if introduced into the circuit at the same time is generally equivalent to $\sqrt{a^2 + b^2 + c^2 +}$.

Cross-talk between telephone circuits which is due to the design or arrangement of apparatus is not considered in this discussion. It is a question of apparatus design. Cross-talk which is due to electrostatic or electromagnetic interference between telephone lines may be reduced or eliminated by proper transpositions in the circuits.

The general use of phantom circuits and the necessity for transposing these with respect to other phantom circuits and to side circuits greatly complicates the design of transpositions.

In a long circuit the current and voltage varies in magnitude and phase at various points in the circuit at any instant and there are always irregularities in line construction, so that it is impossible to entirely eliminate inductive effects in the disturbed circuit.

If it were necessary, in the design of transpositions to consider the effect on the disturbing circuit of the current and voltage in the disturbed circuits, computations would become impractically complicated, but fortunately advantage may be taken of the fact that if the cross-talk in the disturbed circuits is reduced to such a degree that it is not serious, the currents and voltages have also been reduced to such a degree that their effect on the disturbing circuit may be neglected.

It is possible to locate the conductors of transposed parallel circuits so there will be no interference between them. This is accomplished by so arranging the conductors that both sides of the disturbed circuit are on the same line of the magnetic field and in the same equipotential surface of the electrostatic field of the disturbing circuit. Transposition designs of this character have been devised for telephone "leads" carrying phantom as well as physical circuits.

Transpositions should always be co-ordinated with discontinuities in the telephone lines, such as loading coils, and with discontinuities in disturbing power lines. In general there should be a complete set of transpositions between each pair of such discontinuities.

Grounded telephone lines cannot be transposed except by the use of repeating coils. This possible method of transposing grounded telephone lines has never been generally followed.

In Fig. 12 is shown a section of a system of transpositions.

Interference with telephone circuits from power lines may be reduced or eliminated by the following methods:

(1) The first, and by far the most effective way to prevent interference is to prevent the construction of power and telephone lines on the same right-of-way. In many cases, however, such construction cannot be avoided. Then the following precautions should be taken.

(2) Build the lines as far apart as possible preferably on opposite sides of the road. If a high tension power line and a telephone line parallel each other on

(Continued on page 21)

CROSS TALK AND INDUCTIVE INTERFERENCE

(Continued from page 6)

the same side of the road for several miles, interference is almost certain to occur even if both circuits are properly transposed.

In many cases for reasons of economy, poles are used jointly by both power and telephone companies. In addition to the danger to life of such a practice, there is the possibility of serious interference and special precautions should be taken to prevent it.

(3) The power and telephone lines should be properly transposed as discussed above.

(4) The power and telephone lines should be cleared of grounds and maintained in that condition. The most serious cases of interference are frequently caused by failure to observe this precaution.

(5) Single-phase taps from three-phase power lines unbalance the line and increase the residual voltage and current. If such taps cannot be avoided, they should be made through a transformer. This will reduce the interference, especially that from the single-phase line. If a schematic circuit is drawn of the capacities through which the interfering current flows, it will be seen that inserting the transformers opens the circuit through which the residual voltage of the three-phase line forces current through the capacities between the single-phase line and the telephone line and ground.

(6) It is sometimes possible to better the wave form of the distribution system. Where there is one harmonic which is causing most of the disturbance, the use of a drainage shunt, which is resonant for the frequency of the harmonic, will frequently eliminate this harmonic from the wave form.

(7) There might be cases where drainage coils on the telephone line and screening wires will reduce interference, but they have not been generally satisfactory. Drainage coils on telephone lines which would shunt interfering current would also decrease the telephone transmission over the circuit.

Other means have been employed to reduce interference in special cases, notably where the induction is from the lines of electrified railroads, but as such cases are unusual they have not been included in this discussion.