RAILROAD COMMISSION OF THE STATE OF CALIFORNIA

REPORT

BY THE

Joint Committee on Inductive Interference

TO THE

Railroad Commission of the State of California

Approved by the Railroad Commission on July 30, 1914

CALIFORNIA
STATE PRINTING OFFICE
1914

REPORT

BY THE

Joint Committee on Inductive Interference

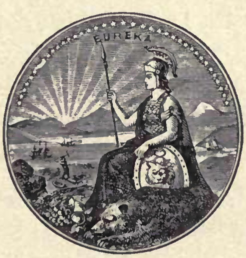
TO THE

Railroad Commission of the State of California

Presenting the results accomplished to date in the study of inductive interference and including recommendations for rules designed to prevent or mitigate inductive interference to communication circuits by power circuits

---

San Francisco, California, July 7, 1914



CALIFORNIA
STATE PRINTING OFFICE
1914

12191

LETTER OF APPROVAL.

SAN FRANCISCO, July 30, 1914.

Joint Committee on Inductive Interference:

GENTLEMEN: We desire to acknowledge receipt of yours of the 7th instant, transmitting the report of the Joint Committee on Inductive Interference, and also of yours of the 23d instant, referring in greater detail to future work of your committee, and to thank you for the same.

The Commission realizes the arduous labor which your committee and the individual members thereof have performed in seeking to ascertain the causes of inductive interference between power and communication circuits, and to prescribe rules and regulations for preventing or minimizing such interference, and extends to the committee, and each member thereof, its congratulations on the results accomplished and its thanks for the scholarly, scientific, painstaking manner in which the work has been performed.

The Commission has adopted the rules as proposed by your committee and has added two new rules, one dealing with the applicability of the rules to existing and future construction and the other declaring the principle that these rules shall be subject to the laws of this State and the orders of this Commission, now or hereafter in effect. The Commission's order will be published as a general order.

Your report will be printed by this Commission for free distribution. While the general conclusions will be given to the press in the usual course, we shall be glad to have the report printed in full in the Proceedings of the American Institute of Electrical Engineers.

The Commission hereby requests your committee to continue its work along the lines indicated in your report and your letter of the 23d instant, and authorizes the raising of the necessary funds by assessment as heretofore, with the understanding that the Commission will assign one of its stenographers to the work of the committee, and that our engineering department will at all times co-operate with your committee.

With sincere appreciation for the work hitherto performed and assurances of continued interest in the work to which you will now devote yourselves,

We remain, respectfully,

RAILROAD COMMISSION,
JOHN M. ESHLEMAN,
H. D. LOVELAND,
ALEX GORDON,
MAX THELEN,
E. O. EDGERTON,
Commissioners.

LETTER OF TRANSMITTAL.

San Francisco, July 7, 1914.

To the Railroad Commission of the State of California,
San Francisco, California:

Gentlemen: The Joint Committee on Inductive Interference submits herewith a report based on its work to date, containing provisional rules which tend to improve conditions in respect to inductive interference. The investigation undertaken by the committee has not been completed, but the results already obtained serve to point out a number of requirements and precautionary measures which should be complied with in future work. These have been embodied in the rules presented herewith, and *it is the recommendation of the committee that these rules be made effective immediately without waiting for the completion of the investigation.*

The committee desires to explain, in respect to certain of the rules, that while the general character of their essential provisions is well understood, the information available at present is not sufficiently complete to make it possible to set definite quantitative limits and to make all the rules explicit, such as they should be in order to afford the maximum reduction of inductive interference consistent with the burdens imposed by the rules. In a few instances, rules have been drawn with definite limits which have been set somewhat arbitrarily, in accordance with the committee's best judgment. Therefore, the rules are not put forth as being complete or final, but must be regarded as provisional and subject to such change as the results of further investigation and experience may determine. They are, however, recommended unanimously by the committee as the best which can be formulated at this time, and thus having the support of all the interests represented on the committee, it is hoped that the rules will appeal to the Commission as being reasonable and proper.

The report also outlines other experimental work, some of which is now in progress, which the committee considers essential in order that additional information may be acquired for amplifying and revising these rules to make them more definite and complete.

Respectfully submitted,

(Signed) RICHARD SACHSE,
A. H. BABCOCK,
R. W. GRAY,
F. EMERSON HOAR,
J. E. WOODBRIDGE,
J. P. JOLLYMAN,
P. M. DOWNING,
H. A. BARRE,
C. H. TEMPLE,
A. H. GRISWOLD,
R. W. MASTICK,
V. V. STEVENSON,
J. A. KOONTZ,
A. L. WILSON,
Joint Committee on Inductive Interference.

Honorary Members:
HOWARD S. WARREN.
JAMES T. SHAW.

REPORT

BY THE

Joint Committee on Inductive Interference to the Railroad Commission of the State of California.

SCOPE.

This report presents briefly an account of the formation of this committee, its activities and results accomplished to date, and recommendations for such rulings by the Railroad Commission of the State of California as the committee believes are justified at this time; together with a technical discussion in explanation of the results and recommendations.

HISTORICAL.

The formation of the Joint Committee on Inductive Interference was the outgrowth of certain differences involving power, communication, and railroad interests which were brought to the attention of the Railroad Commission of California. As an alternative to contesting the issue at that time it was agreed by the power and communication companies, with the approval of the Commission, that a joint investigation should be made to obtain certain information essential to a proper solution of the difficulties. The Commission desired that the matter be thoroughly investigated before passing upon the general principles involved in these difficulties. To this end a general conference was called to select representatives to form a "Joint Committee" empowered to conduct tests, experiments, and investigations, the results of which would serve as a basis of recommendations for rules and regulations to be issued by the Commission, tending to minimize inductive interference and physical hazard arising from parallelism of different classes of circuits. This conference was held December 16, 1912. As a result the Joint Committee on Inductive Interference, representing the Railroad Commission and railroad, power, and communication interests of the State, was organized and authorized by the Railroad Commission of California to conduct the desired investigation.

The personnel of the committee selected is given below.

Representing Railroad Commission:

Mr. R. A. Thompson, Chief Engineer.
Mr. A. R. Kelley, Assistant Engineer.
Mr. James T. Shaw, Assistant Rate Expert.
Mr. F. Emerson Hoar, Assistant Rate Expert.

Representing Railroad Interests:

Mr. A. H. Babcock, Consulting Electrical Engineer, Southern Pacific Company.

Representing Telephone and Telegraph Interests:

Mr. A. H. Griswold, Plant Engineer, The Pacific Telephone and Telegraph Company.
Mr. R. W. Gray, Division Superintendent, Western Union Telegraph Company.

Mr. C. H. Temple, General Manager, United States Long Distance Telephone Company.

Mr. L. M. Ellis, General Manager, Union Home Telephone Company.

Representing Power Interests:

Mr. H. A. Barre, Electrical Engineer, Pacific Light and Power Corporation.

Mr. Louis Elliott, Engineer, Great Western Power Company.

Mr. P. M. Downing, Engineer, Pacific Gas and Electric Company.

Mr. J. E. Woodbridge, Chief Engineer, Sierra and San Francisco Power Company.

The organization and personnel of the Joint Committee on Inductive Interference were approved by the Railroad Commission on January 6, 1913, and the committee thereupon proceeded with the necessary tests and investigations.

For the more efficient conduct of its work the Joint Committee was divided into several smaller subcommittees, each assigned to and responsible for certain branches of the investigation. The present organization of the Joint Committee is given on a chart presented as Appendix VI.

Since the formation of the committee, through additions, resignation or death, the personnel of the committee has changed as follows:

Mr. Louis Elliott resigned and Mr. J. A. Koontz, Engineer of the Great Western Power Company, was appointed in his place.

Mr. V. V. Stevenson, Electrical Engineer of the Postal Telegraph Cable Company, and Mr. L. N. Peart, General Superintendent of the San Joaquin Light and Power Company, were added to the original membership by action of the committee.

Mr. R. A. Thompson, Chairman of the Joint Committee, resigned. Mr. W. C. Earle, his successor as Chief Engineer of the Commission, was elected to membership and chairmanship. Subsequently Mr. Earle resigned and Mr. Richard Sachse, Acting Chief Engineer of the Railroad Commission, was elected to membership and chairmanship.

Mr. L. M. Ellis resigned and Mr. R. W. Mastick, Transmission and Protection Engineer of The Pacific Telephone and Telegraph Company, was elected to membership.

Mr. H. S. Warren, Electrical Engineer of the American Telephone and Telegraph Company, was elected to honorary membership.

Mr. James T. Shaw, Secretary of the Joint Committee, resigned. Mr. A. R. Kelley was elected to the office of secretary. The vacancy in membership created by the resignation of Mr. Shaw was later filled by the election of Mr. A. L. Wilson, Assistant Rate Expert of the Railroad Commission. Mr. James T. Shaw was elected to honorary membership.

The death of Mr. L. N. Peart created a vacancy in membership which was filled by the election of Mr. J. P. Jollyman, Engineer of Electrical Construction of the Pacific Gas and Electric Company.

Mr. A. R. Kelley resigned. To date the vacancy created by Mr. Kelley's resignation has not been filled nor has a permanent secretary been elected.

Early in its work the Joint Committee established a field engineering staff, reporting to the Subcommittee on Tests, to conduct the necessary tests and investigations. This field staff was composed of engineers in the employ of The Pacific Telephone and Telegraph Company and the American Telephone and Telegraph Company, and was later augmented by the addition of two engineers and a stenographer engaged by the Joint Committee.

Previous to the formation of this committee in December, 1912, The Pacific Telephone and Telegraph Company had started an investigation of inductive interference between the lines of the Coast Counties Gas and Electric Company and the lines of the telephone company in the neighborhood of Morgan Hill in Santa Clara County. This investigation was completed by the Joint Committee and its results have been considered in connection with other work carried out by the Joint Committee.

In January, 1913, the Joint Committee established its field staff at Salinas, to investigate parallels on the lines of the Sierra and San Francisco Power Company north of Salinas and on the line of the Coast Valleys Gas and Electric Company south of Salinas, both of these power lines being parallel with the lines of The Pacific Telephone and Telegraph Company, the Western Union Telegraph Company and the Southern Pacific Company's signalling system. The investigation at Salinas continued from January, 1913, until July, 1913.

The specific work undertaken at Salinas was: a determination of the magnitude and characteristics of the induction produced in the communication circuits, the factors in the power circuits causing this induction, the quantitative relationship of cause and effect, and a comparison of the effects on the parallels north of Salinas with the neutral of the power circuit alternatively grounded beyond one end of the parallel and beyond both ends of the parallel.

In July, 1913, the field headquarters were moved to Santa Cruz. At this point the committee desired to test the relative merits of various schemes of transpositions for both power and telephone circuits, and to complete the investigation begun at Morgan Hill on the system of the Coast Counties Gas and Electric Company, which system is of a different character from that studied at Salinas. A mathematical study of transpositions in general, and particularly of those for the parallel between Santa Cruz and Watsonville, has been completed. The experimental study of these schemes of transpositions has not yet been completed.

Owing to the peculiar nature of the experimental work and the refinements required, suitable apparatus was not easily obtainable and in many instances it was necessary to design and develop special apparatus for certain of the tests. A considerable amount of time has necessarily been spent at all points of the tests in choosing from the almost innumerable things which could be investigated with profit, those of greatest value which could be carried out with the means at hand.

In the course of its investigations the committee has prepared a series of fifty technical reports which present and discuss in detail the various features of the work, the methods and apparatus employed and the results accomplished. These reports, which are on file at the committee headquarters in the offices of the Railroad Commission of California, are listed in Appendix V.

RESULTS ACCOMPLISHED.

The following paragraphs summarize very briefly the principal results accomplished to date. These statements of results are accompanied by brief explanatory comment upon the conclusions reached. The reasons for and explanations of these conclusions are given in more detail in the appendices, to which reference is made.

1. *Interference to telephone circuits under normal operating conditions of power circuits arises almost wholly from the harmonic voltages and currents of the power system.* (See Appendix I.)

This is due chiefly to the fact that the frequencies of the harmonics generally present in the voltages and currents of power systems cover a considerable portion of the range of the voice frequencies, particularly those frequencies at which telephone instruments and the human ear are of maximum sensibility. Extraneous currents of frequencies approaching the average voice frequency have a more injurious effect upon telephone conversation than currents of lower frequencies.

2. *The effect of induction of the fundamental frequency on telephone circuits is comparatively unimportant unless it is of magnitude sufficient to constitute a physical hazard.* (See Appendix I.)

This is due to the fact that the fundamental approaches the lower limit of audible frequencies, at which the telephone and the human ear are not efficiently responsive.

3. *Interference to telegraph and other signalling circuits is due principally to the fundamental and lower harmonics.* (See Appendix I.)

Telegraph receiving instruments are relatively insensitive, as compared with the telephone, to the higher harmonics, but are sensitive to disturbances of lower frequencies, such as the fundamental and lower harmonics which more nearly approach the normal operating frequency of such circuits.

4. *The power circuit currents and voltages may be divided into two factors: balanced and residual, of which, for equal magnitude, the latter in general produce the greater inductive interference.* (See Appendix II.)

Residual currents and voltages act inductively in a similar manner to single-phase currents and voltages acting in a circuit composed of the line conductors in parallel with earth return, which is a condition favorable to very large induction. Moreover, such a circuit which includes the earth as one side can not be transposed. Transpositions in the power circuit can not reduce the inductive effect of residuals except as they reduce the magnitudes of the residuals themselves, which they do in some cases. The inductive interference arising from such currents and voltages can be reduced only in the case of metallic circuits, such as telephone circuits, by transposing these circuits. It is, therefore, important that the telephone circuits be transposed at frequent intervals throughout parallels and carefully balanced throughout their entire length, and that the residual currents and voltages be kept sufficiently small to give negligible induction in telephone circuits so arranged.

5. *Inductive interference to communication circuits, arising from the balanced voltages and currents can in a large measure be prevented by means of an adequate system of transpositions applied to both power and communication circuits (assuming the latter are metallic) and located with due regard to each other.*

This is accomplished partly by creating mutually neutralizing inductive effects in neighboring lengths of each side of the communication circuit or circuits by transposing the power circuit, and partly by equalizing the inductive effects on the two sides of the communication circuit or circuits by exposing each side equally to the influence of the power circuit by transposing the communication circuit.

6. *Abnormal conditions and at times switching operations produce transient disturbances of a very severe character.*

This is due to the fact that abnormal conditions almost invariably give rise to residuals of large magnitude, often including high harmonics. Abnormal occurrences incident to electrical power transmission do not give warning of their occurrence, and since they can not be produced artificially on transmission systems without subjecting the apparatus to great risk or danger, it has been deemed unwise to attempt any experimental tests of these effects. This conclusion is therefore drawn from general experience and data of actual occurrences collected by the committee.

RULES RECOMMENDED BY THE COMMITTEE.

The following are the rules which the committee, as the result of its study to date, recommends be issued at this time to govern the future construction and operation of power and communication circuits which are or are proposed to be so located as to create a parallel, as hereinafter defined:

OUTLINE OF RULES.

DEFINITIONS.
- a. *Power Circuit.*
- b. *Communication Circuit.*
- c. *Telephone Circuit.*
- d. *Line.*
- e. *Parallel or Parallelism.*
- f. *Residual Current.*
- g. *Residual Voltage.*
- h. *Transposition.*

I. AVOIDANCE OF PARALLELISM.

II. CONDITIONS UNDER WHICH PARALLELISM WILL BE PERMITTED.
- a. *Minimum Horizontal Separation.*
- b. *Balance of Power System.*
- c. *Limitation of Residual Currents and Voltages.*
- d. *Transpositions Inside Limits of Parallel.*
- e. *Transpositions Outside Limits of Parallel.*
- f. *Uniformity of Parallel.*
- g. *Transformer Connections.*
- h. *Switch Equipment.*
- i. *Switching.*
- j. *Use of Air Switches.*
- k. *Abnormal Conditions.*
- l. *Devices for Indicating Abnormal Conditions on Systems Isolated from Ground.*
- m. *Procedure Under Abnormal Conditions.*
- n. *Ammeters in Neutral Ground Connections.*
- o. *Charging Electrolytic Lightning Arresters.*
- p. *Wave Form of Rotating Machines.*
- q. *Exciting Current of Transformers.*

III. PROVISIONS APPLYING TO EXISTING PARALLELS.

IV. WAIVER OF CONDITIONS BY COMMUNICATION COMPANY.

V. PARALLELISM WITH ALTERNATING CURRENT RAILWAYS.

DEFINITIONS.

The following definitions are given of certain technical terms employed herein:

a. *Power Circuit.* The term "power circuit" includes any overhead constant potential alternating current power transmission or distribution circuit or electrically connected network which has a voltage of five thousand volts or more between any two conductors, or of three thousand volts or more between any conductor and ground.

b. *Communication Circuit.* The term "communication circuit" includes any overhead, open wire telephone, telegraph, or signalling circuit which is used in the service of the public.

c. *Telephone Circuit.* The term "telephone circuit" includes any inter-exchange metallic telephone circuit, and therefore excludes subscribers' circuits. This term also includes any metallic telephone circuit operated by any railroad or other company for dispatching purposes or for public use between separate communities.

d. *Line.* The term "line" means any circuit or aggregation of circuits carried on poles or towers.

e. *Parallel or Parallelism.* The terms "parallel" or "parallelism" refer to cases where a power line and a communication line follow substantially the same course, or are otherwise in proximity for a sufficient distance, so that the power circuit is liable to create inductive interference in the communication circuits.

f. *Residual Current.* The term "residual current" denotes the vector sum of the currents in the several conductors of a power circuit.

g. *Residual Voltage.* The term "residual voltage" denotes the vector sum of the voltages to ground of the several conductors of a power circuit.

h. *Transposition.* The term "transposition" denotes the interchange of position of the several conductors of a circuit.

I. AVOIDANCE OF PARALLELISM.

Every reasonable effort shall be made to avoid new parallelism. The party proposing to build a new communication or power line, which will create a parallel, or generally to reconstruct an existing line involved in a parallel shall give due notice (at least thirty days wherever possible) of its intention to the other party, including detailed information as to the location and character of the proposed line. If a plan can be devised and agreed upon by the two parties for maintaining an adequate separation between the two classes of lines so as to avoid interference, this shall be done. In case it is impracticable to secure adequate separation between a power line and a communication line, parallelism will be permitted, subject to the conditions set forth in II.

II. CONDITIONS UNDER WHICH PARALLELISM WILL BE PERMITTED.

a. *Minimum Horizontal Separation.* The minimum horizontal separation between the power line and communication line shall be equal to the height of the taller line. The only exceptions to this provision are angle crossings and other unavoidable cases of close proximity, and in all such cases the power line shall be kept above the communication line and constructed in conformity with the National Electric Light Association's specifications for overhead crossings or other approved equivalent which may be agreed to by both companies.

b. *Balance of Power System.* The power company shall exercise due diligence to keep the currents in, and the voltages to ground of, the conductors of any power circuit involved in a parallel as closely balanced as practicable. In all cases where telephone circuits are involved, special consideration shall be given to the prevention or elimination of harmonics in the residual current and in the residual voltage.

c. *Limitation of Residual Currents and Voltages.* Pending additional rules on specific means other than those given herein, the parties concerned shall endeavor to agree upon the means to be employed for the prevention or limitation of residual currents and voltages, and in the event of disagreement the matter shall be referred to the Railroad Commission of the State of California.

d. *Transpositions Inside Limits of Parallel.* An adequate system of transpositions shall be installed in the power circuit (or circuits), and in the communication circuit (or circuits) provided the latter is metallic. When both circuits are transposed the transpositions in both the communication and power circuits shall be located with due regard to each other.

Every reasonable effort shall be made by both parties concerned to fix the limits of the parallel and the location of crossings, branch lines, and connected apparatus so as to facilitate the application of an effective transposition scheme.

In the case of a parallel between a power line and a telephone line the company owning or operating the telephone line involved shall have the right to specify the number, type (in respect to electrical characteristics) and location of the transpositions in the power circuit, subject to the following limitations:

1. For power circuits of 50,000 volts or over the average distance between successive transpositions shall not be required to be less than one mile and the minimum distance between any two successive transpositions shall not be required to be less than two thirds of a mile.

2. For power circuits of less than 50,000 volts the distance between successive transpositions shall not be required to be less than one sixth of a mile.

The transposition system of the telephone circuits shall be modified where necessary in order that the power and telephone circuits shall be, as nearly as practicable, mutually non-inductive.

For short parallels less than six miles in length (or short sections of longer parallels which have to be treated independently because of abrupt change in conditions) with power circuits of 50,000 volts or over, where it is impracticable to obtain an adequate balance by the location of transpositions in accordance with the limit specified above, the company owning or operating the telephone line involved shall have the right to specify the number, type and location of transpositions, provided the distance specified between successive transpositions is not less than one half mile.

When necessary (due to variations in lengths of telephone transposition sections) in order to secure an adequate balance, a reduction of 10 per cent in the limiting distances between successive power circuit transpositions as given above shall be allowed.

In the case of a parallel between a power line and a telegraph line or other grounded communication circuit, the location of the transpositions in the power line shall be with due regard to the limits of the parallel in order to form as nearly as practicable a balanced system. The location and type of such transpositions shall be as specified by the communication company, subject to the condition that the transpositions in the power circuit may not be required to be less than one mile apart.

In no case shall the power company be required to relocate poles or towers for the transpositions.

The parties concerned in any proposed parallel shall endeavor to agree upon a transposition scheme for such parallel in accordance with the above. In the event of a disagreement, the matter shall be referred to the Railroad Commission of the State of California.

e. *Transpositions Outside Limits of Parallel.* In addition to transpositions within the limits of a parallel, as provided in "d" hereof, each new power circuit isolated from ground (or extension of such existing circuit) which is constructed subsequent to the date when these rules become effective, shall be transposed throughout its entire length in such manner as to balance the electrostatic capacities to earth of its several conductors, so as to avoid inequalities among the voltages to earth of the several conductors, which would create inductive interference. Such transpositions shall not be more than eight miles apart, provided, however, that circuits less than three miles in length are not required to be transposed until they are extended to a greater length; except that extensions or spurs from existing lines, the electrostatic capacities to earth of whose conductors are balanced, shall be so constructed as not to change materially the balance of the existing lines to which they are connected.

f. *Uniformity of Parallel.* To facilitate the application of effective transpositions, both parties shall endeavor to maintain uniform separation, uniform arrangement of conductors and uniform relative location of the two classes of circuits within the limits of a parallel. However, when it is feasible to secure a substantial increase of separation between the two lines for a considerable portion of a parallel this shall be done, as such an increase of separation is of more benefit than uniformity.

g. *Transformer Connections.* (1) On any power circuit involved in a parallel, no grounded single-phase, or grounded open-star transformer connections shall be employed.

NOTE.—This does not apply to railroads operating alternating current trolleys with ground return which are covered by V.

(2) On a power circuit involved in a parallel no star-connected transformers or auto-transformers with grounded neutral shall be employed, unless delta-connected secondary or tertiary windings or other equiva-

lent means are used of suppressing the third harmonic components of the residual voltages and currents introduced by the transformers.

(3) Where single-phase loads are connected to a polyphase power circuit involved in a parallel the power company shall endeavor to arrange successive connections of this type so as to equalize the loads upon the several phases.

(4) On a three-phase circuit involved in a parallel, the power company shall use, wherever practicable, a closed-delta connection in preference to an open-delta connection, and where the latter is employed an effort shall be made to distribute such connections equally upon the several phases.

h. *Switch Equipment.* A power circuit involved in a parallel shall be equipped, between the source of supply and the parallel, with oil switches, all poles of which shall be mechanically interconnected for simultaneous action. With the exception of stations where an operator is constantly on duty, these switches shall be rendered automatic for short-circuits, grounds, and abnormal neutral currents.

i. *Switching.* All switching on all parts of a system connected to a circuit involved in a parallel, which causes harmful transient disturbances in communication circuits, shall be done by means of oil switches, all poles of which are mechanically interconnected for simultaneous operation.

j. *Use of Air Switches.* The use of air switches, on a power circuit involved in a parallel, is prohibited except for purposes of isolating sections of dead line, or for disconnecting transformers under no load. This applies to the entire power system, any circuit of which is involved in a parallel, unless such switching is so remote as not to cause harmful transient disturbances in the communication circuits.

k. *Abnormal Conditions.* A power circuit involved in a parallel shall not be operated at any time with an open, grounded or short-circuited line wire or wires or transformer winding.

l. *Devices for Indicating Abnormal Conditions on Systems Isolated from Ground.* If a power circuit involved in a parallel is electrically isolated from ground, reliable indicating devices shall be installed at its source of supply to inform the operator immediately of abnormal conditions, such as grounds and wherever possible, open-circuits, which have not operated automatic switches. Upon indication of trouble by such devices, the operator shall immediately open the oil switches and proceed in the manner outlined in "m."

m. *Procedure Under Abnormal Conditions.* In case of the opening of an oil switch due to an abnormal condition in a power circuit involved in a parallel, or any circuit supplying or supplied by the same, such switch may be closed once; if opened a second time due to the continuance of the fault or abnormal condition, said switch shall not be closed again until the line has been sectionalized. The fault may then be located by energizing sections of line, provided that further sectionalization of the line be done in such sequence as to cause the minimum disturbance to parallel communication circuits, and provided further that where practicable the faulty section of line shall be energized but once in this process of sectionalization, where the fault exists within or beyond the parallel, until such fault is remedied.

n. *Ammeters in Neutral Ground Connections.* Wherever a neutral ground connection is employed on a circuit involved in a parallel an ammeter, suitable for measuring as accurately as practicable the current in the neutral under normal operating conditions, shall be installed in all neutral connections at the main generating and substations on the power system electrically connected to the circuit involved in the parallel. The power company shall maintain a record of hourly measurements of the neutral current at all such points.

o. *Charging Electrolytic Lightning Arresters.* Where a power system is equipped with electrolytic lightning arresters so charged as to cause inductive interference in communication circuits, the method of charging the arresters shall be modified to eliminate the disturbances as far as possible. The charging of such lightning arresters shall be done at such time as to give the minimum liability of interference with communication circuit operation, preferably between the hours of 2 a. m. and 4 a. m.

p. *Wave Form of Rotating Machines.* The power company shall make every effort to obtain generators and synchronous motors for use on all parts of the system, giving, as nearly as reasonably possible, pure sine waves of voltage at fundamental frequency. In no case shall the deviation from a pure sine wave exceed the limit set forth in the Standardization Rules of the American Institute of Electrical Engineers.

q. *Exciting Current of Transformers.* In order that the wave shapes of voltage and current may be distorted as little as practicable by transformers, the main line transformers employed on circuits involved in a parallel and on future extensions of such circuits shall have an exciting current as low as is consistent with good practice, and in no case shall the exciting current at rated voltage exceed ten per cent of the full load current. Such transformers shall not be operated at more than ten per cent above their rated voltage.

III. Provisions Applying to Existing Parallels.

The following sections of II shall apply also to power circuits involved in existing parallels: b, i, j, k, l, m, o, p, and q. Also, g-3 and g-4 shall apply to existing parallels to the extent that transformers added hereafter shall be connected as provided in said rules.

IV. Waiver of Conditions by Communication Company.

At the option of the company operating the communication circuit or circuits any of the provisions of II and III may be waived, provided that such waiver does not increase the hazard.

V. Parallelism With Alternating Current Railways.

It is recognized that railroads operating alternating current trolleys with ground return create serious inductive interference with parallel communication circuits. In the present state of the art, no means for completely overcoming inductive interference from such parallels is known, hence, they are to be avoided if possible and where unavoidable, the responsibilities arising therefrom must be settled by mutual agreement or in case of inability to agree the matter shall be referred to the Railroad Commission of the State of California.

DISCUSSION OF RULES.

It will be noted from the definitions that the terms "power circuit" and "telephone circuit" are used in these rules in a special, restricted sense.

(I) The first and most obvious means of preventing inductive interference is to avoid the close association of power and communication circuits. Further, it is recognized that in no other way can complete freedom from interference be secured. While, with the ever increasing network of electrical circuits of all kinds, adequate separation to avoid interference is becoming increasingly difficult to maintain, the committee feels that the importance of such separation justifies its being made the first premise in rules designed to prevent inductive interference.

Notice, sufficiently in advance, should be given the other party or parties concerned in any proposed parallel in order that thorough consideration may be given by both parties to possible means of avoiding the parallel or, in case the parallel can not be avoided, to the necessary remedial measures to be employed.

(II-a) The best insurance against physical hazard in case of close proximity is to maintain a separation equal to the height of the taller line, thus avoiding the possibility of physical contact in case of failure. In the case of crossings and unavoidable cases of close proximity for short distances extra strength construction is necessary as a precaution against failure.

(II-b-c) As has been pointed out under the heading "Results Accomplished," and more fully explained in Appendix II, residual voltages and currents are particularly troublesome factors in causing interference. Means to eliminate or reduce such residuals in power systems are highly important and while information at this time does not enable the committee to formulate as explicit a rule as is desirable, yet the importance of the subject justifies its inclusion in the rules. The acquisition of further information on which to base a more explicit rule upon this subject is a most important problem, the experimental study of which is discussed in the following section of this report.

(II-d) Transpositions properly located in both power and communication circuits offer the most reliable and effective means for preventing interference from balanced voltages and currents of power circuits. While the inductive effects increase in severity for the higher voltage circuits, due in part to the increased separation of the line conductors, which renders more frequent transpositions desirable, the mechanical difficulties involved are so great as to overbalance the other reasons and the rules, therefore, provide for less frequent transpositions in the higher voltage circuits than in the lower voltage circuits. A further reason for frequent transpositions in the lower voltage circuits is the necessity of a flexible system of transpositions applicable to short parallels which generally occur with such circuits.

(II-e) The provision requiring transpositions outside the limits of a parallel on systems electrically isolated from ground is an explicit measure for carrying out the purpose of the more general provision given under II-b-c, "Balance of Power System" and "Limitation of Residual Voltages and Currents."

(II-f) Non-uniformity of separation and type of construction within the limits of a parallel are inequalities which can not in many cases be taken into account in the design and layout of transposition schemes. Such inequalities tend to nullify the effectiveness of the transpositions, hence it is desirable that they be avoided. A precautionary statement is included in the rule in order that the possibility of securing a wide separation for a considerable portion of a parallel may not be sacrificed for the sake of absolute uniformity throughout the entire length.

(II-g) Some types of transformer connections and methods of operation give rise to large residual voltages and currents and certain provisions of the rules are designed to prohibit or restrict the use of such connections and methods of operation. These rules may be considered as explicit provisions complying with the general provision in II-b-c, "Balance of Power System" and "Limitation of Residual Voltage and Currents." The sufficiency of these specific provisions as an insurance against harmful residual voltages and currents is subject to future determination.

The present information of the committee does not warrant the definite recommendation of any one type of connection or method of operation as best from the standpoint of inductive interference. This is true as to the relative merits of the two general types of systems, the grounded neutral and the isolated system. The advantages and disadvantages of these general types and any modifications of these types are dependent upon their inherent characteristics in respect to residuals and the limitations and control of residuals under both normal and abnormal conditions. Both types are on an equality with respect to the interference caused by balanced voltages and currents.

(II-k) Continued operation under certain abnormal conditions is possible in some power systems. In particular, it is possible to operate a grounded star-connected system with one phase open, and it is possible to continue the operation of an isolated system when one phase becomes grounded accidentally. The former gives rise to a large residual current and the latter to a large residual voltage, both of which are liable to render parallel communication circuits inoperative. For these reasons the rule prohibits such operation which, aside from the consideration of inductive interference, does not constitute good practice in power system operation.

(II-h-l-n) To provide that operation under the abnormal conditions mentioned above may not continue without the knowledge of the power company, the rules specify that devices for indicating grounds shall be installed on isolated systems. With respect to grounded star-connected systems, the rules specify with certain exceptions the automatic opening of switches by abnormal neutral currents. In such systems ammeters are required in all main neutral ground connections. Such ammeters, read regularly, afford means of detecting abnormal neutral currents and are of value in showing the degree of balance of the system, as the neutral current is easily affected by unbalanced conditions.

(II-m) Accidental causes give rise to occasional abnormal conditions. These can only be guarded against by good construction and maintenance, and careful operation which, however, can not prevent entirely such occurrences. When trouble develops on a power circuit involved in a parallel, it is always liable to cause serious interference to the communication circuits, if the exposure is severe. In the present state of the art, the method of fault location on power circuits is a process of repeated sectionalization and energization of the faulty line until the fault is located within certain limits. This process causes repeated interruptions with loss of time in the operation of the communication circuits, and in the case of telephone circuits is accompanied sometimes by injury to the operators. It should be explained that the loss of time is much greater than the duration of the disturbance, owing to the time required to restore the protective devices on the communication circuits to their normal condition. No method of locating faults on power circuits is known which meets the requirements of practice and yet avoids the disadvantages of the present method. The inductive disturbances due to fault location can be to a considerable degree ameliorated by disconnecting the faulty line from the rest of the system and energizing this line by a single generator at such excitation as may be necessary to overcome the insulation of the fault. Whenever practicable this method is employed by power companies; hence, it has not been thought necessary to cover it by a specific rule.

In view of these facts, the committee is recommending the limitation of the present practice in this regard so as to avoid, as far as seems practicable, the repeated interruptions to communication circuit operation. It is highly desirable that some better method of fault location be developed, not only because of the attendant consequences of the present method on communication circuits, but also because of the abnormal strains to which the power apparatus is necessarily subjected.

(II-h-i-j) Normal switching operations on power circuits produce at times severe transient disturbances in parallel communication circuits. The commonly recognized fact that oil switches produce less severe transient disturbances in power circuits, affords the basis for the provisions in the rules dealing with switches and switching. The automatic features required are designed to prevent continued operation under abnormal conditions.

(II-o) Transient disturbances of severe nature to telephone circuits are sometimes caused by the charging of electrolytic lightning arresters. There are available methods of diminishing the transients due to this cause, and a general provision to the effect that such methods shall be employed when necessary is included in this rule. It is further provided that the charging of arresters should be done at times when the telephone circuits are least used.

(II-p-q) Fundamentally, interference to telephone circuits by power circuits in normal operation is largely due to the existence of harmonics in the currents and voltages. While the complete elimination of these harmonics seems impracticable, still beneficial results may be obtained by practical efforts in this direction, and the committee feels that the two general provisions as to the wave form of rotating machines and the exciting current of transformers are of great importance both from a practical standpoint and also as enunciating a general principle. The matter of generator wave form particularly is of importance for all types of systems. The provision with reference to the exciting current of transformers, while desirable in all cases, is particularly so on grounded star-connected systems.

(III) Certain of the measures in II, particularly those referring to power system operation, which are helpful in mitigating inductive interference have been recommended to apply to existing parallels.

(IV) Since these rules are designed for the protection of communication circuits, it is proper that the companies operating such circuits be given the right to waive any measures of protection which they may in any particular case consider unnecessary.

(V) The committee has undertaken no investigation of cases of parallelism with alternating current railways, but as the seriousness of this class of exposure is recognized, it was thought desirable that it be referred to specifically.

FUTURE WORK.

The further work necessary in order to secure the information essential as a basis of determining more explicit and effective rules than those herein recommended, is particularly concerned with the subjects of transpositions and residual voltages and currents. In order to cover these subjects in as effective and economical a manner as possible it is thought that the procedure should be along the following lines:

1. Experimental study of transpositions which includes the determination of:

(*a*) The practical effectiveness of transpositions in both power and communication circuits as a means of reducing induction arising from balanced voltages and currents; involving considerations of different co-ordinated transposition schemes, particularly with different lengths of power circuit barrels.

(*b*) The practical effectiveness of transpositions in communication circuits as a means of reducing inductive interference arising from residual voltages and currents; involving considerations of different systems, particularly different lengths of balanced communication circuit transposition sections.

(*c*) The influence of imperfect electrical balance of communication circuits in impairing the effectiveness of transpositions.

(*d*) The practical effectiveness of transpositions in a power circuit isolated from ground as a means of balancing the electrostatic capacities to earth of the several conductors, and thereby reducing residual voltages and currents; involving considerations of the relative efficiency of different lengths of power circuit barrels.

2. Experimental study of the causes and effects of residuals, including:

(*a*) A comparison of the different types of power system connection and apparatus in common use and their characteristics in respect to the production of residuals, particularly harmonic residuals.

(*b*) Means to be employed in limiting residual voltages and currents.

(*c*) A determination of the minimum values of residual voltages and currents which will produce harmful inductive interference.

It is thought that these two studies could progress simultaneously. The work indicated under (1) could best be done on an actual parallel selected to be as uniform and as free from secondary disturbances as possible. Some preliminary work has been done along these lines which indicates the best methods of procedure, and this should facilitate the carrying out of the investigation.

The study mentioned under (2) consists in part of an investigation of the characteristics and magnitudes of residual voltages and currents in typical power systems, both those with grounded neutrals and systems entirely isolated from ground. A part of the study of residuals is logically related to the study of transpositions and could be carried out in connection with the study outlined under (1) and at the same time and place.

In addition to the above the committee has already arranged for the investigation of the two following subjects:

1. A determination of the detrimental effect of extraneous currents on a telephone circuit as a function of the frequency including a determination of the maximum amount of extraneous current, of different frequencies and combinations of frequencies, which is allowable in a commercial telephone circuit.

2. A determination of the effects of extraneous current of different amounts and characteristics, in limiting the speed of telegraph operation.

This work is now in progress.

APPENDIX I.

HARMONICS.

Any complex electrical wave of periodic structure may be resolved into component sine waves of suitable amplitudes and phase differences, having frequencies which are in integral relation to the fundamental frequency. The simple sine wave of lowest frequency is termed the fundamental, and those of higher frequency are termed harmonics of the fundamental wave. The fundamental may be considered the first harmonic. The analysis of a periodic wave into its constituent sine waves or harmonics is not merely a mathematical conception or process but is in accordance with the facts of electricity and acoustics.

In general, alternating current systems, by virtue of their inherent characteristics, do not permit the existence of harmonics other than odd integral mulitples of the fundamental frequency, *i. e.*, 3d, 5th, 7th, 9th, 11th, etc., harmonics. Such harmonics may exist in either or both the current and voltage waves of a power system.

Commercial frequencies of power transmission in California are 25, 50 and 60 cycles per second. The power systems, so far investigated, operate at a fundamental frequency of 60 cycles per second. The investigation has shown harmonic currents and voltages of appreciable magnitude up to the 35th harmonic. On one system the 23d (corresponding to a frequency of 1,380 cycles per second) has been found to be prominent. Induced currents and voltages in parallel communication circuits have been observed corresponding to these harmonics.

The detrimental effect of the induced voltages and currents in parallel communication circuits depends, in general, upon their magnitude and upon the frequency of the induction as compared with the operating frequency of the communication circuit. The presence of extraneous current of a frequency approaching that of normal operating frequency of the communication circuit has a more injurious effect than the same amount of current of a frequency far removed from the operating frequency of the circuit.

The frequency of the voice currents flowing in a telephone circuit ranges from about 200 cycles per second up to possibly 2000 cycles per second. The average voice frequency is considered to be approximately 800 cycles per second, and at about this frequency the telephone receiver is most sensitive. It is on account of these considerations that extraneous currents of the higher frequencies, arising from the harmonics of a power system, are relatively more detrimental to telephone service. The harmonics of the power systems have been found to be responsible for the greater portion of the inductive interference to telephone service, under normal operating conditions of parallel power circuits. Any extraneous current of a frequency within the audible range produces a disturbance which impairs the efficiency of a telephone circuit. The combined effects of all extraneous currents present, of frequencies within the range of audition, constitute the humming "noise" heard in the receiver of a telephone circuit which is subject to induction.

The effect of currents of the fundamental frequency (60 cycles or less) on telephone circuits is relatively unimportant as compared to that of higher harmonics, owing to the fact that the fundamental approaches the lower limit of audible frequencies. However, if the induction due to the fundamental becomes sufficiently great, constituting a physical hazard, or of such magnitude as to operate the protective devices on the telephone circuits or interfere with superimposed telegraph service or other grounded signalling devices, it is then of great importance from the standpoint of interference.

In regard to the effect of extraneous currents on the operation of telegraph circuits, for reasons analogous to those given above, such circuits are relatively more affected by extraneous currents of fundamental frequency or of the frequencies corresponding to the lower harmonics such as the 3d and 5th.

At the present time the American Telephone and Telegraph Company is undertaking, on behalf of the Joint Committee on Inductive Interference, an extensive series of tests in regard to the detrimental effect of extraneous currents of various frequencies on the intelligibility of telephone conversation. In addition, this company, in conjunction with the Western Union Telegraph Company and the Postal Telegraph Cable Company, is undertaking an investigation of the effect of extraneous currents on the operation of telegraph circuits and apparatus of different types.

Harmonic currents and voltages in power circuits arise from many causes. Generators or other rotating machines do not, in general, produce pure sine waves of fundamental frequency. This is due to several features in the design of the apparatus. A certain amount of distortion of wave form, with the consequent introduction of disturbing harmonics, is inherent with the use of transformers. This distortion of wave form is due to hysteretic action in the iron core of the transformer. The distortion varies in character and magnitude with the saturation and characteristics of the iron employed. Certain connections of transformers are possible which will suppress the third harmonic and its multiples in a three-phase power system. The fact that practically all inductive interference to telephone circuits is due to the harmonic currents and voltages, renders it important that an effort be made to obtain rotating machinery for use in power systems which produces as nearly as is reasonably possible pure sine waves of fundamental frequency, and also that an effort be made to obtain transformers and to arrange connections of the same in such a manner as to reduce as far as practicable the distortion of wave form.

APPENDIX II.

BALANCED AND RESIDUAL VOLTAGES AND CURRENTS.

This appendix comprises the four following sections:

1. Analysis of Voltages and Currents and Discussion of the Effects of their Components.
2. Causes of Residual Voltages and Currents.
3. Means for Preventing or Reducing Residual Voltages and Currents.
4. Discussion of Tests.

1. Analysis of Voltages and Currents and Discussion of the Effects of Their Components.

To facilitate the analysis of inductive effects in parallel communication circuits, arising from a power circuit, the voltages and currents of the power circuit can be conveniently regarded as consisting of components which exhibit distinct characteristics and which may be treated separately.

Considering a three-phase circuit having equal voltages between any two conductors, the voltages to ground from the conductors can be resolved into two sets of components, balanced components and residual components. Since the voltages between any two conductors are equal. the voltages between the conductors may be graphically represented by three vectors forming an equilateral triangle. The potential of the ground may be represented by a point which may be inside or outside of the triangle depending on the magnitude and character of the residual voltage, and the actual voltages to ground from the conductors may be represented by three vectors drawn between the point representing the ground potential and the corners of the triangle. The balanced components of the voltages to ground from the conductors consist of three equal voltages whose vector sum is zero and which are therefore displaced one third cycle in time phase with respect to one another. These balanced components may be represented by three vectors drawn from the center of the equilateral triangle to the corners. The residual components of the voltages to ground from the conductors consist of three equal voltages which are in phase with one another and which may be represented by three identical vectors drawn from the point representing the ground potential to the center of the equilateral triangle. If the residual voltage is zero the point representing the ground potential will be at the center of the triangle. The residual voltage of the system is defined as the vector sum of the voltages of the three conductors to ground. It is, therefore, by definition, three times the residual voltage of the individual conductors, or three times the equivalent single-phase voltage of the three conductors in parallel with respect to the earth. It should be noted that the inductive effect of the residual voltage is equal to that of a single-phase voltage between ground and the three conductors in parallel, equal to the residual voltage of the individual conductors, or to one third the residual voltage of the system.

If one conductor is grounded the residual components (assuming the voltages between wires remain unchanged) will each equal the voltage between conductors divided by the square root of three, and the residual voltage of the system will be equal to the voltage between conductors multiplied by the square root of three.

If a power circuit consists of a single conductor with ground return, the residual voltage will be equal to the voltage from the conductor to ground.

The currents flowing in the three wires of a three-phase, three-wire circuit can be considered to be composed of three sets of currents; namely, (1) balanced components consisting of equal currents in each of the three line wires whose vector sum is zero, and which are, therefore, displaced one third cycle in time-phase with respect to one another; (2) a single-phase current flowing in a loop composed of two of the line wires; (3) a residual current divided equally between the three line wires and returning through the earth. The residual current of the three-phase circuit is defined as the vector sum of the three line currents. It is, therefore, the equivalent of a single-phase current flowing through the three line conductors in parallel, with the earth completing the circuit.

In the case of a power circuit consisting of a single conductor with a ground return the entire current flowing in the conductor is residual.

In the above discussion, reference is made to three-phase, three-wire power circuits, but the analysis there given may be generalized so as to apply to a power system of any number of phases. Most electrical power transmission systems are of the three-phase, three-wire type and subsequent statements will apply particularly to such systems, unless otherwise stated.

At a point in the vicinity of a power circuit, such as might represent the location of an element of a communication circuit conductor, the resultant electromagnetic field due to the balanced currents would be zero if the power circuit conductors were equidistant from the point (disregarding the effect of the earth). In general, the power circuit conductors are not exactly equidistant from such point, and therefore the resultant electromagnetic field due to balanced currents is not zero. For this reason, the balanced currents in the power circuit have unequal effects on the communication circuit, hence there is a resultant induction. For residuals, there is, in general, a much greater inequality in the distances between the affected conductors (or circuits) and the sides of the residual circuit (power conductors in parallel one side, earth other side) than in the distances to the several power conductors, which constitute the circuit for the balanced components. Thus the resultant electromagnetic field due to residual currents is large in comparison with the field set up by balanced currents of the same magnitude. It may be noted that the electromagnetic forces at any point due to residual currents in the different power conductors are in the same time-phase, hence the inductive effects of all the residual components are cumulative and not differential as in the case of the balanced components.

In a similar way it may be shown that residual voltages produce proportionately far greater inductive effects than balanced voltages.

Computations based on the physical characteristics of two of the parallels investigated show that, for an exposure near Salinas for eight miles with a 55,000-volt line on the opposite side of the county road from a communication line, one ampere of residual current produces as much induction in a ground return communication circuit as would forty amperes of balanced current; and one volt residual produces as much induction as one hundred and ten volts balanced. Similar computations based on the physical characteristics of an exposure between Santa Cruz and Watsonville, where the communication circuits are paralleled for seventeen miles by a 22,000-volt line on the opposite side of the county road, show that one ampere residual produces as much induction in a ground return communication circuit as would two hundred and forty amperes of balanced current; and one volt residual produces as much induction as ten volts balanced. All of the above comparative values are for currents and voltages of sixty cycles frequency.

The above values illustrate the relative induction-producing powers of balanced and residual currents and voltages in two specific cases. Such values will vary considerably for different parallels, but these cited may be taken, in a general way, as indicative of the relative severity of the effects on a single conductor produced by these two factors. Such values for a unit length of non-transposed circuit in any given parallel, are dependent upon the separation, height, and configuration of the conductors of the two classes of circuits, and upon the character and condition of the ground and neighboring objects. For the entire parallel, or total length of exposure, these values are further dependent upon transpositions. The actual amount of induction arising from each of the two components depends also upon the actual magnitudes and the frequencies of the components in the power circuit.

It will be shown in Appendix III that inductive interference arising from balanced currents and voltages can be reduced by proper transpositions in the power circuit, but that power circuit transpositions do not reduce the inductive interference produced in a parallel communication circuit by residuals. Residual currents and voltages act inductively to produce the same effects as a single-phase grounded circuit operating with the three line conductors in parallel. This generally represents the worst possible condition from the standpoint of inductive interference. Transposing the conductors of the power circuit can not reduce the inductive interference arising from residuals, except in so far as the magnitude of the residual voltages and currents is reduced by such transpositions. The effect of power circuit transpositions on the magnitude of these components is discussed below.

In the detailed discussion of transpositions in Appendix III it is shown that transpositions in a communication circuit can reduce the induced voltages from residuals only as between the two sides of a metallic circuit.

In view of the above it is evident that attention must be given to the problem of restricting residuals to amounts which do not cause material interference either to grounded communication circuits or to properly transposed and balanced metallic circuits.

2. Causes of Residual Voltages and Currents.

While a degree of balance of the voltages and currents of the power system may be obtained which satisfies all the practical demands of power operation, this may not be sufficient to prevent the production of residuals sufficient to cause serious inductive interference to parallel communication circuits.

Residual currents and voltages may arise from one or more causes which act singly or together. The principal sources of residual currents and voltages are,

1. Unbalanced loads between the three phases and the neutral of a grounded star-connected system.
2. The introduction of the third harmonic and its odd multiples as residual current and voltage due to certain apparatus and connections employed on a grounded star-connected system.
3. Unbalanced capacity and leakage between the several phases of the system and ground. This applies more particularly to systems isolated from ground.

There are two principal types of commercial three-phase power circuits used in California.

1. The grounded neutral circuit or network, in which all important generating points have a grounded neutral and in which all or part of the receiving points may be connected with a grounded neutral. No resistances are inserted between the neutrals and ground.
2. The isolated circuit or network, which normally has no metallic connection to ground at any point.

The characteristics of the grounded neutral system with particular reference to residuals are as follows:

Under Normal Conditions.

(*a*) The impedances between line conductors and ground are determined very largely by the load impedances of the transformers. With balanced loads the residual voltage other than the third harmonic and its odd multiples may be eliminated.

(*b*) The effect of unbalanced loads on the residual voltage is small, as the tendency of generators and transformers is to maintain equal voltages between the several conductors and ground.

(*c*) With balanced loads the residual current, other than the third harmonic and its odd multiples, may be eliminated.

(*d*) Unbalanced loads between line and neutral cause corresponding residual currents, which will be large if the unbalance is large, as such unbalanced load currents flow through the neutral to earth.

(*e*) The varying permeability of the iron in star-connected transformers with grounded neutrals introduces the third harmonic and its odd multiples as residual voltages and currents. The use of delta-connected secondary windings reduces this effect greatly below that of star to star-connections.

(*f*) Grounded star-connected generators connected directly to the line or through grounded star to star-connected banks of transformers, may introduce the third harmonic and its odd multiples as residual voltages and currents.

Under Abnormal Conditions.

(*g*) A ground on one phase short-circuits that phase through the neutral connection and causes a residual current throughout the whole length of the circuit, this current being practically equal to the short-circuit current to ground on that portion of the circuit between the sources of power supplying the fault and the point where the circuit is grounded. A large residual voltage (approaching as maximum 58 per cent of the voltage between phases) will be created in proximity to the fault and, if the low tension side of the receiving transformers is star-connected, throughout that portion of the circuit between the fault and such receiving transformers. If the neutral of the receiving transformers is isolated, the short-circuit current will exist only between the source of supply and the fault and there will be no residual current between the fault and such receiving transformers. The above mentioned residual voltage will in this case exist not only in proximity to the fault on the supply side but also throughout the length of circuit from the fault to the receiving transformers. The power circuit is rendered inoperative.

(*h*) An open condition of one phase causes a large residual current, as the unbalanced load currents of the other two phases must flow through the neutral to earth. A large residual voltage will exist beyond the fault if the low tension side of the receiving transformers is star-connected. The power circuit may not be rendered inoperative for three-phase supply beyond the fault, in case the receiving transformers are grounded star-delta connected.

The characteristics of the isolated system with particular reference to residuals are as follows:

UNDER NORMAL CONDITIONS.

(*a*) The impedances between line conductors and ground are determined by the electrostatic capacities and the leakage between the several conductors and ground. With balanced loads a residual voltage may exist, due to unbalanced capacity and leakage. Such residual voltage as is due to unbalanced capacity may be eliminated by transposing the circuit so as to equalize the electrostatic capacities to ground of the several phases. If there are single-phase branches making the total lengths of the three conductors unequal, this will introduce inequalities among the capacities to ground which it may not be possible to balance by transpositions. Inequalities in capacity or leakage result in unequal voltages between the different line conductors and ground.

(*b*) The effect of unbalanced loads on the residual voltage is very slight.

(*c*) With balanced loads a small residual current consisting of unbalanced charging current may flow due to non-uniform distribution of unbalanced capacity and leakage.

(*d*) Unbalanced loads have but a slight effect upon the residual current.

(*e*) The transformers can not introduce the third harmonic and its odd multiples as residual voltages or currents.

NOTE.—Due to unsymmetrical three-phase connections sometimes employed (such as open-delta and Scott connections) the third harmonic and its odd multiples may appear in the voltages between lines and in the line currents, creating dissimilarities in the wave forms for the several phases. These harmonic components of the line voltages and currents are affected by unbalanced capacity and leakage in the same way as any other components as may appear in the residuals. It should be noted, however, that such harmonics are not impressed directly upon the line as residuals, as in the case with grounded neutral systems.

(*f*) The generators can not introduce the third harmonic and its odd multiples as residual voltages and currents.

NOTE.—If a two-phase generator containing a third harmonic in its voltage wave supplies the line through Scott or other two to three-phase transformer connections the third harmonic will appear in the voltage between lines. Subject to the conditions of the circuit as regards capacity and leakage balance, this harmonic along with all others may or may not appear in the residuals.

UNDER ABNORMAL CONDITIONS.

(*g*) A ground on one phase causes a large residual voltage (173 per cent of the voltage between phases) throughout the entire length of the circuit. A residual current will be created in proximity to the fault, its magnitude increasing with the extent, voltage and frequency of the system. The power circuit may not be rendered inoperative and the power company operators may be unaware of the existance of the abnormal condition. In some cases the residual voltage and currents are greatly augmented by the resonant effects accompanying arcing grounds.

(*h*) An open condition of one phase may cause a large residual voltage, a certain amount of residual current will flow, due to the interchange of unbalanced charging current, between sections of line on either side of the fault. The power circuit is rendered inoperative for three-phase supply beyond the fault.

A consideration of the characteristics of the two types of systems indicates that under normal operating conditions with balanced loads upon all phases, the residuals of the grounded neutral system may be limited to the third harmonic and its odd multiples. The magnitude of these harmonics is dependent largely on the type of connection on the low tension side of the transformer banks, the delta being preferable to star-connection. Under the same condition the residuals of the isolated system may be limited to those resulting from unbalanced leakages to ground, which should be small on a well maintained system. The effect of an unbalance in the loads connected between conductors upon the residuals of either type of system is small, while the effect of an unbalance in the loads connected between conductors and ground upon a grounded neutral system is to cause a residual current which is proportional to the amount of such unbalance which will be large if the unbalance is severe. The residual current, due to this cause, consists of the fundamental and all harmonics present in the line currents, in addition to which the third and its odd multiples are introduced as before by the varying permeability of the transformer iron, and in some cases by the generators.

Under abnormal conditions both types of systems give rise to residuals which are liable to cause interruption and damage to parallel communication circuits. The most frequent abnormal condition which produces severe interference is an accidental ground. A ground on one phase of a grounded star-connected system creates a severe and widespread electromagnetic unbalance, giving rise to corresponding inductive effects. This is accompanied by an electrostatic unbalance in the vicinity of such ground. On the lower voltage systems this latter effect is relatively of little importance. On the other hand, a ground on one phase of an isolated system creates a severe and widespread electrostatic unbalance, giving rise to corresponding inductive effects. This is accompanied by an electromagnetic unbalance in the vicinity of the ground. On small low-voltage isolated systems, such electromagnetic unbalance is relatively of little consequence, but it should be noted that with increased voltage and extent of the system such effects do become of great importance, giving rise to electromagnetic disturbances in exposed communication circuits in addition to the electrostatic disturbances.

The magnitude of the inductive effects from either type of system is dependent upon the character of the exposure, extent of the power circuit and other factors which render it impossible with the information at hand to draw a definite conclusion as to the relative total amounts of interference inherent with the two types of system. Furthermore, it is not necessarily true that either type of connection has an advantage from the inductive interference standpoint for power systems of all sizes and voltages.

3. Means for Preventing or Reducing Residual Voltages and Currents.

To minimize or prevent residual voltages and currents due to cause 1, it is necessary to equalize as closely as practicable at all points the load between the several phases of the circuit and the neutral, or to remove the ground path for unbalanced load currents, thus allowing a grounded neutral at one end of the circuit only. As it is difficult, if not impossible, to maintain all loads in a state of equilibrium at all times, the latter method has the advantage of greater reliability.

Single-phase connections to ground should not be employed. Where single-phase loads or unbalanced three-phase loads must be supplied, the transformers supplying such loads may be connected across the line wires, or may be connected star to delta, with the neutral not grounded. It should be noted that single-phase or unbalanced three-phase loads on the low tension or delta side of grounded star to delta-connected transformers produce effects on the high tension side similar qualitatively to single-phase loads between line and ground, but these effects are greatly reduced in magnitude by the inherent balancing influence of transformers so connected, due to the fact that all three transformers participate in supplying such a single-phase load.

Residuals which arise from cause 2 may be greatly reduced by means of certain types of connections for generators and transformers. Thus, for example, connecting the secondary windings of the transformer banks in delta largely suppresses these components of the residual voltage and current but does not entirely prevent them. Where the transformers are connected grounded star to star, these components can be, to a certain extent, kept out of the line by the use of a second bank of transformers having a delta connection on one side and a star connection on the side in common with the first bank with the neutrals interconnected.

The possibility of the introduction of third harmonic residuals on the line due to the use of grounded star-connected generators may be avoided by the employment of transformers between generators and line, the windings on the generator side of the transformers being isolated from ground.

To eliminate or reduce residual currents and voltages which may be due to cause 3, it is necessary to transpose the conductors of the power circuit so as to equalize the electrostatic capacities of the several phases to ground, and this equalization must be attained within distances sufficiently short to prevent the accumulation of large unbalances. With a horizontal arrangement of conductors, the capacities to ground are more nearly equal than with the triangular or vertical arrangement. It is probable that the electrostatic capacities are the controlling factors in determining the residual voltage and current of an isolated system under normal operation, and while an investigation of the extent to which such residuals may be reduced by properly spaced transpositions has not as yet been made, it is reasonable to suppose that transpositions will be substantially effective. The effect of unbalanced leakage can not be controlled, except through proper construction and maintenance of the power system. It is to be noted that the maintenance of the system free from accidental grounds and partial grounds becomes increasingly difficult the larger the extent of the power network.

On a grounded star-connected system, the electrostatic capacity and the leakage of the several phases to ground are relatively less effective in producing residual voltage, as on such systems the voltages to ground are determined almost entirely by the generators and transformers.

4. Discussion of Tests.

Having given a general analysis of the causes and effects of and means to reduce residual currents and voltages, it is desirable to call attention to the results of tests which have been conducted, which have a bearing on this subject.

At Salinas the effect of grounding or isolating the neutral of the auto-transformers, which have also a secondary delta winding, was investigated. These auto-transformers are supplied at 55,000 volts over a transmission line which parallels the circuits of The Pacific Telephone and Telegraph Company in what have been termed exposures No. 1 and No. 2. These auto-transformers in turn supply a 33,000-volt line of the Coast Valleys Gas and Electric Company, extending from Salinas to King City, a distance of approximately 45 miles, and paralleling throughout practically this entire length, the coast route toll lead of The Pacific Telephone and Telegraph Company. These same telephone circuits are involved in the parallels with the 55,000-volt line north of Salinas. In addition to supplying the King City line, this bank of auto-transformers at Salinas supplies a 22,000-volt line extending to Monterey, a distance of approximately 18 miles. Aside from the ground on the transformer neutral at Salinas, there are no grounds on either the 33,000-volt line or the 22,000-volt line. The 55,000-volt line supplying the Salinas transformers is energized at the Guadalupe substation of the Sierra and San Francisco Power Company, approximately 73 miles distant from Salinas through grounded star-connected auto-transformers, which have delta-connected secondary windings, and which are supplied by the 104,000-volt line of this same system which operates with grounded neutral connections at its main generating station and substations. It will be understood from this statement of conditions that the neutral current at Salinas is not identical with the residual current of any one of the three high-tension lines which are connected together by these auto-transformers. The condition of the Salinas neutral affects the induction arising from the several exposures through its effect on the residual currents and voltages of the high tension lines connected to the auto-transformers at that point. A representative value of the neutral current at Salinas during these tests is 0.3 ampere. It is composed almost entirely of the ninth harmonic, the fundamental and the third harmonic, their magnitudes decreasing in the order named. With the power system in normal operation, isolating the neutral of the auto-transformers at Salinas did not greatly affect the resultant induction in the particular exposures under observation. The values in the following table, taken from the data of the tests, indicate the effect of the condition of this neutral on the residual currents of the 55,000-volt and the 33,000-volt lines.

Residual Current at Salinas—Amperes.

Order of harmonic	55,000-volt line		33,000-volt line	
	Neutral at Salinas		Neutral at Salinas	
	Grounded	Non-grounded	Grounded	Non-grounded
1	0.120	0.057	0.061	0.073
3	0.054	0.160	0.075	0.120
9	0.073	0.100	0.120	0.075

Two reasons may be given for the fact that the condition of the Salinas neutral does not greatly affect the resultant residual current of these lines: (1) The load balance on these lines is such that a relatively small amount of load current flows through this neutral; (2) As three high tension lines are connected together by these auto-transformers, opening their neutral connection to ground does not completely eliminate the path for the residual current of any one of the three lines, since it may then flow to earth through the admittance to ground of the other two lines.

These particular conditions are not commonly found but a similar condition, in that there is a path to ground for residual current aside from the neutral connection, prevails in any case where the power circuit extends for a considerable distance beyond such neutral connection. The investigation showed, for the conditions which applied to the 55,000-volt line, that removing the neutral ground connection beyond the parallel decreased the fundamental and increased the third and ninth harmonics in the residual current, as shown in the above table. It is not to be concluded, however, from this one case that the third harmonic and its odd multiples in the residual current would in all cases be increased by removing the neutral ground connection of a bank of receiving transformers where the circuit extends beyond the point of measurement of such residual current. If the circuit is terminated at the transformer bank, the removal of the neutral ground connection must eliminate the residual current at that point.

In the case of the 33,000-volt line, the grounding of the neutral at Salinas merely gave another and nearer grounded neutral point on the line supplying power, but did not give a grounded neutral point in each direction from the point of measurement of the residuals, as it did in the case of the 55,000-volt line. As the 33,000-volt line has no ground connection beyond Salinas, the residual current must flow to ground entirely through the admittance of this line to ground. The residual current, therefore, diminishes to zero at the King City end of the line. Isolating the neutral of the Salinas transformers affects the constituents of the residual currents in this line arising from the Salinas transformers and those impressed by the 55,000-volt line, in such a way that they combine vectorially to give a different resultant from that with the Salinas neutral grounded. The result is to increase the fundamental and third harmonic and to decrease the ninth harmonic when the neutral is isolated. The residual current in the 22,000-volt line was not determined, but residual voltage measurements were made with the Salinas neutral isolated and grounded and the results are included in the following table, from which it may be noted that the fundamental, third and ninth harmonics were all greater with the Salinas neutral isolated.

The banks of star-connected auto-transformers at the Guadalupe and Salinas substations are provided with closed-delta secondary windings, which in the case of Salinas supply power for local consumption. An experimental opening of the delta at Salinas demonstrated, as would be anticipated, that the use of such delta-connected secondary windings reduces, in a large measure, the third harmonic introduced by these transformers in comparison with its value without the use of such delta-connected windings. If grounded star-connected transformers are used, it is important, therefore, from the standpoint of induction, to provide such transformers with closed-delta connected secondary windings or with other means of reducing the third harmonic and its odd multiples. Such means may, however, in some cases be insufficient to reduce the residuals to such low values that they will not produce harmful inductive interference to parallel communication circuits.

The investigation on the system of the Coast Counties Gas and Electric Company shows results which are summarized in the following table with reference to the residual current and residual voltage. Santa Cruz, where the measurements were made, is 20 miles from one source of supply and 75 miles from the other end of the line where power was also supplied. For the sake of comparison the averages of the residual voltage of the 22,000-volt line between Salinas and Monterey, a distance of 18 miles, are also given:

Order of harmonic	Residual voltage—volts			Residual current amperes
	Santa Cruz	Salinas		Santa Cruz
		Neutral		
		Grounded	Non-grounded	
1	360	50	90	0.094
3	—	150	320	—
9	19	40	50	0.021
11	14	—	—	0.017
13	10	—	—	—
23	14	—	—	—

The system of the Coast Counties Gas and Electric Company is isolated from ground and employs a number of Scott-connected and open delta-connected transformers. The residuals at Santa Cruz on this system are composed principally of fundamental, ninth and eleventh harmonics. The fundamental is predominant. The third harmonic is absent or too small to measure accurately. It should be noted here that the use of Scott and open delta-connected transformers permits the third harmonic and its odd multiples to exist in the line voltages and currents of a three-phase isolated system. In all probability the residuals on this system are caused by unbalanced admittances to ground of the power line conductors. As has already been pointed out, that part of the unbalance due to electrostatic capacity could be greatly reduced by properly spaced transpositions in the power circuit. In contrast to the results at Salinas, the residuals of this system exhibit a prominent fundamental and the absence of, or relatively small amounts of, the third harmonic and its odd multiples.

APPENDIX III.

TRANSPOSITIONS.

The sources of the disturbances in communication circuits, which arise from parallel power circuits, have been treated in the first section of the preceding appendix. The effect of transpositions on the induction in communication circuits produced by parallel power circuits will now be considered.

This appendix comprises the four following sections:

1. Effect of Transpositions in Reducing Induction.
2. Characteristics of Present Transposition Systems.
3. Characteristics of Proposed Transposition Schemes.
4. Results of Tests.

1. Effect of Transpositions in Reducing Induction.

Transposing a circuit is the interchanging of the positions occupied by the conductors.

By transposing a power line the phase of the resultant electromagnetic field, due to balanced currents and the phase of the resultant electrostatic field due to balanced voltages is changed, and the induction is reduced by the production of neutralizing effects in the neighboring lengths of a parallel conductor. Thus, by locating the power circuit transpositions so that each conductor occupies all of the several possible conductor positions for equal distances, a section or "barrel" is obtained within which the resultant induction on a parallel conductor due to balanced currents and voltages is completely neutralized, neglecting attenuation and remanent electrostatic effect and assuming the parallel is uniform throughout the barrel.

Inasmuch as residual currents and voltages are in phase in the several conductors, the transposition of the power circuit does not reduce the inductive effects therefrom in a parallel conductor, except as the magnitudes of the residual currents and voltages are reduced by the power circuit transposition. (See Appendix II.)

As usually constructed, the conductors of a telephone circuit are close together as compared with their distances to a power line, and the circuit is usually isolated from ground. Could the conductors of a metallic communication circuit be located at the same point in space, as is approximately true of a pair of wires twisted together, the resultant electromagnetic and electrostatic induction between the sides of the communication circuit would be zero. The voltage induced along the conductors of the telephone circuit and the induced voltage to ground would be present but would not be effective in producing any voltage between the conductors of the telephone circuit, provided the capacity and leakage to ground of each side of the telephone circuit were equal. On overhead lines the conductors of a metallic communication circuit must be at least several inches apart, hence in general when paralleled by a power line, the resultant electromagnetic and electrostatic induction in the two conductors will be unequal in magnitude. The result is that a voltage exists between the sides of the circuit which causes a current to flow in apparatus connected between the conductors, such as a telephone receiver.

Transpositions in communication circuits tend to equalize the induction in the two sides of the circuits by exposing each side equally to the influence of the power circuit, that is, by reversing in successive lengths the phase of the induction between the two sides of the circuit.

In an exposure where the induction from balanced currents and voltages would be completely neutralized by the power circuit transposition system if there were no communication circuit transpositions, or where such induction would be completely equalized by the communication circuit transpositions, if there were no power circuit transpositions this induction will practically always be partially cumulative if both power and communication circuit transpositions are installed without due reference to each other. It should be noted, however, that the maximum disturbances which may be set up in a parallel communication circuit by balanced currents and voltages in the power circuit will be present when neither the power circuit nor the communication circuit is transposed. Hence it is very important that the power and communication circuit transpositions be properly located with respect to each other, and in this way only can the maximum benefits from the transpositions be derived.

Induction from residual currents and voltages is reduced by communication circuit transpositions.

If the communication circuit has a ground return, it can be transposed and the power circuit transpositions alone will be effective in reducing interference arising from the balanced currents and voltages. Also, the induction into a ground return communication circuit from residual currents and voltages is not affected by transpositions, except indirectly as previously stated. It is possible, though not of general practical application, to obtain the effect of a transposition in a grounded alternating current power or communication circuit by means of a transformer or repeating coil.

Induction between wires and ground is harmful to metallic as well as to ground return circuits, for in case the metallic circuit is not perfectly balanced electrically, such induced voltage forces a current to circulate in the metallic circuit through the terminal apparatus. It is not practical to maintain communication circuits in a state of perfect balance at all times.

2. Characteristics of Present Transposition Systems.

The transposition systems used on long distance metallic telephone circuits are designed primarily to reduce the "cross-talk" or induction from one telephone circuit into another, and provide for a high degree of balance between any circuit and all others on the line.

The length of standard balanced telephone transposition sections used by The Pacific Telephone and Telegraph Company is approximately eight miles (more exactly, 41,600 feet) and this is representative of the length of sections of the transposition systems used by other companies operating similar lines. To improve the transmitting qualities of telephone circuits used for long distance work, loading coils are introduced in certain circuits at the ends of the standard transposition sections. Uniform spacing of the telephone "S" poles (end poles of transposition sections) is an important consideration in the application of loading. It is important that the induction be neutralized in each section between loading points, as these are points of discontinuity in the circuits.

The system now used also provides for the transposition of every circuit at actual intervals ranging from one quarter mile to two miles, the average intervals for different circuits varying from approximately one quarter mile to three quarters of a mile, hence every circuit is to a certain extent balanced to induction from parallel power circuits.

In addition to the metallic circuits composed of two conductors, the telephone companies employ phantom circuits which are made up from two physical (two wire) circuits. Each "conductor," or side of the phantom circuit, consists of the two conductors which form one physical circuit. As usually made up, the physical circuits occupying adjacent horizontal positions are used for the phantom circuit. Hence, the average distance between the sides of the phantom circuit is equal to twice the distance between the conductors of the physical circuits. Due to the greater distance between the sides of the phantom circuit as compared with the physical circuits, the phantom circuits are more subject to inductive interference than the physical circuits. The phantom circuit possesses marked advantages in economy and transmission efficiency over the physical circuits composing it, hence is extensively used for the longer distances. The transpositions in the phantom circuits are spaced at average intervals for different circuits, varying approximately from three quarters of a mile to two miles.

The purpose of transposition systems applied to power circuits has been to reduce the disturbance in parallel communication circuits and in some cases to equalize the separation of the pairs of conductors forming the several phases. Usually when transpositions have been applied to power circuits to reduce the disturbance in existing parallel communication circuits, one or more complete barrels have been provided within the total length of the exposure. The best obtainable results from power circuit transpositions will be had only when they are located with due regard to the transposition points of the communication circuit. No such practice as this has been followed in the past. The transposition systems heretofore applied to parallel power and communication circuits have therefore failed to meet the requirements for maximum effectiveness. Hence, balanced currents and voltages in the power circuits have, in general, caused more disturbance than necessary in parallel communication circuits.

3. Characteristics of Proposed Transposition Schemes.

It would be possible to fulfill the conditions for balance with regard to induction arising from balanced currents and voltages, by cutting a "barrel" into the power circuit between successive communication circuit transpositions. Inasmuch as telephone transposition points are ordinarily spaced at one fourth mile intervals, this solution in the case of a three-phase power circuit would necessitate transpositions at an average spacing of one eighth mile and a minimum spacing of one twelfth mile, which is impracticable in most cases.

It would be possible to satisfy the conditions for balancing the induction in metallic circuits, from both balanced and residual currents and voltages, by installing any completely balanced system of communication circuit transpositions between each two successive power circuit transpositions. Assuming twelve mile "barrels" in the power circuit, the conditions for balance could be fulfilled with the present standard telephone transposition system. However, with power circuit barrels of a length such as is essential in most parallels, this solution would require the redesign and relocation of all telephone transpositions in the exposure, involving several times as many transpositions as are normally required, with the liability of interference with the location of loading coils.

Both the above solutions satisfy the conditions for balancing the induction in metallic circuits, arising from residuals, in length of circuit equal to or twice the distance between successive communication circuit transpositions, assuming these are uniformly spaced. In the standard transposition section as now used, balance is thus obtained in distances varying from an average of approximately one fourth to four miles.

Between these two comparatively simple but extreme solutions the practical but more complicated solution for general cases is to be obtained. This involves the combination of power circuit "barrels" of moderate length with a modified communication circuit transposition system designed to procure balance as far as practicable for all circuits. In this way co-ordinated transposition systems may be designed which are sufficiently flexible to meet the requirements of short parallels and portions of longer parallels separated by points of discontinuity.

In the discussion above with reference to schemes of transpositions the balances or unbalances mentioned are those which would occur, due solely to the relative locations of transpositions in an exposure whose physical characteristics are uniform throughout. Even with a scheme of transpositions, balanced in the sense described, applied to both power and communication circuits involved in an actual parallel, there are a number of factors as noted below, which in general are not capable of being taken into account quantitatively and because of which effective neutralization may not be obtained. These factors are:

1. Non-uniformity of separation, configuration and other physical characteristics.
2. Variation in magnitude and phase of the inductive effects along the exposure (applying particularly to the higher frequencies).
3. Inherent inability of transpositions to completely neutralize electrostatic induction (this remanent effect can be reduced as far as desired by inserting a sufficient number of transpositions).
4. Imperfect electrical balance of the communication circuit.

While these factors which prevent complete neutralization of the induction can not be entirely eliminated, their effects can be abated by reducing the length of balanced transposition sections. Thus it is not sufficient merely to install transpositions in both lines so that they are balanced to each other; but, also, it is necessary to take into consideration the length of section within which balance is obtained and to make this length as short as the conditions of the particular case require.

Points of discontinuity, such as abrupt changes in power line current where a material amount of load is taken off, cross-overs, or substantial changes in separation, should, if practicable, be made neutral points (junction points of balanced sections) in the transposition scheme. Where cross-overs occur balance should in general be obtained independently for the portions of the communication line on each side of the power circuit.

The transposition system and the location and spacing of transposition poles are factors of prime importance in the successful operation of telephone lines, on account of the mutual effects among the many circuits carried on such lines. On the other hand, transpositions in power circuits are, relatively, of minor importance in the operation of a power system and from this standpoint the effect of small changes in the location of such transpositions is negligible. Hence, in general, the requirements of the communication circuits are the chief factors which should govern the location of all transpositions in both power and communication circuits.

An individual study is necessary to determine the best procedure for any given parallel owing to the wide variation in conditions. Thus only is it possible in each case to determine the best location and method of transpositions with regard to the requirements of both power and communication systems.

4. Results of Tests.

The investigation at Salinas demonstrated that the induction in a ground return circuit in the exposures concerned arises principally from the residual voltages and currents, while the induction in a metallic circuit shows principally the characteristics of the balanced voltages and currents together with some effect from the residuals. This result was to be expected as there are power circuit transpositions which reduce the induction in the conductors used as ground return circuits, due to the balanced components, but these transpositions and the transpositions in the telephone circuits are improperly located with respect to each other and therefore are inefficient as regards the induction in the metallic circuits. On the other hand, the telephone transposition system tends inherently to reduce the induction in the metallic circuits, arising from residuals. A study of the relative location of power and telephone circuit transpositions for exposure No. 2 at Salinas, indicated that by modifying the present transpositions of both circuits, it is possible to reduce materially the induction from balanced currents and voltages. Had it been feasible to take the power circuit out of service for the purpose of experimental retransposition, the above scheme as well as one for the King City exposure, would probably have been installed and the effects thereof experimentally determined. Under the conditions existing, however, it was deemed advisable to postpone the matter of transpositions for both these exposures, pending the acquisition of further information as to the extent to which retransposition would be warranted as a permanent improvement.

The experimental study of transpositions was, therefore, transferred to another point where a power line is not the sole source of supply and can, therefore, be shut down for alterations and tests under special conditions.

The experimental determination of the practical effectiveness of transpositions has not been completed. However, an extended theoretical study of transpositions has been made, including the design of a modified telephone transposition system. This system, which requires many additional transpositions, is more flexible in its properties of coordination with different lengths of power circuit "barrels."

A study made to determine the relative efficiency of various schemes of transpositions designed for the Santa Cruz-Watsonville exposure of

The Pacific Telephone and Telegraph Company's toll lead to the 22,000-volt line of the Coast Counties Gas and Electric Company, emphasizes the following general principles:

1. The necessity of proper relative location of power and telephone circuit transpositions.

2. The importance of the effect of cross-overs and the desirability of making them neutral points in the transposition scheme.

3. The necessity of some modifications of the telephone transposition system.

APPENDIX IV.

APPARATUS.

For the proper conduct of its tests and experiments the Joint Committee on Inductive Interference has secured, either through purchase or on loan account from various power and communication interests, apparatus of an aggregate value of over twelve thousand dollars.

The following is a brief schedule of the property in use by this committee, together with its estimated replacement value:

Buildings (portable laboratory)		$480 00
Furniture and fixtures		128 00
Apparatus—		
Oscillograph	$1,115 00	
Oscillator	600 00	
Motor generator set	260 00	
Meters	1,202 50	
Batteries	100 00	
Condensers	990 00	
Bridges	675 00	
Galvanometers	265 00	
Rheostats	734 80	
Switchboards	135 40	
Miscellaneous apparatus	1,505 00	
Coils and relays	645 00	
Transformers	2,412 50	
Miscellaneous	787 00	
Photographic	293 60	11,820 80
Grand total		$12,428 80

The above property is owned by the Joint Committee on Inductive Interference and various power and communication companies as follows:

Joint Committee on Inductive Interference	$1,251 15
The Pacific Telephone and Telegraph Company and American Telephone and Telegraph Company	8,293 65
Sierra and San Francisco Power Company	2,002 50
San Joaquin Light and Power Company	300 00
Pacific Gas and Electric Company	110 00
Western Union Telegraph Company	235 00
Testing force	256 50
Total	$12,428 80

APPENDIX V.

LIST OF TECHNICAL REPORTS.

The following is a list of the technical reports which have been prepared in connection with the investigation of the Joint Committee on Inductive Interference:

Technical report number	Subject
1.	General outline of tests to be made at Salinas on parallels between lines of the Sierra and San Francisco Power Company, the Western Union Telegraph Company, the Southern Pacific Company, and The Pacific Telephone and Telegraph Company. (6 pages.)
2.	Summary of results of tests at Morgan Hill on parallel between lines of the Coast Counties Gas and Electric Company and The Pacific Telephone and Telegraph Company between Morgan Hill and Gilroy. (8 pages.)
3.	A description of the noise standard in use for measuring noise on telephone circuits in terms of a standard unit. (4 pages.)
4.	A description of the instruments and methods used for the measurement of effective values of induced voltages and currents. (2 pages.)
5.	A description of apparatus and connections used in measuring line and residual currents and voltages of power circuits. (6 pages.)
6.	Tests of the effects of opening the secondary delta of the auto-transformer bank at Salinas. (7 pages.)
7.	Tests of the induction in the block signalling circuits of the Southern Pacific Company paralleled by the Salinas-King City circuit of the Coast Valleys Gas and Electric Company. (4 pages.)
8.	Tests of the induction in the telephone circuits of exposure No. 2 at Salinas under normal operating conditions of the power system with particular reference to the effects of grounding and isolating the neutral of the Salinas auto-transformers. (16 pages.)
9.	Experimental determination of the coefficients of induction for residual currents and voltages in exposure No. 2 at Salinas. (4 pages.)
10.	Measurements of the harmonics of the neutral current at Salinas. (4 pages.)
11.	Investigation of current transformers, ratios, and errors due to the use of current transformers under the conditions of the tests. (21 pages.)
12.	Formulæ for the computation of electrostatic and electromagnetic induction from power circuits in neighboring communication circuits. (18 pages.)
13.	An investigation of errors in measurements of residual voltage due to the potential transformers used and a discussion of the method of measurement at Salinas. (30 pages.)
14.	Comparative tests of the noise in exposed telephone circuits with power on and off the 55,000-volt power circuit of the Sierra and San Francisco Power Company between Guadalupe and Salinas. (8 pages.)
15.	Supplementary to Technical Report No. 8, differing from the earlier report in that the telephone circuits were shielded. Contains a discussion of transpositions. (22 pages.)
16.	Tests of the induction in telephone circuits exposed to the Coast Counties Gas and Electric Company's 22,000-volt line between Morgan Hill and Gilroy with the power circuit untransposed and open at Gilroy. (4 pages.)
17.	Tests of the induction in telephone circuits exposed to the Coast Counties Gas and Electric Company's 22,000-volt line between Morgan Hill and Gilroy, before and after installing power circuit transpositions. (25 pages.)
18.	Tests of the effect, on exposed telephone circuits, of grounding one phase of the Coast Counties Gas and Electric Company's 22,000-volt three-phase delta-connected line. (4 pages.)
19.	Tests of the combined effects of the Coast Counties Gas and Electric Company's and the Sierra and San Francisco Power Company's circuits on the telephone circuits in the exposure between Morgan Hill and Gilroy. (4 pages.)
20.	Tests of the effect on the residual voltage of transposing the Coast Counties Gas and Electric Company's 22,000-volt line within the exposure between Morgan Hill and Gilroy. (3 pages.)
21.	Tests to determine the comparative effect on the noise in the exposed telephone circuits of having the power on and off the Coast Counties Gas and Electric Company's 22,000-volt between Morgan Hill and Gilroy, and the effect of shielding the telephone circuit under test by grounding other circuits on the lead. (4 pages.)
22.	Computation of the coefficients of induction from balanced and residual currents and voltages for the telephone circuits of exposure No. 2 at Salinas. (19 pages.)
23.	Experimental determination of the coefficients of induction from residual currents and voltages, for the telephone circuits of exposure No. 2 at Salinas—more complete than Technical Report No. 9. (24 pages.)

Technical report number	Subject
24.	Comparison of computations of Technical Report No. 22 with experimental data of Technical Report No. 23. (16 pages.)
25.	Tests of induction in telephone circuits in exposure between Salinas and King City under normal operating conditions, with the neutral of the Salinas auto-transformers grounded and isolated. (20 pages.)
26.	Tests of accuracy of measurement of residual current by certain current transformers. (4 pages.)
27.	Tests of induction in telephone circuits in exposure No. 2 at Salinas with the North Beach steam station energizing the Sierra and San Francisco Power Company's line. Supplementary to Technical Reports Nos. 8 and 15, differing in the source of supply of the power system. (27 pages.)
28.	Supplementary to Technical Reports Nos. 8 and 15. Voltage lowered 5 per cent at the Guadalupe auto-transformers which supply the power circuit. (20 pages.)
29.	Determination of impedances of lines, by computations and by measurements—numerous curve sheets and tables. (65 pages.)
30.	Tests of induction in telephone circuits in exposures Nos. 1 and 2 at Salinas, with the neutral of the Salinas transformers grounded and isolated. (10 pages.)
31.	Supplementary to Technical Reports Nos. 8 and 15 and more complete. Includes tests with Salinas neutral grounded and isolated and with telephone circuits shielded and unshielded. (29 pages.)
32.	Supplementary to Technical Report No. 25. (22 pages.)
33.	Induction in test leads used at Salinas for connecting testing apparatus to the circuits of exposure No. 2 and the effect of such on the measurements of the induction from the exposure. (20 pages).
34.	Effect of changes in the insulation resistance of the telephone line on the induction in telephone circuits of exposure No. 2 at Salinas. Also supplements Technical Reports Nos. 8, 15, and 31. (24 pages.)
35.	General outline of tests to be made at Santa Cruz on the parallel between lines of the Coast Counties Gas and Electric Company and The Pacific Telephone and Telegraph Company. (4 pages.)
36.	Induction in telegraph circuits of the Western Union Telegraph Company and the Southern Pacific Company in exposure No. 1 between Salinas and San Jose. (8 pages.)
37.	Noise tests on telephone circuits radiating from Salinas, with the neutral of the Salinas auto-transformers grounded and isolated. (4 pages.)
38.	General review of tests at Salinas, summarizing reports, 1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 22, 23, 24, 25, 26, 27, 28, 30, 31, 32, 33, 34, 36, and 37. (53 pages.)
39.	General consideration of transpositions and a study of the results to be expected from the application of various transposition schemes to the Santa Cruz-Watsonville exposure. (36 pages.)
40.	Method of measurement of capacity and conductance unbalances. (2 pages.)
41.	Harmonic analysis of alternating current waves, by oscillograph and resonant shunt. Comparison of the methods. (30 pages.)
42.	Investigation of the current transformers in use at Santa Cruz, to determine their ratios of transformation and suitability for residual current measurements. (35 pages.)
43.	Outline of tests to determine the effect of extraneous currents on the intelligibility of telephone conversation. (8 pages.)
44.	Induction in the telephone circuits of the Santa Cruz-Watsonville exposure and in the test leads, from sources other than the 22,000-volt line. (12 pages.)
45.	Induction in the telephone circuits of the Santa Cruz-Watsonville exposure under commercial operating conditions, with the original transpositions in both power and telephone lines. (15 pages.)
46.	Supplementary to Technical Report No. 39. A study of additional transposition schemes for the Santa Cruz-Watsonville exposure. (14 pages.)
47.	Computation of the coefficients of induction for balanced and residual currents and voltages for the Santa Cruz-Watsonville exposures. (11 pages.)
48.	Experimental determination of coefficients of induction in the Santa Cruz-Watsonville exposure, with the original transpositions. (42 pages.)
49.	Further experimental determination of coefficients of induction for balanced voltages, in the Santa Cruz-Watsonville exposure, with the original transpositions. (13 pages.)
50.	Study of the influence of various transformer connections and flux densities on the third harmonic and its multiples in a three-phase circuit. (In preparation.)

APPENDIX VI

ORGANIZATION—JOINT COMMITTEE ON INDUCTIVE INTERFERENCE

JUNE 15, 1914.

CHAIRMAN
RICHARD SACHSE

SUBCOMMITTEE ON FINANCE
CH., R. SACHSE
P. M. DOWNING
V. V. STEVENSON

SUBCOMMITTEE ON TESTS
CH., J. E. WOODBRIDGE
A. H. GRISWOLD
A. H. BABCOCK
R. W. GRAY
J. A. KOONTZ
F. E. HOAR

ACT'G SEC'Y
R. W. MASTICK

TREAS.
F. E. HOAR

SUBCOMMITTEE ON PUBLICITY
CH., A. H. BABCOCK
J. E. WOODBRIDGE
A. H. GRISWOLD

SUBCOMMITTEE ON PUBLICATION
CH., R. W. MASTICK
J. A. KOONTZ
V. V. STEVENSON

SUBCOMMITTEE ON PROGRAM
CH., A. H. GRISWOLD
A. H. BABCOCK
R. W. GRAY

FIELD ENGINEERING STAFF
ENGINEER IN CHARGE
R. W. MASTICK
ASS'T ENGINEER IN CHARGE
L. P. FERRIS

STENOGRAPHER
L. MAHONEY

SUBCOMMITTEE ON NOMINATIONS
CH., R. SACHSE
R. W. MASTICK
J. E. WOODBRIDGE
R. W. GRAY

STENOGRAPHER
J. R. NEWLOVE

ENGINEERS
L. N. ROBINSON
C. A. TURNER
D. I. CONE
R. G. McCURDY

DRAFTSMAN AND PHOTOGRAPHER
E. G. DOLDER

ENGINEERS FORMERLY ON FIELD STAFF
A. J. CHAMPREUX
H. S. OSBORNE
S. H. HESS
F. E. PERNOT

MEMBERS

R. SACHSE	J. E. WOODBRIDGE
F. E. HOAR	J. P. JOLLYMAN
A. L. WILSON	A. H. BABCOCK
P. M. DOWNING	A. H. GRISWOLD
J. A. KOONTZ	R. W. MASTICK
H. A. BARRE	C. H. TEMPLE
R. W. GRAY	V. V. STEVENSON

HONORARY MEMBERS
H. S. WARREN
J. T. SHAW

INDEX