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INVESTIGATION
OF
SINGLE PHASE SHORT CIRCUITS
AND
REVERSE CURRENT RELAY
CONNECTIONS AND OPERATION

A THESIS
SUBMITTED FOR THE
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INTRODUCTION

With the advent of super-power networks and the attendant inter-connection of transmission systems, many heretofore unforeseen problems presented themselves. Not the least among them was the problem of isolating sections in which short-circuits occurred and at the same time providing for the removal of the apparatus endangered by the short-circuit in time to prevent its ruin. This involved the predetermination of short-circuit currents and the proper relay connections and settings.

In our investigation we have not only attempted to verify existing information, which is by no means extensive, but we have also conducted some original work in order to examine, and if possible determine the limiting conditions of the existing theory of single phase or line to ground short circuits.

After a complete and detailed review of existing information on the subject, the authors decided that the most accurate, practical solution would be obtained by solving according to Mr. A. F. Mackerras of the Central Station Engineering Department of the General Electric Company. His method is called the "Method of Symmetrical Components" and is outlined in Chapter

1 with such additions and subtractions as the authors deemed consistent with the investigation as conducted.

In the study of relay connections and operation as applied to this type of work, we used the Westinghouse Induction Type CR Directional Over-current Relay, three of which were loaned us by the Georgia Railway and Power Company.

Included in the tests and connections of the CR Relays is the test and check of a connection submitted to us for verification and investigation by the Georgia Railway and Power Company Engineers. This connection is in use at the Company's Marietta, Georgia, High-Tension Sub-station.

The investigation divides itself into four chapters or phases as shown on the second page.

The authors are indebted to the Georgia Railway and Power Company for the loan of the relays used, to the General Electric Company for the articles by Mr. Mackerras and particularly to Professor D. P. Savant of the Electrical Engineering Department of the Georgia School of Technology in his constant and invaluable advice and supervision in the preparation and the performance of the tests covered by this thesis.

Chapter 1.

GENERAL THEORY AND METHODS OF CALCULATION

The method used for the calculation is based on the Method of Symmetrical Components as used by A. P. Mackerras of the Central Station Engineering Department of the General Electric Company of Schenectady New York.

This method depends fundamentally on the discovery by Mr. C. L. Fortescue that any three vectors may be resolved into three sets of components, two of which consist of balanced three phase vectors, and the third of three vectors which are equal and in phase.

It will be remembered that $j = \sqrt{-1}$ is an operator which rotates any vector to which it applies thru 90 degrees in the positive direction without changing its length. In the same way the operator " a " rotates any vector thru 120 degrees in the positive direction without changing its length.

We shall assume throughout this paper that the positive direction is counter-clockwise, that all vectors rotate in this direction and that for vectors of positive phase sequence, phase b lags behind phase a by 120 degrees and therefore the phases are lettered clockwise.

(4)

If any vector I in Fig. 1 is operated upon by a , it is rotated 120 degrees in the counter-clockwise direction; and therefore the vector aI leads the vector I by 120 deg.

We see at once from Fig. 1 that the vector

$$aI = -0.5I + j0.866I$$

$$\text{or } a = -0.5 + j0.866 \quad (1)$$

If a operates on aI it rotates it 120 deg. in the counter-clockwise direction and therefore $a^2 I$ leads I by 240 deg., or lags it by 120 deg.

Again from Fig. 1 we see that the vector

$$a^2 I = -0.5I - j0.866I$$

$$\text{or } a^2 = -0.5 - j0.866 \quad (2)$$

From equations (1) and (2) or from Fig. 1

$$1 + a + a^2 = 0 \quad (3)$$

If a operates successively on the vector I it rotates it $3 \times 120 \text{ deg.} = 360 \text{ deg.}$ I is therefore unaltered in position or magnitude, and we have

$$a^3 = 1 \quad (4)$$

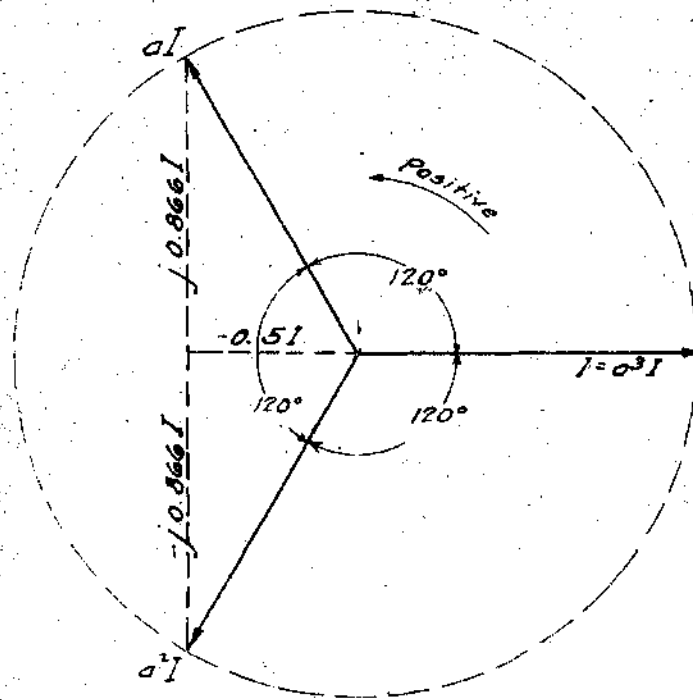


Fig. 1 The Relation Between the Vectors I , a_1 and a_2 .

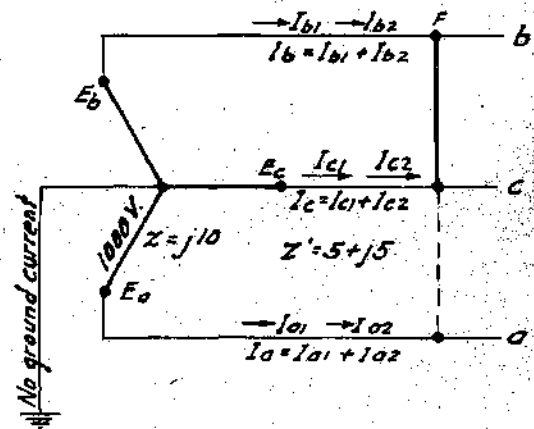


Fig. 3 Example of Line-to-line Short Circuit. There are no zero phase sequence currents.

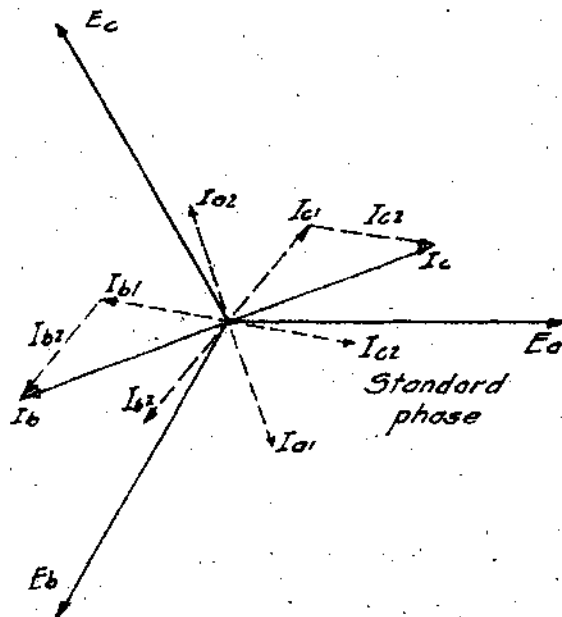


Fig. 4 Vector Diagram for Conditions in Fig. 3

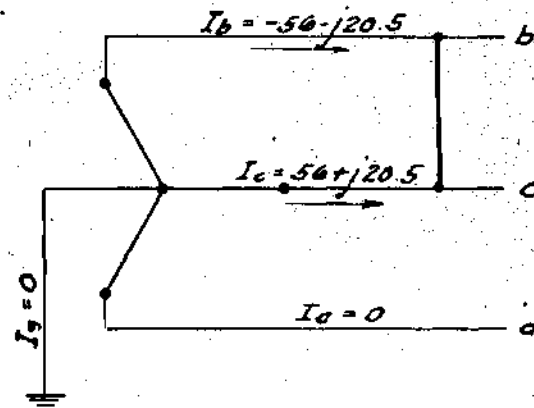


Fig. 5 Total Current Flowing in Fig. 3

THE METHOD OF SYMMETRICAL COMPONENTS

Mr. C. L. Fortescue has shown that any three vectors of a three phase system may be resolved into three systems of vectors known as the positive phase sequence components, the negative phase sequence components, and the zero phase sequence components.

We shall consider the currents in a three-phase grounded neutral system. The actual currents in phases a, b, c we will call I_a , I_b , I_c and the current in the neutral or ground is I_g .

It might be easier to understand the fundamental relations if the vectors are taken equal to the peak values of the sine waves represented. However, the vectors may be arbitrarily taken equal to effective values and the peak values need not be used at all.

Positive Phase Sequence Components

The positive phase sequence components in phases a, b, c. are I_{a1} , I_{b1} , I_{c1} . These components are all equal to each other and separated by 120 deg. in phase. They constitute a balanced set of three-phase currents of positive phase sequence; that is the phases are lettered clockwise. Then

(7)

I_{b1} lags I_{a1} by 120 deg.

and

I_{c1} lags I_{a1} by 240 deg.

Therefore $I_{a1} = aI_{b1} = a^2 I_{c1}$ (5)

$$I_{b1} = a^2 I_{a1} = a I_{c1}$$

$$I_{c1} = a I_{a1} = a^2 I_{b1}$$

These are shown in Fig. 2a.

From equations (3) and (5) we find that

$$I_{a1} + I_{b1} + I_{c1} = 0 \quad (6)$$

Therefore there is no positive phase sequence ground current; and at any instant the positive phase sequence current flowing in any conductor is returning along the other two conductors.

Negative Phase Sequence Components

The negative phase sequence components in phases a, b, c, are I_{a2} , I_{b2} , I_{c2} . These components are all equal to each other and separated by 120 deg. in phase. They make up a balanced set of three-phase currents of negative phase sequence; that is the phases are lettered counter-clockwise. Then,

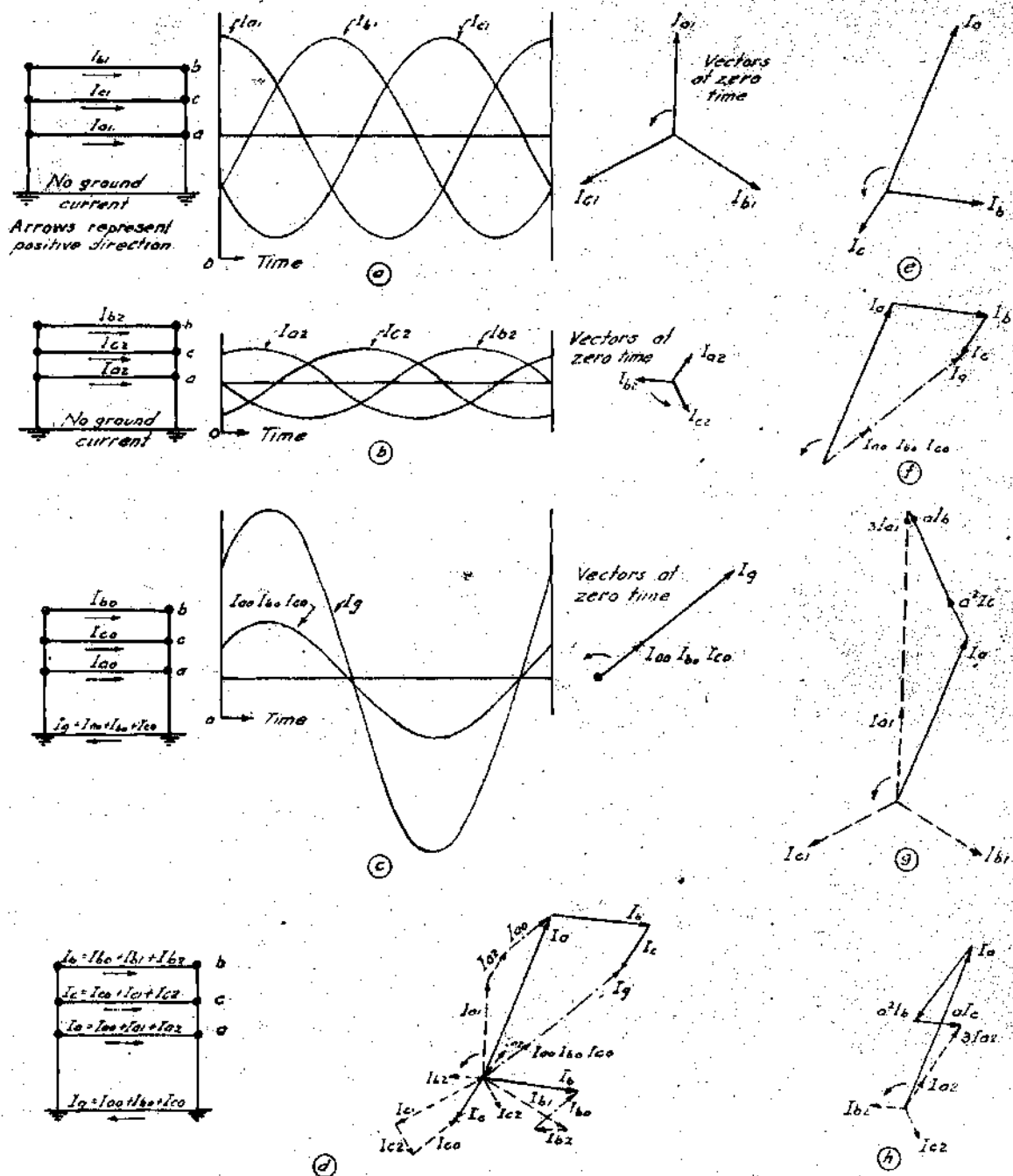


Fig. 2 Diagrams Illustrating Phase Sequence Components.

Fig. 2 a. Positive Phase Sequence Components of Vectors in Fig. 2 d

Fig. 2 b. Negative Phase Sequence Components of Vectors in Fig. 2 d

Fig. 2 c. Zero Phase Sequence Components of Vectors in Fig. 2 d

Fig. 2 d. Relationship Between Total * and Their Phase Sequence Components (* currents)

Fig. 2 e. Three Given Vectors; e.g. Total Currents of Fig. 2 d

Fig. 2 f. Method of Finding the Zero Phase Sequence Components of the Vectors in Fig. 2 e

Fig. 2 g. Method of Finding the Positive Phase Sequence Components of the Vectors in Fig. 2 e

Fig. 2 h. Method of Finding the Negative Phase Sequence Components of the Vectors in Fig. 2 e

(9)

I_{b2} leads I_{a2} by 120 deg.

and

I_{c2} leads I_{a2} by 240 deg.

Therefore,

$$I_{a2} = a^2 I_{b2} = a I_{c2}$$

$$I_{b2} = a I_{a2} = a^2 I_{c2}$$

$$I_{c2} = a^2 I_{a2} = I_{b2} \quad (7)$$

An example of this is given in Fig. 2b.

It is evident from equations (3) and (7) and Fig.

2b that

$$I_{a2} + I_{b2} + I_{c2} = 0 \quad (8)$$

Therefore there is no negative phase sequence ground current; and at any instant the negative phase sequence current in any conductor is returning along the other two conductors.

Zero Phase Sequence Components

The zero phase sequence components in phases a, b, c, are I_{a0} , I_{b0} , I_{c0} . These components are all equal and are in phase with each other. Therefore,

$$I_{a0} = I_{b0} = I_{c0} \quad (9)$$

Since these currents are all in phase, their sum must return thru the ground. But there are no positive or negative phase sequence ground currents; and therefore the total ground current

(10)

$$I_g = I_{a0} + I_{b0} + I_{c0} \quad (10)$$

Also,
$$I_g = I_a + I_b + I_c \quad (11)$$

because the vector sum of the three line currents must be equal to the ground current.

Since the three zero phase sequence components are equal,

$$I_g = 3I_{a0} = 3I_{b0} = 3I_{c0} \quad (12)$$

An example of zero phase sequence components is given in Fig. 2c.

Zero phase sequence currents may be somewhat unfamiliar but it should not be difficult if we remember that they flow from some grounded point, through the three phases of the system in parallel, to one or more other grounded points, where they may enter the ground and return through the ground to their starting point.

Total Currents

The total current in any phase is the vector sum of the three components in that phase. Therefore

$$\begin{aligned} I_a &= I_{a0} + I_{a1} + I_{a2} \\ I_b &= I_{b0} + I_{b1} + I_{b2} \\ I_c &= I_{c0} + I_{c1} + I_{c2} \end{aligned} \quad (13)$$

Expressing the three total currents in terms of the components in phase a with equations (5), (7), and (9).

(11)

$$I_a = I_{a0} + I_{a1} + I_{a2} \quad (14)$$

$$I_b = I_{a0} + a^2 I_{a1} + a I_{a2} \quad (15)$$

$$I_c = I_{a0} + a I_{a1} + a^2 I_{a2} \quad (16)$$

To solve the above for I_{a0} , I_{a1} , I_{a2} , multiply (14), (15), (16) through by the appropriate operator, either, 1, a or a^2 and add, remembering that $1 + a + a^2 = 0$ that $a^3 = 1$ and that $a^4 = a$

Thus,

$$I_{a0} = 1/3(I_a + I_b + I_c) \quad (17)$$

$$I_{a1} = 1/3(I_a + a I_b + a^2 I_c) \quad (18)$$

$$I_{a2} = 1/3(I_a + a^2 I_b + a I_c) \quad (19)$$

The components in the other phases may then be found from equations (5), (7), (9).

Fig. 2d shows the relationship between the total currents in phases a, b, c, and their positive, negative and zero phase sequence components. This shows graphically the physical meaning of equations (5) to (16) inclusive. If the phase sequence components are given the total currents may be found graphically as in Fig. 2d.

The positive, negative and zero phase sequence components act as if there were a metallic contact

(12)

across all three phases to ground at each end of the circuit. This is necessary from the very nature of the components; but it will be found in the different cases that the components combine together in such a way that the total currents satisfy the conditions of the short circuit under consideration.

(13)

Method of Resolving Any Three Vectors Into
Their Phase Sequence Components.

Let the three given vectors, as shown in Fig.
2e, be

$$I_a = 4 + j10$$

$$I_b = 6 + j1$$

$$I_c = 3 - j3$$

The sum of the three vectors from equation (11), is

$$\begin{aligned} I_g &= I_a + I_b + I_c \\ &= 17 + j6 \end{aligned}$$

The zero phase sequence components are equal to
one-third of the sum of the three vectors, as seen
from equation (17). Therefore

$$\begin{aligned} I_{ao} &= I_{bo} = I_{co} = \frac{I_g}{3} \\ &= 2.33 + j2 \end{aligned}$$

This is shown graphically in Fig. 2f.

From equation (18) we see that the positive
phase sequence component in phase a is one-third of
the sum of I_a , I_b rotated through 120 deg. in the
positive direction, and I_c rotated 240 deg. in the
positive direction.

Now

(14)

$$\begin{aligned} aI_b &= (-0.5 + j0.866) (6 + j1) \\ &= -3 + j5.196 + .866 + j5. \\ &= -2.134 + j5.696 \end{aligned}$$

and

$$\begin{aligned} a^2 I &= (-0.5 - j0.866) (-3 - j3) \\ &= 1.5 + j2.598 + 2.598 + j1.5 \\ &= -1.098 + j4.098 \end{aligned}$$

Therefore

$$\begin{aligned} I_{a1} &= 1/3(4 + j10 - 2.134 + j5.696 - 1.098 + j4.098) \\ &= 0.256 + j6.598 \end{aligned}$$

Then I_{b1} lags I_{a1} by 120 deg. and I_{c1} lags I_{a1} by 240 deg.

Therefore

$$\begin{aligned} I_{b1} &= a^2 I_{a1} = (-0.5 - j0.866) (0.256 + j6.598) \\ &= .128 - j3.299 + 5.715 + j0.222 \\ &= 5.587 + j3.521 \end{aligned}$$

and

$$\begin{aligned} I_{c1} &= a I_{a1} = (-0.5 + j0.866) (0.256 + j6.598) \\ &= -0.128 + j3.299 - 5.715 + j0.222 \\ &= -5.843 + j3.077 \end{aligned}$$

The above process is shown graphically in Fig. 2g.

From equation (12) we see that the negative phase sequence component in phase a is one-third of the sum of I_a , I_b rotated through 240 deg. in the positive direction, and I_c rotated through 120 deg. in the positive direction. Then

(15)

$$\begin{aligned} a^2 I_b &= (-0.5 - j0.866) (6 - j1) \\ &= -3. - j5.196 - 0.866 + j0.5 \\ &= -3.866 - j4.696 \end{aligned}$$

and $a I_c = (-0.5 + j0.866) (-3 + j3)$

$$\begin{aligned} &= 1.5 - j2.598 + 2.598 + j1.5 \\ &= 4.098 + j1.098 \end{aligned}$$

Therefore

$$\begin{aligned} I_{a2} &= 1/3(4 + j10 - 3.866 - j4.696 + 4.098 + \\ &\quad j1.098) \\ &= 1.4106 + j1.402 \end{aligned}$$

Then

I_{b2} leads I_{a2} by 120 deg, and I_{c2} leads I_{a2} by 240 deg.

Therefore

$$I_{b2} = a I_{a2} = (-0.5 + j0.866) (1.4106 + j1.402)$$

$$\begin{aligned} &= -0.7053 - j0.701 - 1.215 + j1.222 \\ &= -1.9183 + j0.521 \end{aligned}$$

and $I_{c2} = a^2 I_{a2} = (-0.5 - j0.866) (1.4106 + j1.402)$

$$\begin{aligned} &= -0.7053 - j0.701 + 1.215 + j1.222 \\ &= 0.5097 + j1.923 \end{aligned}$$

The above process is shown graphically in Fig. 2h.

(16)

We will now test our results by adding together the components in each phase and the sum should be equal to the original vector in that phase, in accordance with equations (13)

Therefore

$$I_a = 2.33 + j2 + 0.256 + j6.598 + 1.4106 + j1.402$$

$$= 4. + j10$$

$$I_b = I_{b0} + I_{b1} + I_{b2} \\ = 2.33 + j2 + 5.587 + j3.52 + 1.9185 + j0.521$$

$$= 6 + j1$$

$$I_c = I_{c0} + I_{c1} + I_{c2} \\ = 2.33 + j2 + 5.843 + j3.077 + .5097 - j1.923$$

$$= -3 + j3$$

This proves the accuracy of the above work. This is shown graphically in Fig. 2d.

Then I_{a1} is in phase and I_{a2} is in phase.

$$I_a = I_{a1} + I_{a2}$$

If I_a is in phase with I_{a1} and I_{a2} is in phase with I_{a1} .

$$I_a = I_{a1} + I_{a2}$$

THREE-PHASE SHORT CIRCUITS

The current in the three phase of a three-phase short circuit are equal in magnitude and spaced at 120 deg. from each other and there is no ground current. It follows then that the negative and zero phase sequence components are all zero and that the positive phase sequence components are the total short-circuit currents.

Thus the method reduces to the ordinary study for symmetrical three-phase short circuits. The positive phase sequence network is the ordinary system network, and the positive phase sequence impedances are the ordinary three-phase impedances, phase to neutral.

If Z_1 = Positive phase sequence impedance to neutral of the system to the point of short circuit

E_a = Induced voltage, from neutral to terminal a

I_n = Normal three-phase current corresponding to the chosen kva. base.

Then if Z_1 is in ohms and E_a is in volts,

$$I_a = I_{a1} = \frac{E_a}{Z_1} \text{ amp.} \quad (20)$$

If Z_1 is in per cent on the chosen kv - a base,

$$I_a = I_{a1} = \frac{100 I_n}{Z_1} \text{ Amp.} \quad (21)$$

We shall always take the positive direction of current from the generators toward the point of short-circuit. This applies to all components as well as to the total currents.

LINE TO LINE SHORT CIRCUITS

The Negative Phase Sequence Network

The negative phase sequence components are balanced three-phase currents, and therefore the circuits involved in the negative phase sequence network are exactly the same as in the positive phase sequence ~~impedance~~^{network} is the same as the positive phase sequence impedance; but the negative phase sequence reactance of synchronous machinery is not equal to its positive phase sequence reactance. This is due to the interaction of one winding on another lying in the same slot, but belonging to a different phase.

Tests show that the negative phase sequence transient reactance of a synchronous machine is about 73% of its ordinary transient reactance.

The negative phase sequence impedance is designated by Z_2 .

Line-to-line Short-circuit Currents.

In a line-to-line short circuit there is no ground connection at the fault and therefore there cannot be any zero phase sequence components of current.

Therefore

$$I_{a0} = I_{b0} = I_{c0} = 0 \quad (22)$$

and $I_g = 0 \quad (23)$

If the short circuit is between phases b and c it can be proved that the positive phase sequence component at the fault in phase a is

$$I_{a1} = \frac{E_a}{Z_1 + Z_2} \text{ Amp} \quad (24)$$

where Z_1 and Z_2 are in ohms

or $I_{a1} = \frac{100 I_n}{Z_1 + Z_2} \text{ Amp.} \quad (25)$

where Z_1 and Z_2 are in per cent on the same kv-a base as I_n . Z_1 and Z_2 are the positive and negative phase impedances of the network to the point of short circuit.

The above equations (24) and (25), are fundamental in the application of the method to the calculation of

(20)

line-to-line short circuits. I_{a1} is the first current to be found and everything follows from it. Since the short circuit is between phases b and c only, there cannot be any total current in phase a.

Therefore

$$I_{a1} + I_{a2} + I_{a0} = I_a = 0$$

and

$$I_{a2} = -I_{a1} \quad (26)$$

since

$$I_{a0} = 0$$

The components in the other phase can then be found from equations (5) and (7).

Example of Line-to-line Short Circuit

To illustrate how the phase sequence currents flow with a short circuit between phases b and c the example shown in Fig. 3 will be worked out in detail.

Since there is no ground connection at the fault, there are no zero phase sequence currents and no ground current.

Therefore

$$I_{a0} = I_{b0} = I_{c0} = 0$$

The positive and negative phase sequence currents are shown in Fig. 5, where the arrows give the positive direction. Since the positive and negative phase sequence components are balanced three-phase currents, the current in each conductor must return along the other two conductors. Therefore the positive and negative phase sequence components behave as if there were a three-phase short-circuit at F. But the components must combine in such a way that the total currents satisfy the conditions of a short circuit between phases b and c only.

Suppose the line to neutral voltage of the generator is 1000 and that the ordinary three-phase impedances, line to neutral, of the generator and transmission line are $Z = j10$ ohms and $Z' = 5 + j5$ ohms, respectively. Then the positive phase sequence transient impedance to the fault,

$$\begin{aligned} Z_1 &= Z + Z' = j10 + 5 + j5 \\ &= 5 + j15 \text{ ohms} \end{aligned}$$

The negative phase sequence transient reactance of the generator is 73 per cent of its positive phase sequence transient reactance, the negative phase sequence transient impedance to the fault is

(22)

$$\begin{aligned}Z_2 &= j7.3 + 5 + j5 \\&= + j12.3 \text{ ohms}\end{aligned}$$

Taking the voltage in phase a as standard phase, that is the positive direction of the axis of real quantities

$$E_a = 1000 \text{ volts}$$

$$\text{Therefore } E_b = a^2 E_a = -500 - j866 \text{ volts}$$

$$\text{and } E_c = a E_a = -500 + j866 \text{ volts}$$

The induced voltages of the generator are taken in positive phase sequence.

The transient impedances are used, therefore the currents will be the instantaneous symmetrical short-circuit values.

Then from equation (24)

$$\begin{aligned}I_{a1} &= \frac{E_a}{Z_1 + Z_2} = \frac{1000}{5 + j15 + 5 + j12.3} \\&= \frac{1000}{10 + j27.3} = \frac{1000 (10 - j27.3)}{10^2 + (27.3)^2} \\&= 11.85 - j32.3 \text{ amp.}\end{aligned}$$

From equations (5)

$$I_{b1} = a^2 I_{a1} = -33.9 + j5.9 \text{ amp.}$$

$$I_{c1} = a I_{a1} = 22.1 + j26.4 \text{ amp.}$$

(23)

As previously noted,

$$I_{ao} = I_{bo} = I_{co} = 0$$

Since the total current in phase a is zero

$$I_a = 0$$

Therefore, $I_{a2} = -I_{a1} = 11.85 + j32.3$ amp.

and $I_{b2} = aI_{a2} = -I_{c1} = 22.1 + j26.4$ amp.

and $I_{c2} = a^2 I_{a2} = -I_{b1} = 33.9 + j5.9$ amp.

Then the total currents in phases b and c from equations (13) are

$$\begin{aligned} I_b &= 0 + 33.9 + j5.9 + 22.1 + j26.4 \\ &= 56.0 + j20.5 \text{ amp.} \end{aligned}$$

$$\begin{aligned} I_c &= 0 + 22.1 + j26.4 + 33.9 + j5.9 \\ &= 56.0 + j20.5 \text{ amp.} \end{aligned}$$

The vector relations are shown in Fig. 4. The short-circuit current flows along one conductor and returns by the other as shown in Fig. 5.

LINE - TO - GROUND SHORT - CIRCUITS

Zero Phase Sequence Network

The zero phase sequence network is much simpler than the other two networks inasmuch as it usually involves only the portions of the network which have grounded neutrals in the particular circuit in which

a ground fault occurs. It should be remembered that the zero phase sequence components in phases a, b, and c are equal in magnitude and are in phase with each other. Therefore the path of the zero phase sequence currents (regarded in the negative direction) is from the ground fault through the three phases of the network in parallel, into the ground through some or all of the grounded neutrals, and through the ground back to the fault.

The nature of the zero phase sequence network depends entirely on the transformer and generator connections, and whether they are grounded or not. The method of setting up the zero phase sequence network will be explained by the example in Fig. 6 which involves most of the common connections.

An arrow represents a zero phase sequence component of current in the positive direction, and a zero close to the conductor indicates that there is no zero phase sequence current in that conductor. The zero phase sequence components are equal in the three phases, therefore it is necessary to consider that the ground fault exists simultaneously on all three phases; otherwise it would be impossible to have zero phase

sequence currents in all the phases. It will be found that the positive and negative phase sequence components ^{WILL NEUTRALIZE THE ZERO PHASE SEQUENCE COMPONENTS.} in the two ungrounded phases at the fault, and the total currents will then satisfy the conditions on a line-to-ground short circuit.

Fig. 7 is a one-line diagram of Fig. 6; and where the circuit is complete for the zero phase sequence current, the conductor is shown grounded at the end, indicating that the current may return through the ground to the fault. Where the zero phase sequence current cannot flow, the branch is left ungrounded at the end, indicating that there is infinite impedance to zero phase sequence current.

Fig. 8 is the zero phase sequence network which is obtained from Fig. 7 by omitting the branches which cannot carry zero phase sequence current. The ordinary three-phase line-to-neutral impedances are given in Fig. 6 on a 30,000 kv-a base, and in Figs. 7 and 8 the corresponding zero phase sequence impedances are given on the same base.

The positive direction of the zero phase sequence currents in the conductors is toward the fault, but in setting up the zero phase sequence

(26)

network it is usually easier to start at the fault and work back through the system, considering which branches provide a path for zero phase sequence currents, and which do not.

We will now consider the portions of the network in detail.

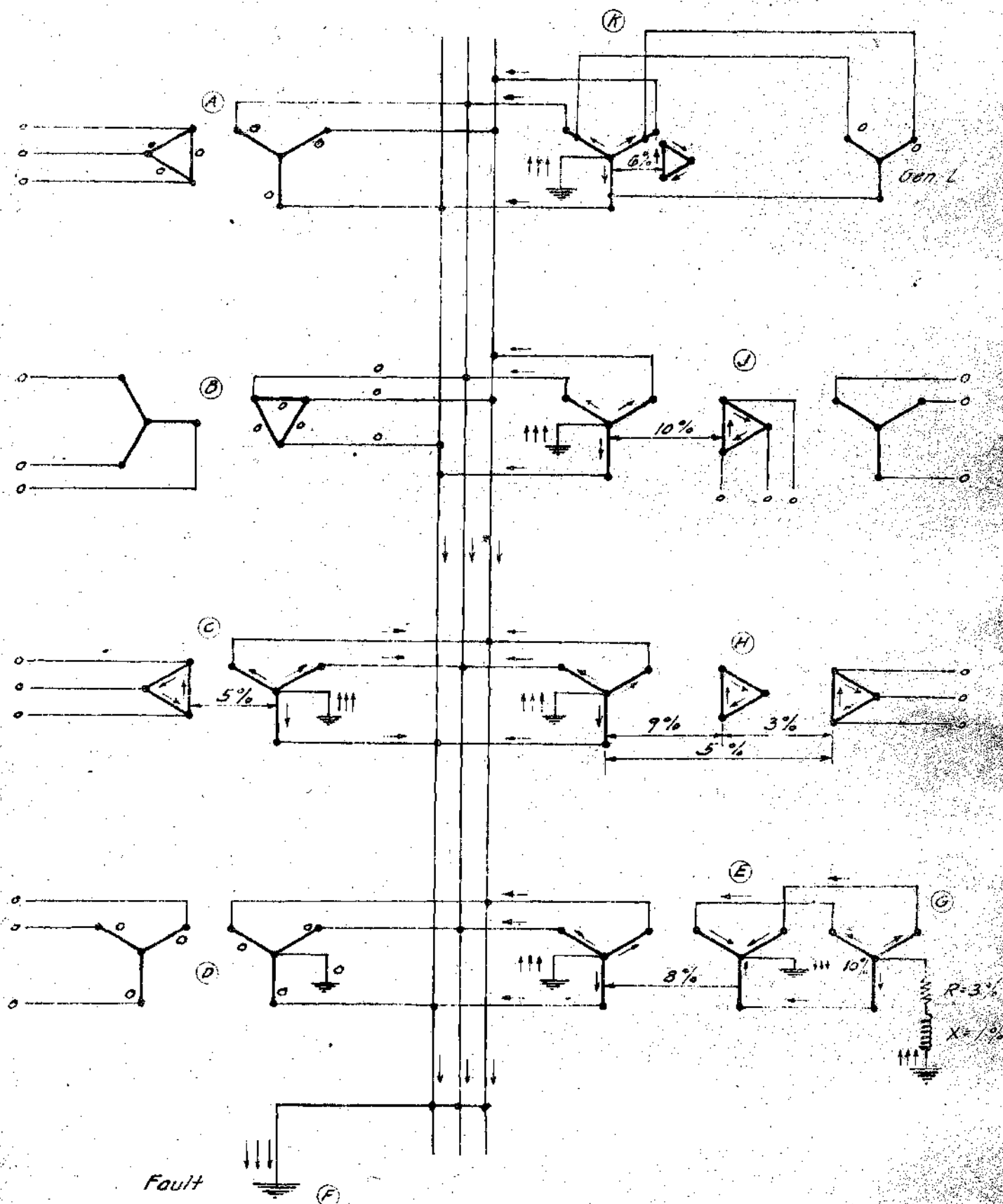


Fig. 6 Diagram Illustrating the Path of Zero Phase Sequence Currents.

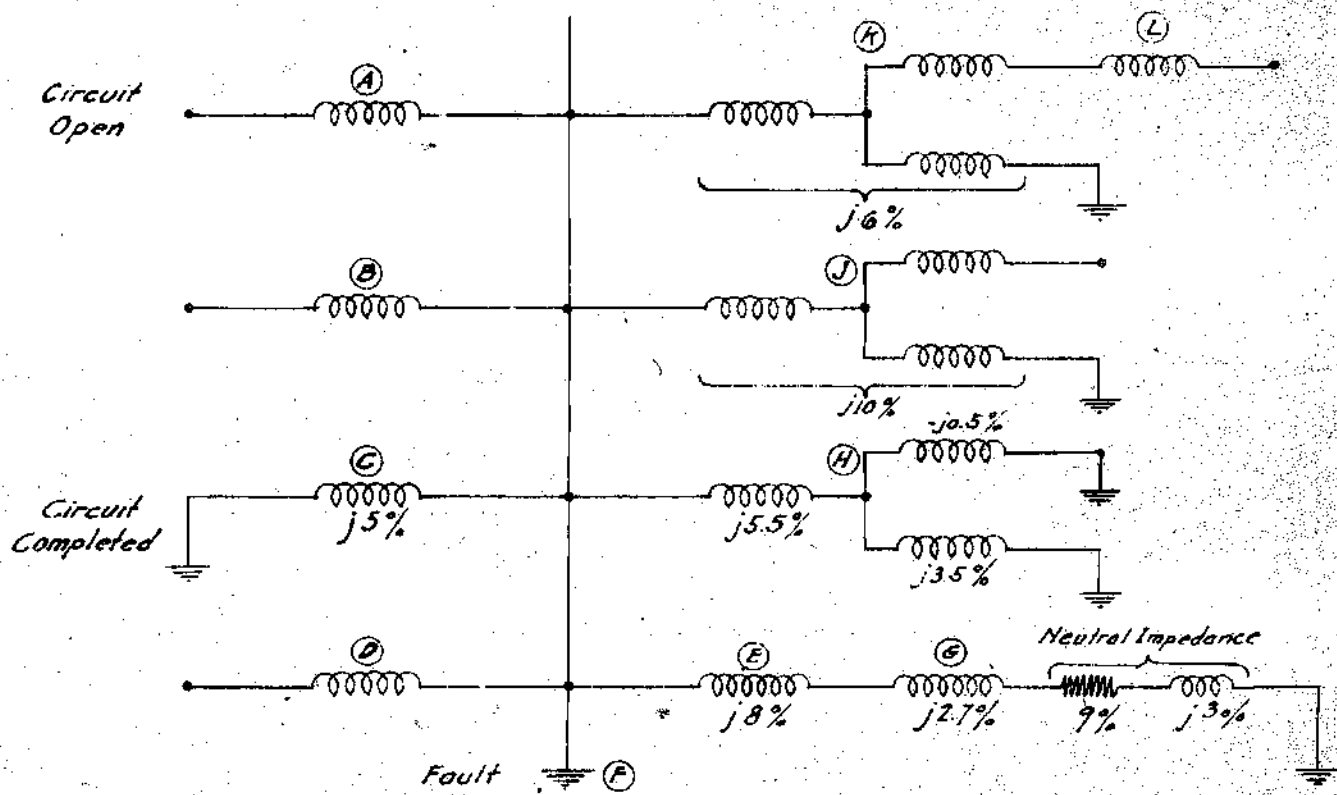


Fig. 7 One-line Diagram of System Shown in Fig. 6

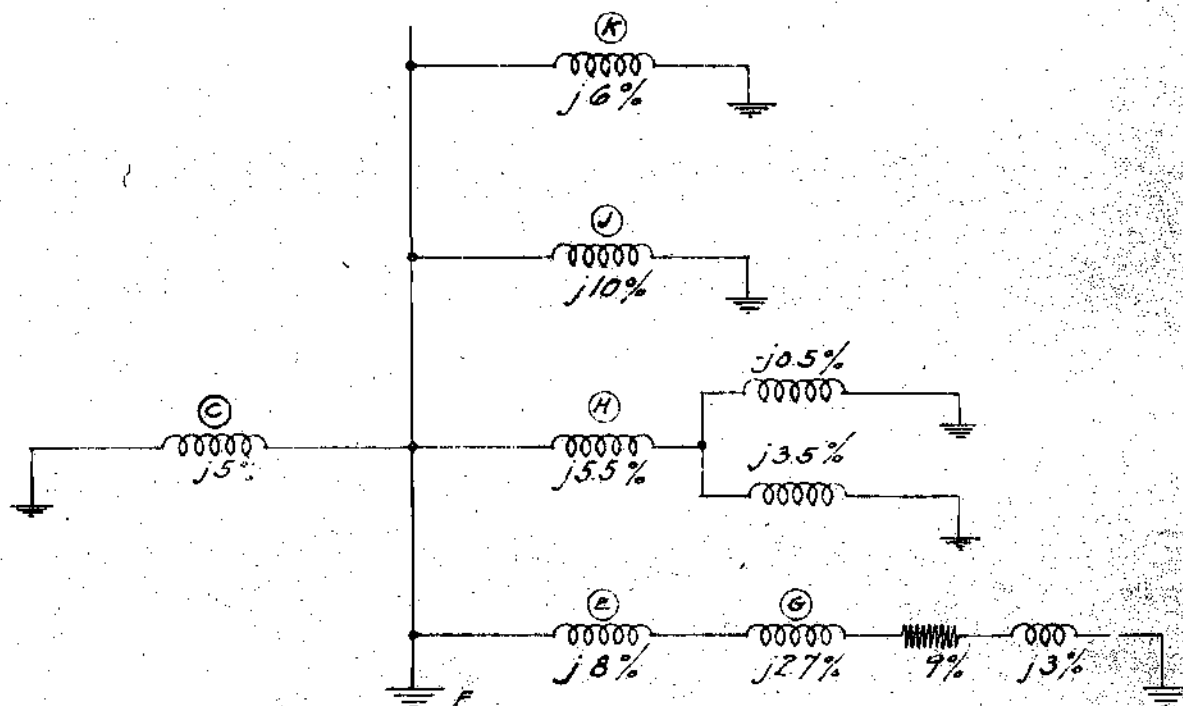


Fig. 8 Zero Phase Sequence Network for System Shown in Fig. 6

Resistance

The zero phase sequence resistance of a conductor in any phase is equal to its ordinary resistance value; but if the conductor is in the neutral its zero phase sequence resistance is three times the ordinary value. This is because the ordinary resistance of a conductor is referred to the total current in it, while the zero phase sequence resistance refers to the zero phase sequence current in one phase only, and this is one-third of the total current in the neutral.

Transformers A and B

Zero phase sequence currents cannot flow in the lines leading to an ungrounded Y or delta because there is no ground connection through which the current may return to the fault. This is always true, no matter what connection is used on the other side of the transformer.

Transformer C

If a Y-delta transformer is grounded and a ground fault occurs on the Y side, its zero phase sequence impedance is equal to its ordinary three-phase impedance, line to neutral. It will be noticed in Fig. 6 that the

currents in the Y all flow away from the neutral point, and that the compensating currents will circulate in the delta. Consequently no zero phase sequence currents can flow in the lines connected to the delta, and the network on the far side of the delta has no influence on the zero phase sequence currents.

Since the currents flowing from the ground through the transformer encounter the impedance of the transformer, the ground in Figs. 7 and 8 is shown on the far side of the transformer reactance, C .

Transformer D

The zero phase sequence impedance of a Y-Y transformer, grounded on the fault side but isolated on the other side is infinite. Although there is a path for the zero phase sequence currents on the grounded side, there is no path for the compensating currents which would have to flow on the ungrounded side to balance the ampere turns on the grounded side. Consequently, it is impossible for zero phase sequence currents to flow in the lines connected to a Y-Y transformer which has one side isolated from ground.

Transformer E

The impedance of a Y-Y transformer with both neutrals grounded is equal to the ordinary three-phase impedance. As far as the transformer itself is concerned, there is a path for zero phase sequence currents on both primary and secondary sides, since there is a connection to each neutral.

Zero phase sequence currents will flow in the lines connected to both sides of the transformer, provided of course that the rest of the path can be completed as shown in Fig. 6. If the generator G had been ungrounded, no zero phase sequence currents could have flowed in transformer E or the lines connected to either its primary or secondary.

Generator G

Since this generator has a neutral connection, it provides a path for zero phase sequence currents to flow from the ground and return to the fault. Tests show that the zero phase sequence transient reactance of a synchronous machine is about 27 per cent of its ordinary transient reactance.

Impedance in Generator Neutral: The zero phase sequence impedance of the generator neutral connection is three times its ordinary impedance, because it is referred to the zero phase sequence current in one phase, which is one-third of the current flowing in the neutral.

Three-winding Transformers

In a one-line diagram, a three-winding transformer is represented by an equivalent circuit. In Fig. 9, let the reactance from primary to secondary be x_{ps} , from primary to tertiary be x_{pt} , and from secondary to tertiary be x_{st} . Then in the equivalent network,

$$x_p + x_s = x_{ps} \quad (27)$$

$$x_p + x_t = x_{pt} \quad (28)$$

$$x_s + x_t = x_{st} \quad (29)$$

Therefore

$$x_p = 1/2(x_{ps} + x_{pt} - x_{st}) \quad (30)$$

$$x_s = 1/2(x_{ps} + x_{st} - x_{pt}) \quad (31)$$

$$x_t = 1/2(x_{pt} + x_{st} - x_{ps}) \quad (32)$$

Transformer H

Let $x_{ps} = 5$

$x_{pt} = 9$

$x_{st} = 3$

Therefore

$$x_p = 1/2(5 + 9 - 3) = 5.5$$

$$x_s = 1/2(5 + 3 - 9) = -0.5$$

$$x_t = 1/2(9 + 3 - 5) = 3.5$$

The negative reactance for x_s means that the secondary leg of the equivalent circuit acts as a capacitance.

The secondary and tertiary are both deltas and both provide circulating currents to compensate for the zero phase sequence currents in the grounded Y primary. The zero phase sequence reactance of the transformer is therefore equal to the ordinary primary reactance x_p in series with the secondary x_s and the tertiary x_t in parallel. The zero phase sequence reactance of transformer H is therefore equal to

$$\begin{aligned} x_p + \frac{x_t x_s}{x_t + x_s} &= 5.5 + \frac{3.5 \times 0.5}{3.5 - 0.5} \\ &= 4.92 \text{ per cent} \end{aligned}$$

Transformer J

In transformer J one winding is an ungrounded Y which cannot carry zero phase sequence currents. Therefore the circulating current in the delta must entirely compensate the zero phase sequence in the grounded Y. This three-winding transformer acts in

exactly the same manner as transformer C.

Auto-transformer K

A grounded Y auto-transformer with a delta tertiary is equivalent to a three-winding transformer with two grounded Y windings and a delta. In setting up the equivalent circuit we look ahead and notice that the secondary is connected to an ungrounded generator L, which will not allow zero phase sequence currents to flow in the lines connected to it. Hence the auto-transformer K acts as if it were a Y-delta transformer with grounded Y, like transformer C; and its zero phase sequence reactance is equal to its ordinary reactance from the high voltage Y to the delta.

Grounding Transformers

A transformer connected either grounded Y-delta or grounded zig-zag, which floats on the line for the purpose of establishing a ground, acts in the same manner as transformer C.

Zero Phase Sequence Impedance

The zero phase sequence network is now completely set up and all the possible paths for zero phase sequence currents are indicated by grounds at both ends. We then

calculate the zero phase sequence impedance, Z_0 , of the network of Fig. 8 to the point of short circuit as follows:

The impedances of the paths in parallel are,

<u>Branch</u>	<u>Impedance</u>	<u>Reciprocal</u>
C	j5	- j0.200
K	j6	- j0.167
J	j10	- j0.100
H	j4.92	- j0.203
E	$9 + j13.7$	$0.0335 - j0.051$
Total =		$0.0335 - j0.721$

$$\begin{aligned} \text{Then } Z_0 &= \frac{1}{0.0335 - j0.721} \\ &= 0.064 + j1.38 \text{ ohms} \end{aligned}$$

Line-to-ground Short-circuit currents

When we have a line-to-ground short circuit the current flowing into the fault must return through the ground; and there must be positive, negative and zero phase sequence components of current:

Take a simple circuit consisting of grounded Y generator feeding a three phase line with a ground fault on line a. We know that the total current in phase a is equal to the current in the ground and

(36)

that the total currents in phases b and c are zero.

$$\text{Then } I_{a1} = 1/3(I_a + a^2 I_b + a I_c) = \frac{I_a}{3}$$

$$\text{Also } I_{a2} = 1/3(I_a + a I_b + a^2 I_c) = \frac{I_a}{3}$$

$$\text{and } I_{a0} = 1/3(I_a + I_b + I_c) = \frac{I_a}{3}$$

Therefore,

$$I_{a1} = I_{a2} = I_{a0} = I_{b0} = I_{c0} = \frac{I_a}{3} = \frac{I_g}{3} \quad (39)$$

It will be noticed that the total currents satisfy the conditions of a ground fault on phase a only; but the component currents behave as if all three phases are short-circuited to ground.

To Find the Value of I_{a1}

Let Z_1 , Z_2 , Z_0 be the positive, negative and zero phase sequence impedances of the circuit from the neutral of the generator to the fault. Then the voltage drop due to the component I_{a1} flowing through impedance Z_1 is $I_{a1} Z_1$. Also the drop due to the negative phase sequence current is $I_{a2} Z_2$; and for the zero phase sequence current, the voltage drop is $I_{a0} Z_0$. Therefore the total drop in phase a is

$$I_{a1} Z_1 + I_{a2} Z_2 + I_{a0} Z_0$$

(37)

Since phase a is shorted to ground, the total drop in phase a is equal to the line-to-neutral induced voltage, E_a , in phase a.

Therefore,

$$E_a = I_{a1} Z_1 + I_{a2} Z_2 + I_{a0} Z_0$$

But we have shown that $I_{a1} = I_{a2} = I_{a0}$.

Therefore,

$$E_a = I_{a1} (Z_1 + Z_2 + Z_0)$$

$$\begin{aligned} \text{or } I_{a1} = I_{a2} = I_{a0} &= \frac{I_a}{3} = \frac{I_g}{3} \\ &= \frac{E_a}{Z_1 + Z_2 + Z_0} \quad \text{Amp.} \quad (40) \end{aligned}$$

where Z_1 , Z_2 , Z_0 are in ohms.

If Z_1 , Z_2 , Z_0 are in per cent on some kv-a base, and I_n is the normal current corresponding to that base, then equation (40) becomes

$$\begin{aligned} I_{a1} = I_{a2} = I_{a0} &= \frac{I_a}{3} = \frac{I_g}{3} \\ &= \frac{100 I_n \text{ amp.}}{Z_1 + Z_2 + Z_0} \quad (41) \end{aligned}$$

Equations (40) and (41) are fundamental in the calculation of line-to-ground short circuits. I_{a1} is first calculated, and all the other currents are derived from it.

GENERAL CONSIDERATIONS

In the calculations of three-phase or single-phase short circuits on complicated systems the solution of networks by Kirchoff's Laws becomes very laborious. The Calculating Board offers a very good solution to this difficulty provided that certain conditions are fulfilled.

The first condition is that the three phases must be symmetrical, so that the system may be represented by a one-line diagram. This is true for the positive, negative and zero phase sequence networks.

The second condition is that the currents throughout one phase of the network must be in phase with each other, so that alternating currents may be represented by direct current so far as their behavior according to Kirchoff's Laws is concerned. This condition is fulfilled if there is no resistance in the circuit.

A third condition is that all generators must have the same induced voltage. This assumption must be made in both three-phase and single phase circuits. Any disadvantages of the Calculating Board are just as serious for three-phase short circuits as they are for single-phase short circuits.

With the Method of Symmetrical Components the calculation of the actual fault current is very simple once the phase sequence impedances of the network have been found; but considerable labor is involved in finding the currents in all the phases of all the branches. Most of the numerical work consists in multiplying vectors by a or a^2 ; and great care is necessary to avoid making mistakes with the signs. If, however, the resistance of the circuit is neglected, the components are entirely reactive, and the multiplication by a or a^2 may be performed directly on the diagram of Fig. 10. For example, if $I_{a1} = -j60$, it will be seen, by projecting to the horizontal and vertical axes of Fig. 10 that $a^2 (-j60) = -52 + j30$.

The signs can be read immediately on Fig. 10 and the values are accurate enough for most purposes. We note however that the numerical values of the real and imaginary components are either 0.866 or 0.5 times the numerical value of the vector. Therefore we may set our slide rule with one end at 0.866 to perform all the multiplications by this factor, and the other component may be found by dividing by

2. The signs and approximate values can be seen at once on Fig. 10.

When the circuit contains both resistance and reactance the phase sequence components are complex quantities. To multiply a complex quantity by a or a^2 with the help of Fig. 10 it is only necessary to treat the real and imaginary parts separately.

Thus,

$$A(30 + j44) = a(30) + a(j44)$$

$$\begin{aligned} &= -15 + j22 - 38 - j22 \\ &= -53 + j4 \end{aligned}$$

This may be verified by translating into the polar form but considerably more work is involved.

Thus,

$$30 + j44 = 53.2 \angle 55.7 \text{ deg.}$$

$$\text{and } -53 + j4 = 53.2 \angle 175.7 \text{ deg.}$$

The magnitudes are the same and the angles differ by 120 deg.

Fundamental Assumptions

In all short-circuit calculations it is necessary to make assumptions which may, in reality, be far from exact.

(41)

- (1) We assume a zero resistance fault. Usually the impedance at the fault is small; but if a conductor falls on a dry wooden crossarm and the only return path is through the wood, the resistance may run into thousands of ohms.
- (2) We neglect load current and charging current. If these are taken into account the calculations become extremely complicated.
- (3) The induced voltages of all generators are assumed to be equal and in phase, so that there is no circulating current before the short circuit occurs.

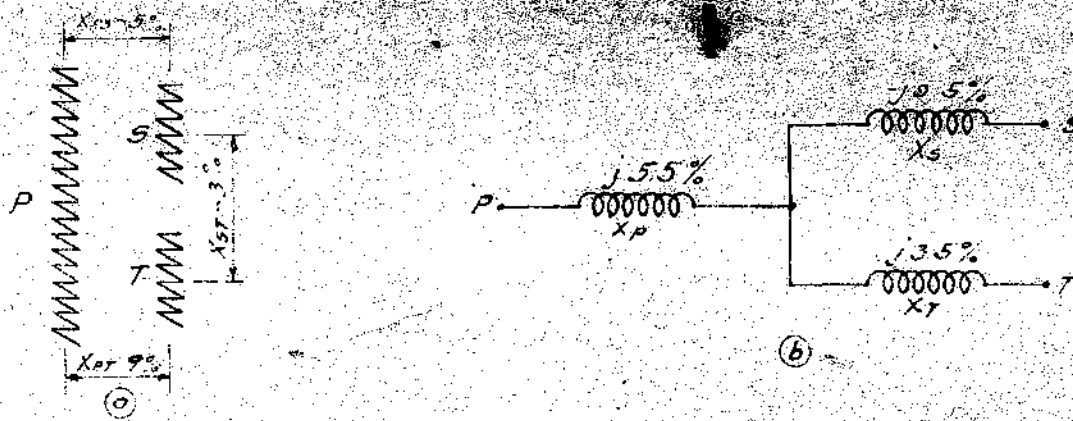


Fig 9 One-line Representation of Three Winding Transformer.

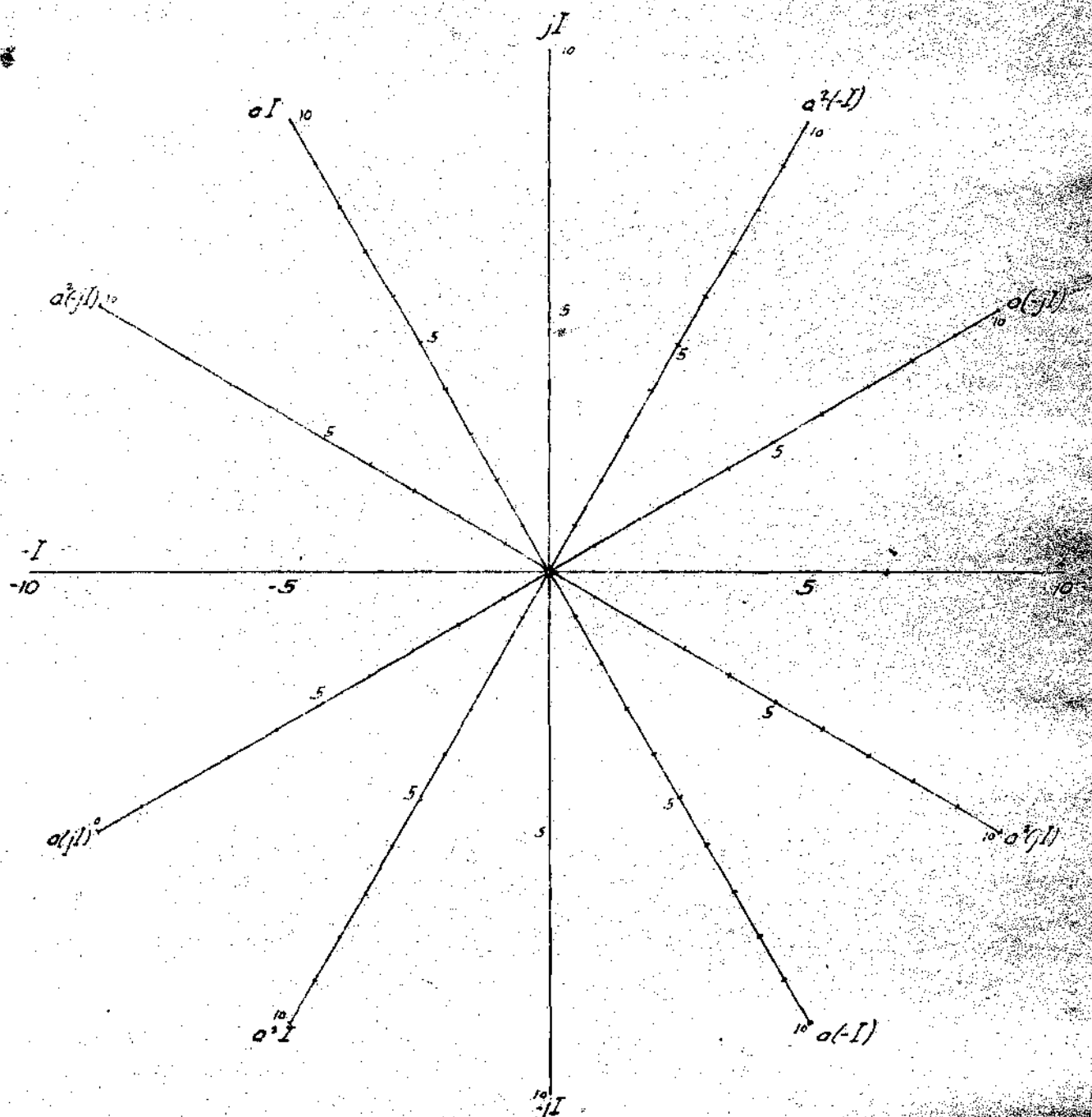


Fig 10 Chart for Reading the Signs and Approximate Magnitudes of the Components of Vectors Which Have Been Operated Upon by a.

CHAPTER 2

DETERMINATION OF CHARACTERISTICS OF
MACHINERY AND APPARATUS USED IN WORK.

In selecting the apparatus to use in our tests we were fortunate to have available in the laboratory a bank of transformers whose characteristics and constants were such as to test the existent theory in its limiting conditions.

The necessary apparatus consisted of: -

- 1 Westinghouse Motor Generator Set; Rotating armature type of alternator.

Westinghouse a-c generator, 7.5 kv-a, 125 volts, Delta connected, 220 volts Star connected; 60 cycle, 1800 r.p.m.

34.3 Amp. per terminal Delta connected

19.7 " " " " " "

Serial number 1470261

- 1 Bank of Wagner Electric Company Transformers

1 kw. 220/110 volts, 7/14 amperes

serial numbers, 54945, 54945, 54947

- 1 Bank of Westinghouse Electric Company

Transformers. 2.5 kv-a, 2.7% Impedance;

240/120 volts - 88/22 volts

Serial Numbers, 1089477, 1092259, 1089479

The runs made for characteristic determination were as follows:-

- A. On the alternator
- 1. Open circuit characteristic or magnetization curve run.
- 2. Short circuit characteristic run.
- 3. Effective a - c resistance of armature with the armature removed from the machine, not including brushes.
- 5. Ohmic or d - c resistance of armature including brushes.

The alternator was run under load for a sufficient time to bring it up to stable operating temperature before the above readings were taken.

Due to the fact the alternator was of the rotating armature type it was necessary to determine the brush drop with direct current with the armature in place, as there was no way of setting the brushes on the slip rings with the armature out of the alternator for effective a - c resistance determination.

The brush drop per phase was obtained by subtracting the resistance per phase obtained from Run 4 from run 3.

Fig. 11 shows the diagram of connections for run #1

Fig. 12 " " " " " " " " #2

Fig. 13 includes the open and short circuit characteristics as obtained in runs (1) and (2)

No diagram of connections is included for runs (3), (4) and (5) due to the fact that standard practice for resistance determination was followed.

The observed data from the above runs follows in Section 1 and the calculated data is tabulated in section 2.

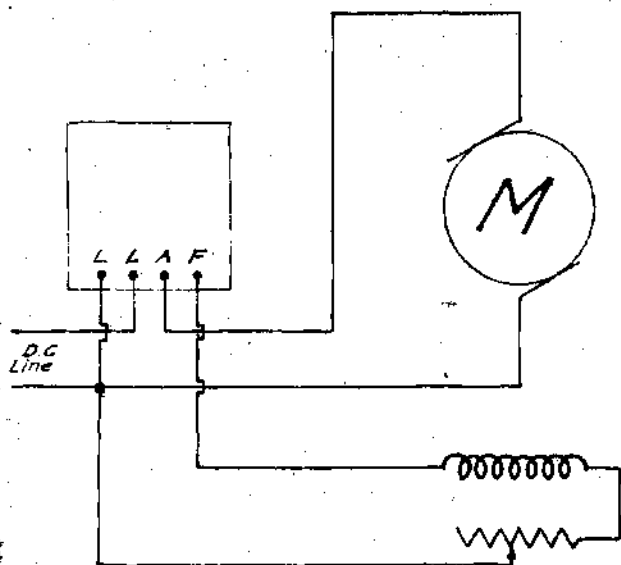
RUN #1

OPEN CIRCUIT CHARACTERISTIC OR MAGNETIZATION CURVE

Volts Per Phase	Field Current	Speed R. P.M
00.0	0.0	1800
22.0	5.0	"
39.5	8.3	"
54.8	11.85	"
67.0	14.8	"
80.0	17.25	"
89.0	19.5	"

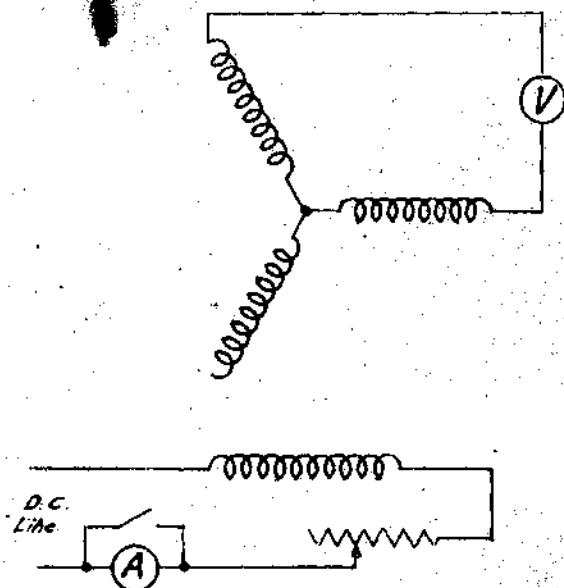
(46)

99.0	22.5	1800
106.3	24.75	11
115.0	27.5	11
121.3	30.0	11
127.	32.0	11
137.5	35.8	11
144.5	39.5	11



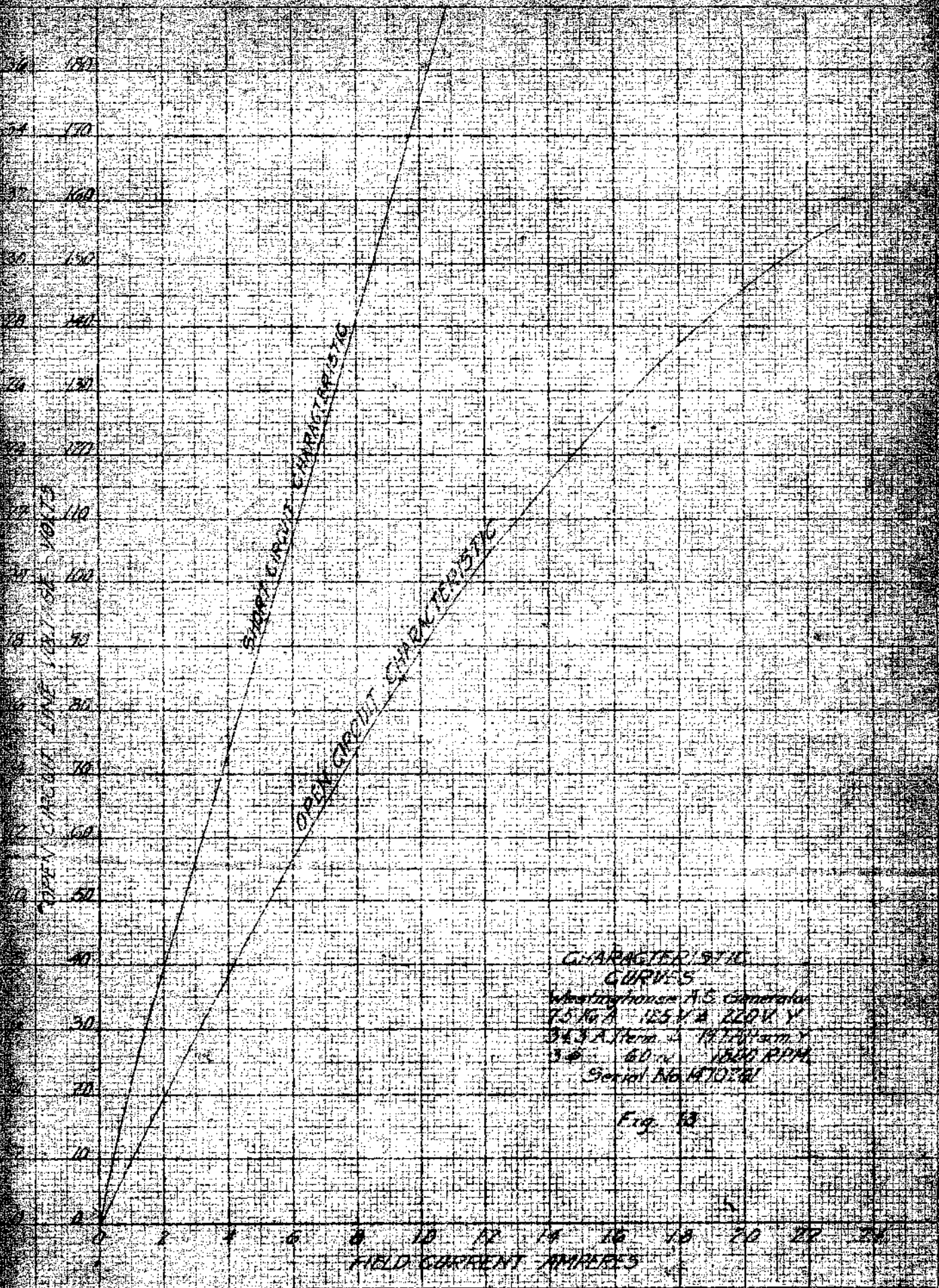
*Open Circuit
Fig. 11*

*D.C. Motor Same
as Above.*



*Short Circuit
Fig. 12*

*Fig. 11 & 12. Diagrams of Connection for Obtaining
the Characteristic Curves of an
Alternator.*



CHARACTERISTIC
CURVES
Westinghouse A.E. Generator
75 KVA 125 V. & 220 V. Y
34.3 A. Term. & 18.2 A. Term. Y
3.6 60 Hz. 1800 RPM
Serial No. 4710241

Fig. 13

(49)

RUN #2

SHORT CIRCUIT CHARACTERISTIC

	I_1	I_2	I_3	I_f	SPEED	$I_{av.}$
k=	5	5	5	.05	1800	5
	.7	.84	.8	1.5	"	.78
	1.78	1.8	1.83	4.8	"	1.803
	2.66	2.62	2.68	7.2	"	2.653
	3.45	3.4	3.48	9.75	"	3.443
	4.00	3.925	4.03	11.0	"	3.985
	<u>4.87</u>	<u>4.825</u>	<u>4.87</u>	<u>14.0</u>	"	<u>4.855</u>
k=	<u>10</u>	<u>10</u>	<u>10</u>			<u>10</u>
	2.98	2.93	2.98	17		2.9633
	3.45	3.4	3.46	19.5		3.437
	3.93	3.86	3.93	22.2		3.907

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(50)

RUN #3

EFFECTIVE A-C RESISTANCE WITH ARMATURE

REMOVED FROM MACHINE (NOT INCLUDING BRUSH
RESISTANCE)

k=	<u>Current</u>	<u>Watts</u>	
	<u>5</u>	<u>1</u>	
	3.875	92.	
	4.725	137.	Phase 1
	2.968	54.	a-a
	3.875	91.8	
	4.725	138.0	Phase 2
	2.95	53.5	b-b
	3.875	92.0	
	4.725	137.5	Phase 3
	2.975	54.0	c-c

(51)

RUNS #4 AND #5

OHMIC RESISTANCE OF ARMATURE

Current	E Terminal	E Without Brushes	
19.7	6.1	4.6	
8.46	3.2	2.	Phase 1
35.	10.3	8.32	
35	10.02	8.35	
19.7	6.2	4.66	Phase 2
8.265	3.2	2.0	
40.0	3.2	1.83	
19.6	6.1	4.52	Phase 3
6.85	10.1	8.28	

(52)

CALCULATIONS

EFFECTIVE RESISTANCE OF ARMATURE WITHOUT BRUSHES

Phase 1

.2448 ohms

.2453 "

.2400 "

Average = .2434

Phase 2

.2455 ohms

.2470 "

.2460

Average = .2462

Phase 3

.2448

.24625

.2440

Average = .24502

OHMIC RESISTANCE

	<u>With Brushes</u>	<u>Without Brushes</u>
Phase 1	.3095	.2335
	.3782	.2365
	.2943	.2375
Phase 2	.2863	.2384
	.3150	.23625
	.3868	.2418
Phase 3	.4000	.2288
	.3113	.2306
	.29085	.2382

Using average of 2 values corresponding to
highest currents:-

AVERAGE VALUES OF RESISTANCE

	<u>Eff. R</u> <u>Arm. alone</u>	<u>Eff. R</u> <u>Inc. Brushes</u>	<u>Ohmic R</u> <u>Inc. Alone</u>	<u>Ohmic R</u> <u>Inc. Brushes</u>
Phase 1	.24505	.31145	.2355	.3019
Phase 2	.24625	.309575	.237325	.30065
Phase 3	.34552	.312195	.2344	.301075

SYNCHRONOUS IMPEDANCE PER PHASE

Taken from Open Circuit and Short Circuit

Characteristics

RUN #3

I, short circuit = 40 amp.

E, open circuit = 100 volts

$$Z = 100 \div 40 = 2.5 \text{ ohms}$$

$$\text{Reactance per phase, } X_s = \sqrt{Z_s^2 - R_o^2}$$

Phase 1, $X_s = 2.48 \text{ ohms}$

Phase 2, $X_s = 2.48 \text{ ohms}$

Phase 3, $X_s = 2.48 \text{ ohms}$

B.

RUNS MADE ON THE TRANSFORMERS FOR DETERMINATION OF CHARACTERISTICS

The only run made for the characteristics or constants of the transformers was a short circuit run from which the reactance, effective resistance and the impedance of the individual transformers was calculated.

The observed data follows in Section 1

The Calculated " " " " 2

for both the Wagner Transformers and the Westinghouse transformers.

SECTION 1

OBSERVED DATA-SHORT CIRCUIT RUNS ON TRANSFORMERS

Wagner Transformers

Coil ratio of turns 2 to 1 i.e. 220/110

<u>Current</u>	<u>Volts</u>	<u>Watts</u>	
4.54	11.48	52	Trans. A #54946
4.54	11.8	52.5	Trans. B #54945
4.54	11.48	52.3	Trans. C #54947

Coil ratio of turns 1;1 i.e. 220/220

4.54	8.3	37.5	Trans. A
4.54	8.65	39	Trans. B
4.54	8.275	37	Trans. C

Westinghouse Transformers

10.4	7.83	77	#1089477
10.4	7.21	68	# 1092259
10.4	7.44	72	# 1089479

(56)

SECTION 2

CALCULATED DATA

TRANSFORMER IMPEDANCES, REACTANCES AND
RESISTANCES

Wagner Transformers

Referred to High Side

	R_e	Z	X		R_e	Z	X
220/110				220/220			
A	2.522	2.528			1.919	1.83	
B	2.545	2.6			1.89	1.904	
C	2.538	2.528			1.793	1.823	

In the above transformers the reactance was so low that it was not possible to measure it. As this will be indicated later this was a fortunate thing.

Westinghouse Transformers

Referred to High Side

220/80

	R_e	Z	X
1089477	.7115	.753	.247
1092259	.628	.693	.2931
1089479	.666	.716	.263

CHAPTER 3

ACTUAL TESTS, DATA AND RESULTS OBTAINED IN
SINGLE PHASE SHORT CIRCUIT TESTS.

The single phase short circuit tests were three in number, each consisting of a different type of connection. The most logical way to label and distinguish them is to call them Tests 1, 2, and 3 since the character of each is best denoted by its diagram of connections.

The current literature on the subject of short-circuits, bases its theory and calculations upon the fact that the resistance of the circuit is negligible on short-circuit and that the inductive reactance is the only factor restricting current flow.

Due to this prevalent assumption our three investigations of single phase short-circuits are subdivided into five parts:-

- a. The calculation of the short-circuit currents using the numerical value of the impedances of the apparatus in question.
- b. The calculation of the short-circuit currents using the complex form of solution.

- c. The calculation of the short-circuit currents using only the inductive reactance of the apparatus in question.
- d. The calculation of the short-circuit currents using only the resistances of the apparatus in question.
- e. The actual tests for the short-circuit currents actually existing under the short-circuit conditions assumed for the apparatus whose characteristic values and constants were used in the calculated results of parts a, b, c, and d above.

For the purpose of our investigation it was indeed fortunate that the transformers available and used in the tests, had a very high value of resistance as compared to their value of reactance. In fact, one bank of transformers, the Wagner, 1 kw. bank to be exact, had a resistance per phase practically equal to impedance. Thus the reactance was negligible in comparison. This is evident from the characteristic or constant determination tests as discussed in Chapter 2.

Due to this fact we were investigating for the extreme case and if we found that the resistance could be neglected in this case, it would show that the common assumption that resistance does not affect the value of current on short-circuit was correct.

SINGLE PHASE SHORT-CIRCUIT TEST

NO. 1

In Test No. 1, the apparatus consisting of the Westing house Y-connected alternator, Wagner bank of Transformers connected Y to Delta with a turn ratio of 1 to 1 and the Westinghouse transformers connected as shown in Fig. 14. The fault was as indicated.

Ammeters were placed in the ground connection or fault and also in the grounded leg of the Y-delta connected Westinghouse grounding transformers. With the fault connection open, the alternator voltage was set at 220 volts and the frequency at 60 cycles. The fault circuit was then closed causing the line-to-ground or as it is called "single phase short-circuit" to take place.

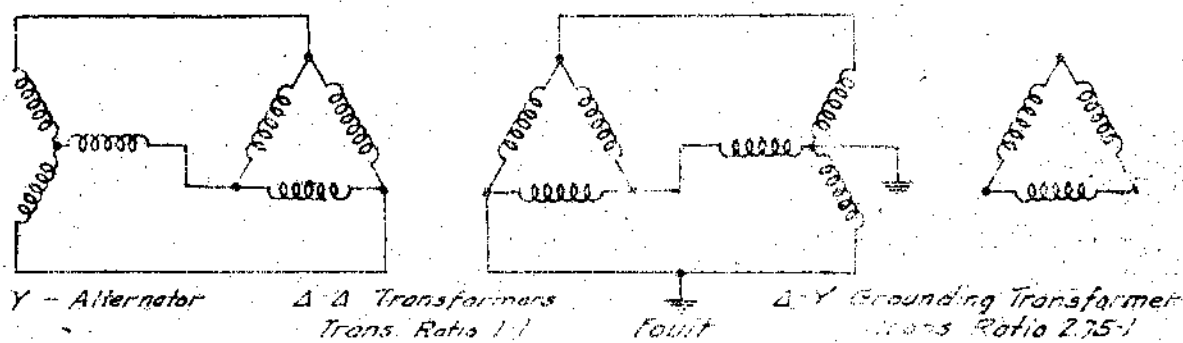


Fig. 14 Test No. 1 Single Phase Short Circuits.
Diagram of Connections.

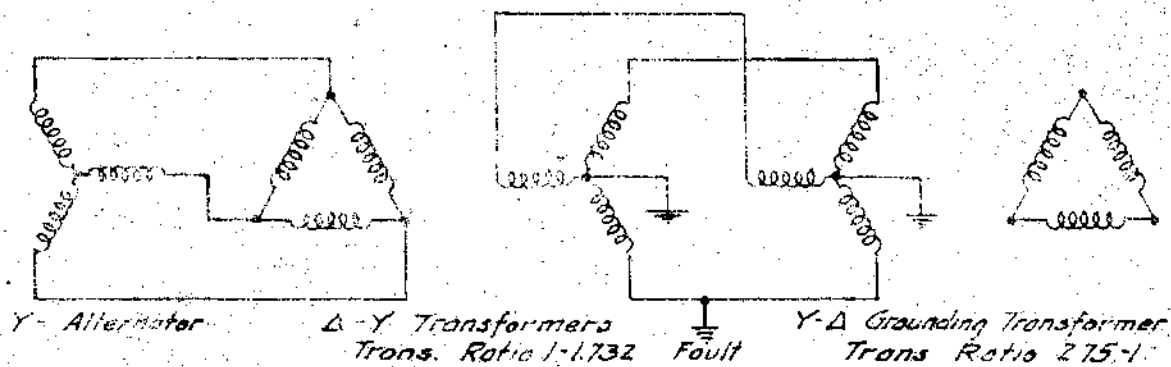


Fig. 15 Test No. 2 Single Phase Short Circuits.
Diagram of Connections.

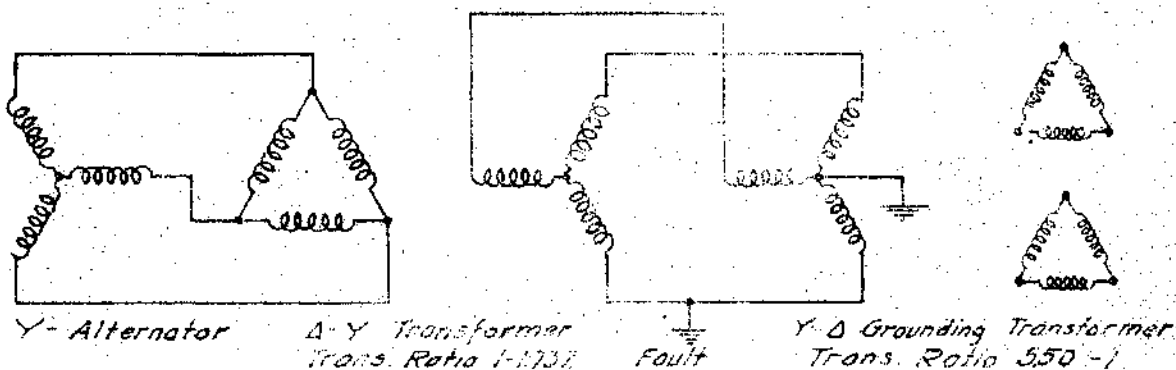


Fig. 16 Test No. 3 Single Phase Short Circuits.
Diagram of Connections. Three Winding Trans-
former as Grounding Transformer.

Two readings were made; first, the instantaneous or transient current in both the ground or fault and the grounded leg of the transformer were read at the instant of causing the fault, and secondly, the same currents were read after steady state conditions had been established.

The instantaneous or transient values are of only passing interest in this paper since they endure for only a few cycles and cannot be accurately investigated without the use of an oscillograph.

The steady state conditions, however, are of primary importance since it is these values that relay settings are based upon, and it is these values that give us a check upon the accuracy of our calculations as made to predetermine their magnitudes.

Following are the calculations as made according to the theory outlined in Chapter 1. In these calculations the average per phase values of the constants determined in Chapter 2 were used. These values will be found on the respective positive, negative and zero phase sequence networks diagrams accompanying the various solutions.

Test 1. Part. 1. Calculation of single phase short-circuit currents using the numerical value of the impedances of the apparatus as the basis for the calculation.

Impedance of the alternator per phase	2.5 ohms
Impedance of Delta to Delta Transformers	
Per Phase	1.83 ohms
Impedance of Y to Delta Transformers	
Per Phase	0.75 ohms

From the positive phase sequence network diagram on following page it is seen that for the positive phase sequence currents the impedance is

$Z, \text{ positive phase} = Z, \text{ alternator} + Z, \text{ Delta-Delta Transformers} = 2.5 + 1.83 = 4.33 \text{ ohms}$

$Z, \text{ negative phase sequence} = Z, \text{ alternator} \times .73 + Z, \text{ Delta-Delta Transformers} = 2.5 \times .73 + 1.83 = 3.66 \text{ ohms}$

$Z, \text{ zero phase sequence} = Z, \text{ Y-Delta Transformers} = .75 \text{ ohms}$

The total impedance is

$$4.33 + 3.66 + 0.75 = 8.74 \text{ ohms}$$

The current in the grounded leg of the Y connected grounding transformers is thus

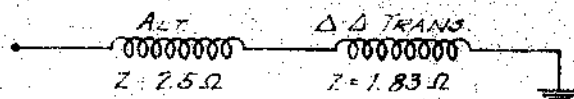
(63)

$$I = \frac{E}{Z} = \frac{220\sqrt{3}}{8.74} = 14.51 \text{ amperes}$$

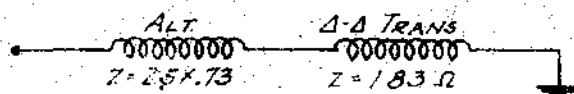
As is proven in Chapter 1 the ground current is three times the above value and is thus:-

$$I_g = 3 \times 14.51 = 43.53 \text{ amperes}$$

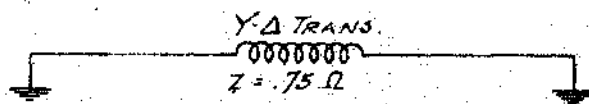
Part 1.



Positive Phase Sequence Network

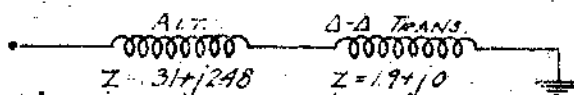


Negative Phase Sequence Network

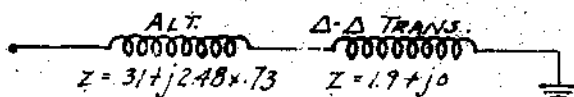


Zero Phase Sequence Network

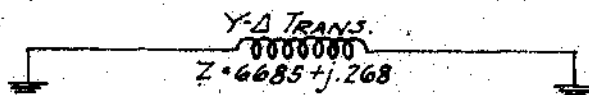
Part 2.



Positive Phase Sequence Network



Negative Phase Sequence Network



Zero Phase Sequence Network

Fig. 17. Test No. 1. Single Phase Short Circuits.
One Line Diagrams of the Positive, Negative and Zero Phase Sequence Networks.

Test 1, Part 2. Calculation of the single phase short-circuit currents using the complex expression for the values of the impedance of the apparatus as the basis for the calculation.

Impedance of the alternator per phase

$$Z = .31 + j2.48 \text{ ohms}$$

Impedance of the Delta-Delta Transformers per phase

$$Z = 1.9 + j0 \text{ ohms}$$

Impedance of the Y-Delta transformers per phase

$$Z = .6685 + j0.268 \text{ ohms}$$

From the positive phase sequence network diagram for Test 1, Part 2 it is seen that for the positive phase sequence current the impedance is

$$\begin{aligned} Z, \text{ positive phase sequence} &= Z, \\ &\text{alternator} + Z, \text{ Delta-Delta Transformers} \\ &= (.31 + j2.48) + (1.9 + j0) \\ &= 2.21 + j2.48 \text{ ohms} \end{aligned}$$

and in same manner

$$\begin{aligned} Z, \text{ negative phase sequence} &= Z, \text{ alternator} + \\ &Z, \text{ Delta-Delta transformer} = (.31 + j.73 \times 2.48) \\ &+ (1.9 + j0) = 2.21 + j1.81 \text{ ohms} \end{aligned}$$

(66)

also,

$$Z, \text{ zero phase sequence} = Z, \text{ Y-Delta transformer} \\ = 0.6685 + j0.268 \text{ ohms}$$

The total impedance is

$$(2.21 + j2.48) + (2.21 + j1.81) + (0.6685 + j0.268)$$

$$Z = 5.089 + j4.56 \text{ ohms, the numeric of which is}$$

$$Z = \sqrt{(5.089)^2 + (4.56)^2} = 6.835 \text{ ohms}$$

The current in the grounded leg of the Y-connected grounding transformer is thus:-

$$I = \frac{E}{Z} = \frac{220/\sqrt{3}}{6.835} = 18.62 \text{ amperes}$$

and the ground current is

$$I_g = 3 \times 18.62 = 55.86 \text{ amperes}$$

Test 1. Part 3. Calculation of the single phase short-circuit currents using only the values of the inductive reactance of the apparatus as the basis for calculation, neglecting the resistance.

From the positive phase sequence network diagram for Test 1. Part 3 it is seen that for the positive phase sequence current the reactance is :-

$$X_L, \text{ positive phase sequence} = X_L, \text{ alternator} +$$

$$X_L, \text{ Delta-Delta transformers} = 2.48 + 0$$

$$= 2.48 \text{ ohms}$$

(67)

and in the same manner

X_L , negative phase sequence = X_L , alternator

+ X_L , Delta-Delta transformers =

$$2.48 \times 0.73 + 0 = 1.81 \text{ ohms}$$

also X_L , = zero phase sequence = X_L , Y-Delta transformers

$$= .268 \text{ ohms}$$

The total reactance is

$$2.48 + 0.73 \times 2.48 + 0.268 = 4.558 \text{ ohms}$$

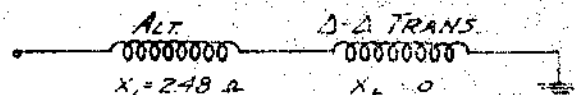
The current in the grounded leg of the Y-connected grounding transformer is thus

$$I = \frac{E}{X_L} = \frac{220}{\sqrt{3} \times 4.558} = 27.9 \text{ amperes}$$

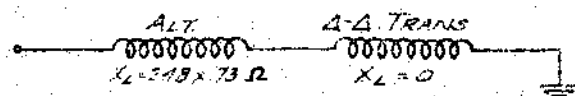
and the ground current is

$$I_G = 3 \times 27.9 = 83.7 \text{ amperes}$$

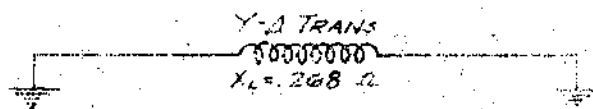
Part 3



Positive Phase Sequence Network

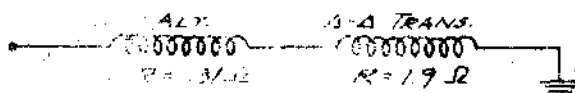


Negative Phase Sequence Network

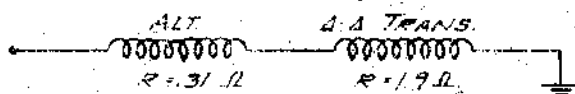


Zero Phase Sequence Network

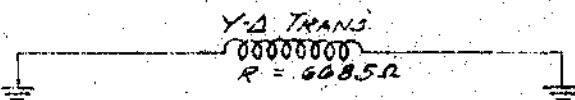
Part 4



Positive Phase Sequence Network



Negative Phase Sequence Network



Zero Phase Sequence Network

Fig. 18. Test No. 1 Single Phase Short Circuits.
One Line Diagrams of the Positive, Negative and
Zero Phase Sequence Networks.

Test 1. Part 4. Calculation of the single phase short-circuit currents using only the values of the resistance of the apparatus as the basis for calculation, neglecting the inductive reactance.

From the positive phase sequence network diagram for Test 1. Part 4 it is seen that for the positive phase sequence current the resistance is

$$R, \text{ positive phase sequence} = R, \text{ alternator} +$$

$$R, \text{ Delta-Delta transformer} = 0.31 + 1.9 = 2.21 \text{ ohms}$$

and in the same manner.

$$R, \text{ negative phase sequence} = R, \text{ alternator} +$$

$$R, \text{ Delta-Delta transformer} = 0.31 + 1.9$$

$$= 2.21 \text{ ohms}$$

$$\text{also } R, \text{ zero phase sequence} = R, \text{ Y-Delta transformer}$$

$$= 0.6685 \text{ ohms}$$

The total resistance is

$$2.21 + 2.21 + 0.6685 = 5.0885 \text{ ohms}$$

The current in the grounded leg of the Y-connected grounding transformer is thus:

$$I = \frac{E}{R} = \frac{220}{\sqrt{3}} \times 5.0885 = 24.93 \text{ amperes}$$

and the ground current is

$$I_g = 3 \times 24.93 = 74.79 \text{ amperes}$$

Test No. 1, Part 5

OBSERVED DATA

(70)

I	I	E	
<u>Grounded Trans. Phase current</u>	<u>Ground Current</u>	<u>Generator Voltage</u>	
39.5	119	89	Instantaneous or Transient Value
30.5	81	125	Sustained or steady State Value

Before closing fault circuit i.e., suddenly applying the short circuit from line to ground, the alternator voltage was set at 220 volts and the frequency at 60 cycles.

TABULATION OF CALCULATED RESULTS

TEST 1	I	I _g	
	<u>Grounded Trans. Phase Current</u>	<u>Ground Current</u>	
Part 1	14.51	43.53	All of these are steady state values.
Part 2	18.62	55.86	
Part 3	27.9	83.7	
Part 4	24.93	74.79	

The steady state values obtained for this hook-up on test were

(81)

I, grounding transformer phase current = 30.5 amperes

I, ground current = 81 amperes

As may be readily seen the observed steady state currents check the values as calculated in part 3.

These values calculated in part 3 were calculated using only the inductive reactance of the apparatus as a basis for calculation, neglecting the resistance.

This shows conclusively that the assumption that the resistance may be neglected in single phase short-circuit calculations, is correct since the ratio of resistance to reactance in the apparatus used was high, and in the delta to delta connected bank of transformers the reactance was so low as to be negligible.

Part 3 calculations are on the only ones checking the actual test results.

SINGLE PHASE SHORT-CIRCUIT TEST

NO. 2

In test No. 2, the apparatus consisting of the Westinghouse Y-connected alternator, Wagner bank of transformers connected Delta to Y with a turn ratio of 1 to 1, and the Westinghouse bank of transformers connected Y to delta with a turn ratio of 2.75 to 1

was connected as shown in Fig. 15. The fault was as indicated.

Ammeters were placed in the ground connection or fault and also in each of the grounded legs of the Y-connected transformers.

With the fault connection open, the alternator voltage was set at 220 volts and the frequency at 60 cycles.

The fault circuit was then closed causing the line-to-ground or as it is called "single phase short-circuit" to take place

Two readings were made; first, the instantaneous or transient currents in the fault, and both grounded transformer legs were read at the instant of causing the fault and secondly, the same currents were read after steady state conditions had been established.

As in Test No. 1, the instantaneous or transient values are of only passing interest in this paper since they only endure for a few cycles and cannot be investigated without the use of an oscillograph.

The steady state conditions are of primary importance since it is these values that relay settings

are based upon and it is these values that give us a check upon the accuracy of our calculations as made to predetermine their magnitudes.

Test 2 Part 1. Calculation of single phase short-circuit currents, using the numerical value of the impedances of the apparatus as the basis for the calculation.

Impedance of the alternator, per phase = 2.5 ohms

" " " Delta-Y trans. " " = 1.90 "

" " " Y-Delta " " " = 0.75 "

From the positive phase sequence network diagram for Test 2 Part 1, it is seen that for the positive phase sequence current the impedance is

Z, positive phase sequence = Z, alternator +

Z, delta-Y transformers = 2.5 + 1.9 = 4.4 ohms

and in the same manner

Z, negative phase sequence = Z, alternator x 0.73

+ Z, delta-Y transformers = 2.5 + 0.73 + 1.9

= 3.725 ohms

also

$$Z, \text{ zero phase sequence} = \frac{1}{\frac{1}{Z, \text{delta-Y}} + \frac{1}{Z, \text{Y-delta}}}$$

(74)

$$1 + (1/1.9 + 1/0.75) = 1 + (0.526 + 1.333) \\ = 0.5375 \text{ ohms}$$

The total impedance is

$$4.4 + 3.725 + 0.5375 = 8.6625 \text{ ohms}$$

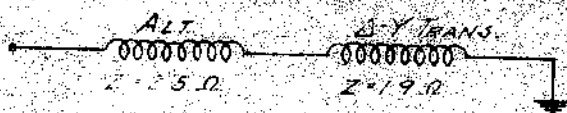
I, combined transformer leg currents =

$$220 \div \sqrt{3} \times 8.6625 = 14.67 \text{ amperes}$$

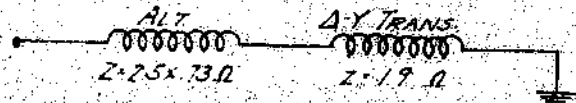
$$I, \text{ delta-Y transformer phase} = \frac{14.67 \times 1.9}{0.5375} = 10.5 \text{ amps.}$$

$$I, \text{ ground} = 3 \times 14.67 = 44 \text{ amperes.}$$

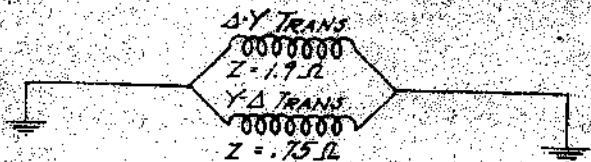
Part 1



Positive Phase Sequence Network

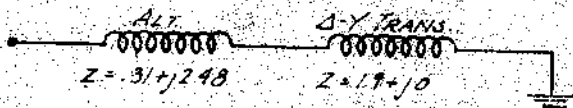


Negative Phase Sequence Network

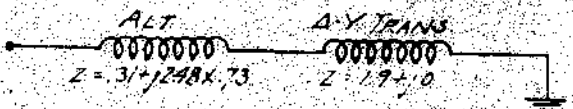


Zero Phase Sequence Network

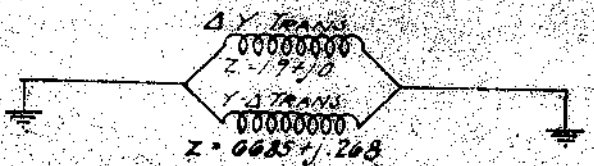
Part 2



Positive Phase Sequence Network



Negative Phase Sequence Network



Zero Phase Sequence Network

Fig. 19 Test No. 2 Single Phase Short Circuits
One Line Diagrams of the Positive, Negative and Zero Phase Sequence Networks

(76)

Test No. 2, Part 2. Calculation of the single phase short-circuit currents using the complex expression for the values of the impedance of the apparatus as the basis for the calculation.

From the positive phase sequence network diagram for Test 2, part 2 it is seen that for the positive phase sequence current the impedance is,

$$Z, \text{ positive phase sequence} = 2.21 + j2.48 \text{ ohms}$$

and in the same manner

$$Z, \text{ negative phase sequence} = (0.31 + j0.73 \times 2.48) + (1.9 + j0) = 2.21 + j1.81 \text{ ohms}$$

also for the zero phase sequence

$$Y, \text{ delta-Y transformers} = 1 + Z, \text{ delta-Y} =$$

$$1 + (1.9 + j0) = .5265 + j0$$

$$Y, \text{ Y-delta transformers} = 1 + (.6685 + j0.268) =$$

$$1 + (.6685 + j.268) \times \frac{(.6685 + j.268)}{(.6685 - j.268)} =$$

$$1.29 - j0.517$$

$$Y, \text{ zero phase sequence} = Y, \text{ delta-Y} + Y, \text{ Y-delta} =$$

$$(0.5265 + j0) + (1.29 - j.517)$$

$$= 1.816 - j.517$$

$$Z, \text{ zero phase sequence} = 1 + Y, \text{ zero phase sequence}$$

(77)

$$= \frac{1}{1.816 - j .517} \times \frac{1}{1.816 + j .517} =$$
$$= .51 + j .145 \quad \text{numeric} = .53 \text{ ohms}$$

Total impedance is thus

adding positive, negative and zero phase sequences,

$$= (2.21 + j 2.48) + (2.21 + j 1.81) + (0.51 + j 0.145)$$
$$= 4.93 + j 4.435 \quad \text{numeric} = \sqrt{(4.93)^2 + (4.435)^2} = 6.63 \text{ ohms}$$

I, combined transformer phase currents

$$= 220 + \sqrt{3} \times 6.63 = 19.3 \text{ amperes}$$

I, ground = $3 \times 19.13 = 57.39$ amperes

I, delta-Y transformers = I, total phases $\times Z$, zero

phase sequence + Z, delta-Y transformers

$$= 19.13 \times .53 + 1.9 = 5.34 \text{ amperes}$$

I, Y-delta transformers = $19.13 \times .53 + .75$

$$= 13.55 \text{ amperes}$$

Test 2, Part 3. Calculation of single phase short-circuit currents using only the inductive reactance of the apparatus as the basis for the calculation, neglecting the resistance.

From the positive phase sequence network diagram for Test 2, Part 3 it is seen that for the positive phase sequence current the inductive reactance is:

(78)

X_L , positive phase sequence = X_L , alternator +

X , delta-Y transformers = $j 2.48 + j) =$

$j2.48$ ohms and in the same manner

X_L , negative phase sequence = X , alternator $\times 0.73$

+ X , delta-Y transformers = $j 2.48 \times .73 + j0$

= 1.81 ohms

also

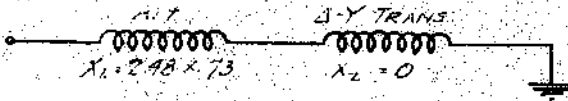
X , zero phase sequence = $\frac{1}{\frac{1}{X_{L, \text{delta-Y}}} + \frac{1}{X_{L, \text{Y-delta}}}}$

$$= \frac{1}{\frac{1}{0} + \frac{1}{.268}} = ?$$

Part 3



Positive Phase Sequence Network

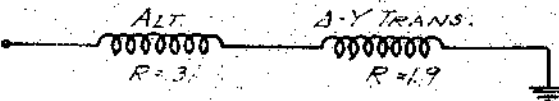


Negative Phase Sequence Network

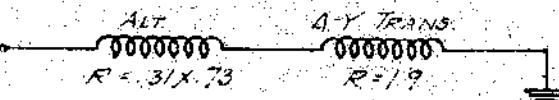


Zero Phase Sequence Network

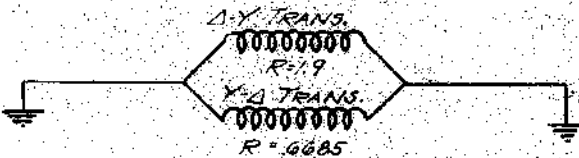
Part 4



Positive Phase Sequence Network



Negative Phase Sequence Network



Zero Phase Sequence Network

Fig. 20 Test No. 2 Single Phase Short Circuits.
One Line Diagrams of the Positive, Negative
and Zero Phase Sequence Networks

As can be readily seen this solution as indicated above would be indeterminate due to the fact that the inductive reactance of the delta-Y bank of transformers was negligible.

This indicates conclusively that the values of single phase short-circuit currents for this particular type of connection cannot be calculated when the resistance is neglected and only the inductive reactance used. This is unfortunate since in view of the previous test the above mentioned method of calculation was evidently the best.

Although the calculation would tend to indicate infinite current in the delta-Y grounded transformer phase, this was not the case as is shown by the test data for this particular hook-up. This indicates conclusively that the resistance must have a limiting effect in this peculiar and particular type of connection.

In view of the above fact, the current could be predicted by calculation by merely using the value of the delta-Y transformer resistance in place of the inductive reactance in making the calculation.

(81)

$$\begin{aligned} X, \text{ zero phase sequence} &= 1 + (1/1.9 + 1/0.268) \\ &= 0.237 \text{ ohms} \end{aligned}$$

The total inductive reactance is:-

Adding the positive, negative and zero phase sequence inductive reactances we have,

$$j 2.48 + j 1.81 + j 0.237 = j 4.527 \text{ ohms}$$

I, combined transformer phase currents

$$= 220 \div \sqrt{3} \times 4.527 = \text{amperes}$$

$$I, \text{ ground} = 3 \times 28 = 84 \text{ amperes}$$

I, delta-Y transformer phase = I, total $\times$ X_L , zero phase sequence + X , delta-Y transformer

$$= 84 \times .237 + 1.9 = 10 \text{ amperes}$$

I, Y-delta transformer phase

$$= I, \text{ total} \times X_L, \text{ zero phase sequence} + X,$$

$$Y\text{-delta transformer} = 84 \times 0.237 + .268$$

$$= 74 \text{ amperes.}$$

As will be readily seen on the final tabulation of data and comparison of calculated and test values, this does not check the test results. This indicates conclusively that this method of calculation of the single phase short-circuit currents is of no value for this type of connection when the transformers have negligible reactance.

Test 2, Part 4. Calculation of the single phase short-circuit currents, using only the resistance of the apparatus as the basis for the calculation, neglecting the inductive reactance.

From the positive phase sequence network diagram for Test 2, Part 4 it is seen that for the positive phase sequence current the reactance is:-

$$R, \text{ positive phase sequence} = R, \text{ alternator} +$$

$$R, \text{ delta-Y transformer} = .31 + 1.9$$

$$= 2.21 \text{ ohms}$$

and in the same manner,

$$R, \text{ negative phase sequence} = R, \text{ alternator} +$$

$$R, \text{ delta-Y transformer} = .31 + 1.9 = 2.21 \text{ ohms}$$

also

$$R, \text{ zero phase sequence} = \frac{1}{\frac{1}{R, \text{ delta-Y}} + \frac{1}{R, \text{ Y-delta}}}$$

$$= \frac{1}{\frac{1}{1.9} + \frac{1}{0.6685}} = .495 \text{ ohms}$$

The total resistance is

$$2.21 + 2.21 + .495 = 4.915$$

I, combined transformer phase =

$$220 + \sqrt{3} \times 4.915 = 25.85 \text{ amperes}$$

$$I, \text{ delta-Y transformer phase} = \frac{25.85 \times .495}{1.9}$$

$$= 6.735 \text{ amperes}$$

(83)

I, Y-delta transformer phase = $\frac{25.85 \times .495}{.6658} = 19.12$
amperes.

Test No. 2, Part 5

OBSERVED DATA

Type of Reading	I grounded current	I Y-delta Trans. Phase	I delat-Y Trans. Phase	
Transient	92	17.5	66	
Sustained	55	13.	39.5	Run #1
Transient	90	17	66	
Sustained	56	13	39	Run #2

Before closing the fault circuit, i.e. suddenly applying the short-circuit from line to ground, the alternator voltage was set at 220 volts and the frequency at 60 cycles.

TABULATION OF CALCULATED RESULTS

Test 2

	I Ground	I Combined Phase	I Delta-Y Phase	I Y-Delta Phase
Part 1	44	14.67	4.15	10.5
Part 2	57.39	19.13	5.34	13.55
Part 3	84	28.	10.	74.
Part 4	77.55	25.85	67.35	19.12

All of the above values are for the steady state condition.

As is readily seen by the comparison of the calculated and observed values, they do not check in any instance. This is due no doubt to the fact that the type of hook-up used made an exact calculation of the currents in part 3 impossible. This does not in any way, however, nullify the results of test 2. It merely shows that when the transformers used have an inductive reactance which is negligible as compared to the resistance, accurate predetermination of the magnitude of the single phase short-circuit currents is impossible when using the present theory which bases its calculation of the inductive reactance only.

This clearly indicates a limiting condition for the theory as used. This condition, i.e., transformers whose inductive reactance is negligible, would never be met with under practical transmission line conditions of operation, thus it is evident that the assumption that the inductive reactance is the only factor limiting current flow under short-circuit conditions is permissible only when the ordinary commercial type of apparatus is used and is not necessarily true for all types of apparatus, experimental and special.

TEST NO. 3

INVESTIGATION OF SINGLE PHASE SHORT-CIRCUIT
CURRENTS USING THREE-WINDING TRANSFORMERS AS
GROUNDING TRANSFORMERS.

The authors spent a great deal of time in pre-determining the single phase short-circuit currents for the apparatus when connected as shown in Fig. 16, using three-winding or tertiary grounding transformers.

Due to the fact that the transformers available and used in the test were not of the usual three-winding type, but were ordinary two winding transformers with a split secondary, and also, the lack of accurate low-reading meters, we were unable to arrive at satisfactory results.

Our results indicated that the theory as developed for the three-winding grounding transformer would not hold for the split secondary type. This is probably because of the great difference between the inter-laced impedances in the two types.

The authors regret the lack of time and instruments which made it impossible to extend our investigation to such an extent as to definitely determine the reasons why the tertiary theory was not applicable to the split secondary type of transformer.

CHAPTER 4

INVESTIGATION OF RELAY CONNECTIONS
AND RESULTS.

We were requested by some engineers of the Georgia Railway and Power Company to investigate the operation of the Type CR Directional Over-Current Relay manufactured by the Westinghouse Company. The Power Company had been having trouble with these relays on their lines and wish to ascertain if the connections were correct. We made four separate tests each involving a different connection of apparatus. These tests will be numbered Tests 4, 5, 6 and 7 and will be discussed separately in detail. We are including in this thesis pages 16-24, inclusive of the Westinghouse bulletin which describes the operation, construction and adjustment of the CR Directional Current Relay.

The Directional Over-Current Relay is designed to protect Transmission lines which feed to a common bus. If a short-circuit or other fault occurs on one line of a system feeding thru a common bus the other line or another line if there are more than two separate lines will feed power thru the station bus and back to the point of trouble on the defective line.

By placing these relays between the line and the sub-station bus that line will be protected against a reverse flow of power back to the fault should one occur.

This relay works similarly to the usual standard Watthour meter. However, it can be easily seen that if the relation between the current and voltage coils were such that the current and voltage were practically in phase with the current in the right direction, should a short occur on the line dropping the power factor to about zero, the current and voltage coils would be 90 degrees out of phase and consequently there would be no torque.

The CR Directional Over-Current Relay is so designed that with unity power factor load on the line the current in the relay directional element will lead the voltage supplying the directional element by 30° . This will allow the current to lag a considerable amount during time of short-circuit without placing a 90° angle between the voltage and current.

Before making any connections to the relays for a three-phase distribution it is absolutely necessary that the phase rotation be determined. We looked through several references but found nothing on the subject. However, after some study on our part we developed a method of determining the phase rotation

which is fairly simple and requires only a single phase wattmeter since the current and potential transformers would be necessary for the relays.

The wattmeter is connected as shown in Fig. 21. One wattmeter can be used and changed from one line to another. The vector diagram shows the relation between the currents and voltage. It will immediately be seen that if a reading is taken of wattmeter A with the potential coils on lines A and B and if a reading is taken of the same wattmeter with the potential coils on lines A and C the wattmeter readings will be respectively $I_A E_{BA} \cos(30+45^\circ)$ and $I_A E_{CA} \cos(30^\circ - \text{a very small angle})$. Consequently the second reading will be the larger of the two. Now take the reading of wattmeter C with the potential leads first from B to C and next from A to C. The wattmeter readings will be $I_C E_{BC} \cos(30^\circ - \text{a very small angle})$ and $I_C E_{AC} \cos(45^\circ + 30^\circ)$. Consequently the first reading will be the larger of the two. Thus with the phase rotation as shown, ABC and the wattmeter in line A the larger wattmeter reading will occur with one potential lead on the line which precedes line A in phase rotation. This is also shown by the readings taken in line C. In any case one potential lead is always kept on the line which goes through the meter and the other lead changed from one line to the other.

If the phase rotation is reversed as shown in Figure 21 the reading of Wattmeter A can be shown in the vector diagram. It will be seen that the wattmeter reading will be larger for wattmeter A when its potential coils are connected from B to A than when connected from C to A. This would indicate from the previous reasoning that the rotation should be such that A follows C in rotation or that the rotation is CBA. These two connections with their accompanying vector diagrams show that this method of determining phase rotation is correct.

After this method had been used for determining the phase rotation in our tests we learned of a method described in the August 29th 1925 issue of the Electrical World by Mr. John Auchincloss of the Switchboard Engineering Department, General Electric Company under the title, "Determining the Sequence of Phases".

This method uses two lamps and a reactance of approximately the same impedance as the lamps. These are connected as shown in Fig. 22. One of the lamps will burn more brightly than the other. In the first case shown, lamp B burns bright. The vector diagram

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is as shown and the point O will be on the right-hand side of the circle. E_B represents the voltage across lamp B and E_A represents the voltage across lamp A. The currents in the two lamps are of course in phase with their voltages, consequently I_R represents the phase position of the current in the reactance. We know that the current in a reactance lags approximately 90 degrees behind its voltage. Therefore, E_R represents the voltage across the reactance and the phase rotation is 1 - 2 - 3.

In the second case shown lamp A burns bright and the point O is on the left-hand side of the circle. The construction is similar to the first case and it will be seen that the phase rotation is 3 - 2 - 1.

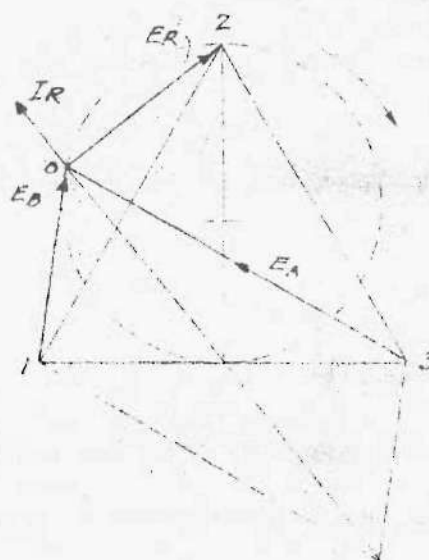
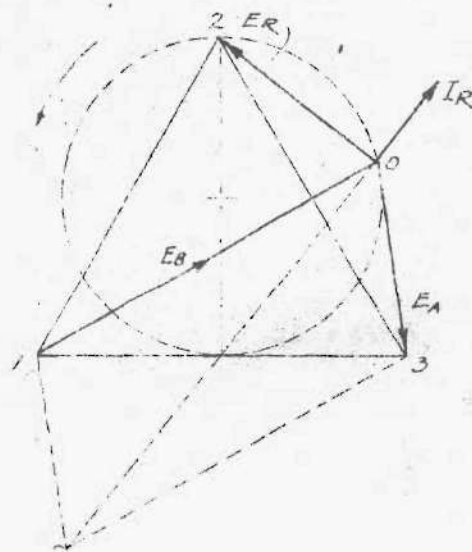
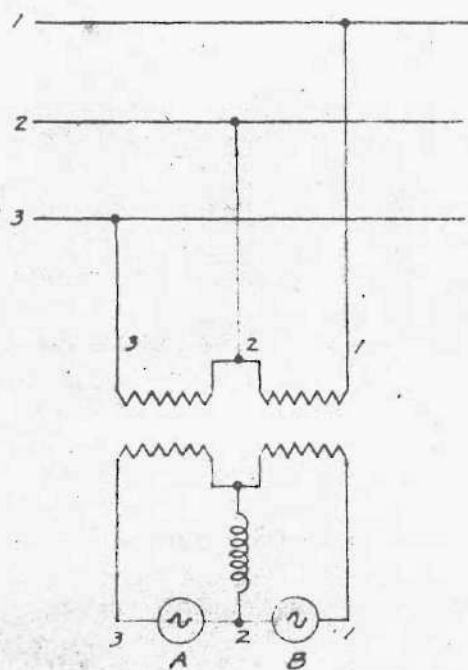


Fig 22 Method of Determining Phase Rotation by Use of Lamps and Inductance.

DESCRIPTION OF TESTS

Test No. 4 was made with the connection as shown in Fig. 35 of the Westinghouse bulletin. The polarities are not shown in this figure but we endeavored to make the connections and polarities consistent. Adjustment was made so that the contacts of the directional element were all open when the power was flowing towards the bus bars. When the power was reversed and with a power factor of about 10% two of the relays closed and the other stayed open. We spent considerable time trying to make this connection work but were unable to do so.

Test No. 5 was made with connections as shown in Fig. 23 which were developed by the authors. An open-delta transformer connection was used for supplying the potential coils of the relays. This connection proved satisfactory as the relays all stayed open with the power flow in the right direction and the phase rotation correct. The relays all closed when the direction of power was reversed with about 10% power factor. The objection to the open-delta connection is that unbalanced voltages are obtained under short-circuit conditions which might prevent the relays from

obtaining enough torque to operate.

Test No. 6 was made with connections as shown in Fig. 24. This connection was given us by Professor Savant and uses a Y-delta connection of power transformers and an open-delta connection of potential transformers for supplying the potential coils of the relays. This worked entirely satisfactorily giving the same results as in the previous test.

Test No. 7 was made with connections as shown in Fig. 25. This diagram of connections ~~were~~ furnished us by some engineers of the Georgia Railway and Power Company and it represents the connections of No. 1 Bank at the Marietta, Georgia, High Tension Station. This uses a delta-Y connection of power transformers and an open-star connection of potential transformers for supplying the potential coils of the relays. The advantage of the open-star connection is that balanced voltages are obtained. The contacts opened with current flow in the right direction and closed with power flow in the opposite direction with about 10% power factor. We then tried the connection with a ground on the line side of the relays and the contacts closed as they should have done. We checked the current and voltage relations between the current

Directional Element Classes
With Power in this Direction

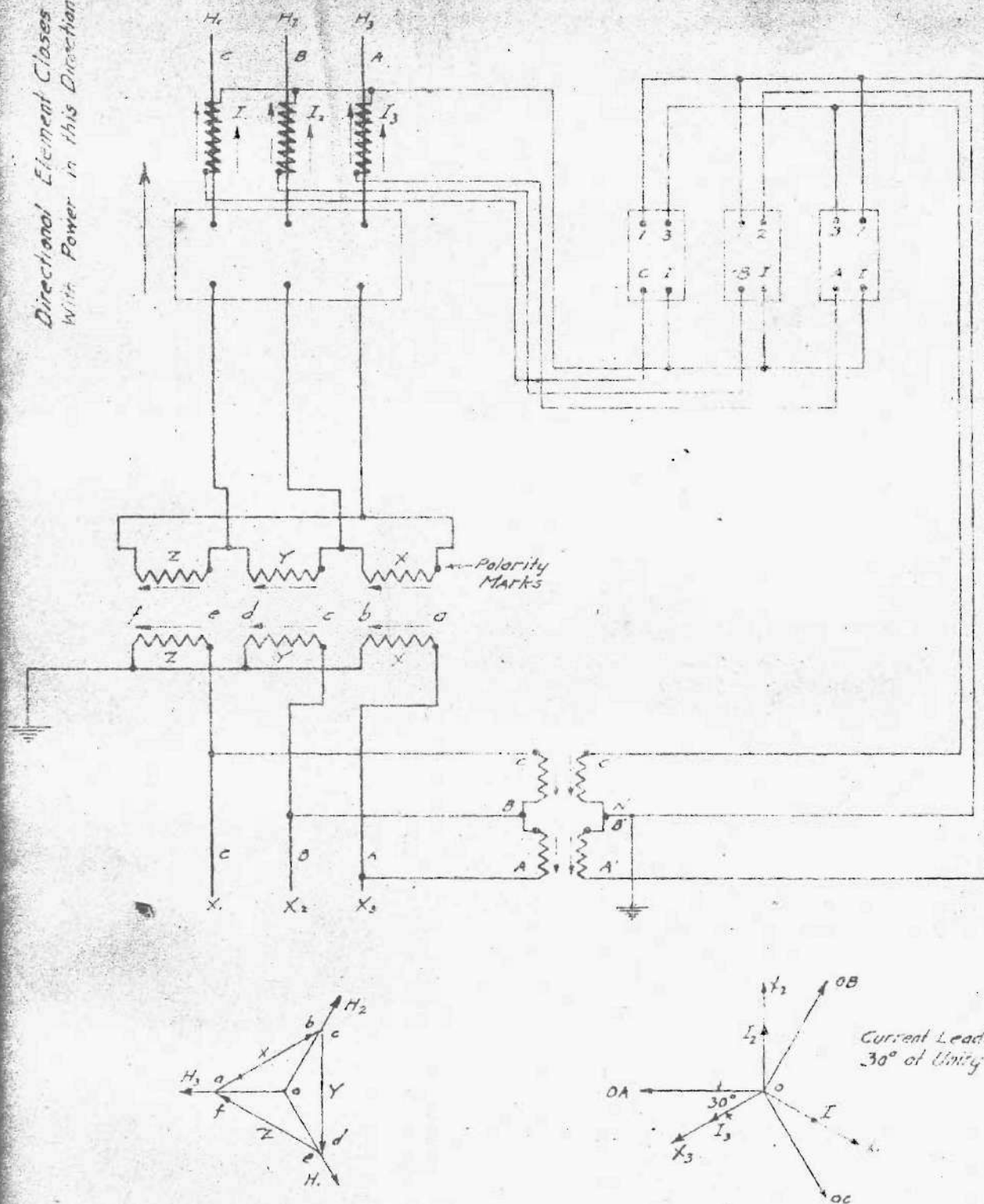


Fig. 23. Type C-R Relay Connections with Δ -Y Power Transformer between Line and Station.

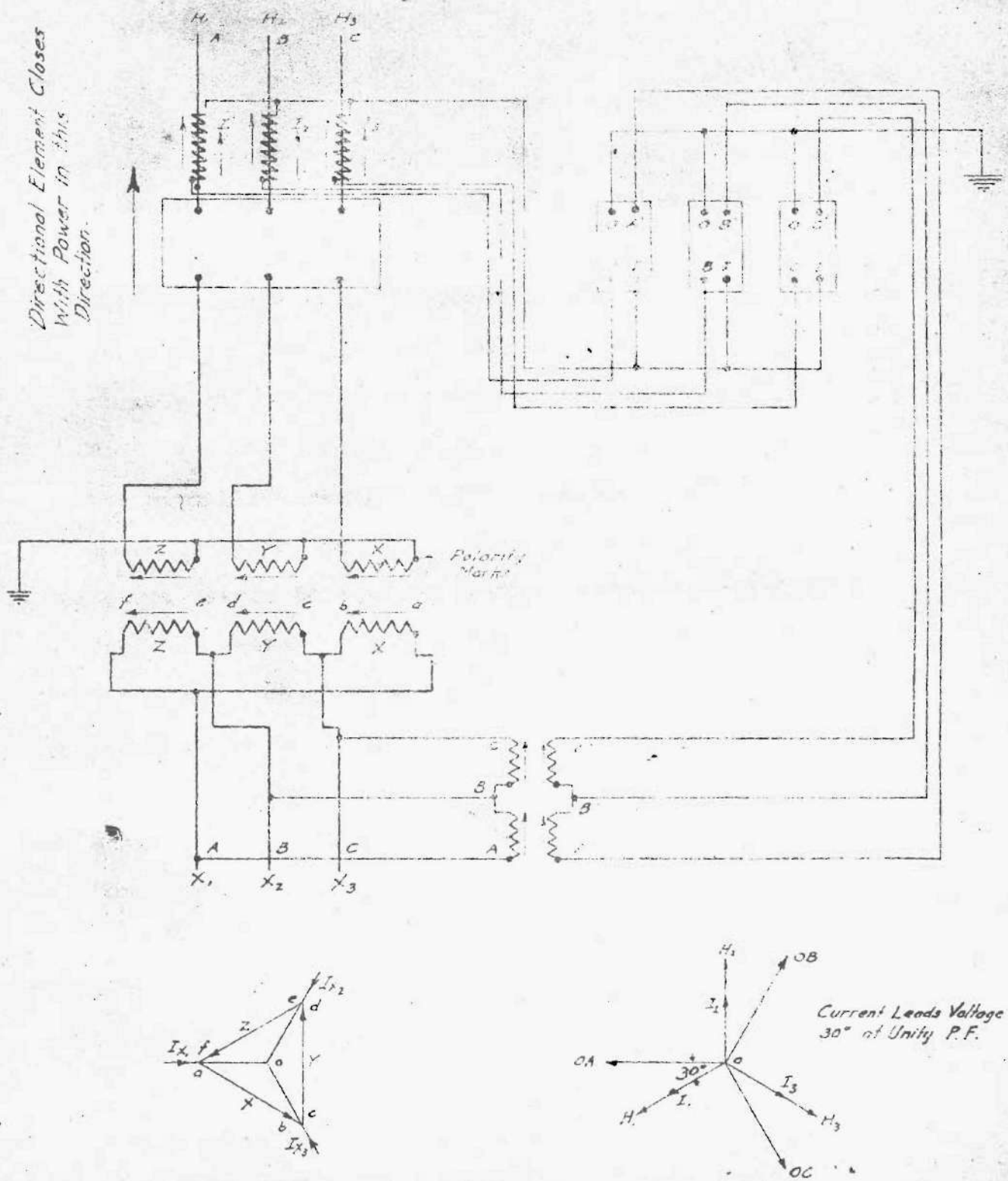


Fig. 24. Type C-R Relay Connections with Y-Δ Power Transformer between Line and Station.

In the current coil of the relay and the potential supplying the potential coil of the relay. The current was found to be leading approximately 28 degrees in all the relays with the power in the right direction and a unity power factor load which checks fairly closely with the value of 30 degrees claimed by the Westinghouse Company. With the power flowing in the opposite direction and a reactive load of about 10% power factor we obtained a current lag of approximately 56 degrees in the relays, as calculated from the wattmeter, voltmeter and ammeter readings. The power factor meter gave a value of 23 degrees lag. Inasmuch as the power factor meter is very often off considerably, the value of 56 degrees as calculated from the other meters is probably nearer the correct value.

In all the above tests except the first the relation between the current and voltage in the relays was approximately 28 degrees lead.

In the first test with the Westinghouse connections we could make the relays open with power flow in the right direction by manipulation of the potential leads but the power factor would

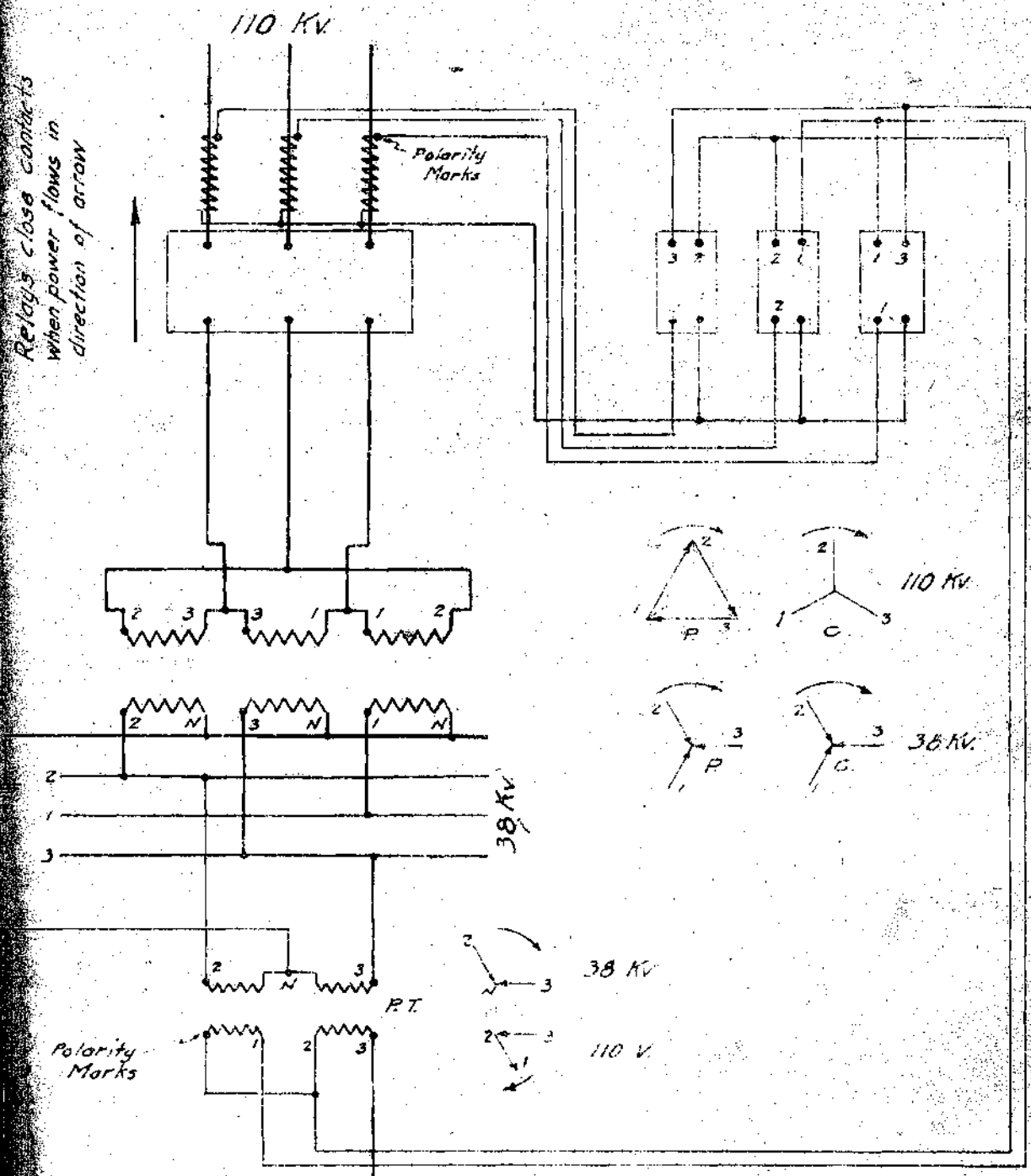
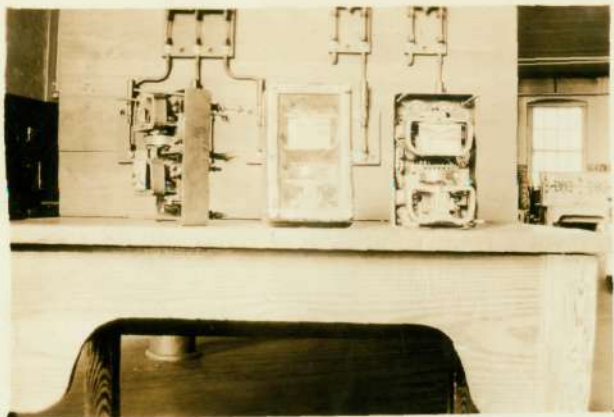


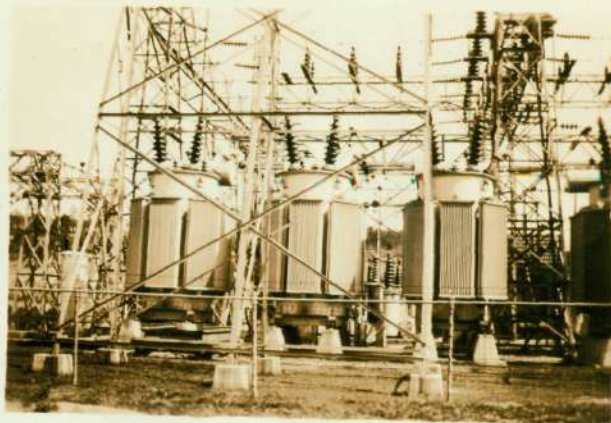
Fig. 25 Vector Diagrams for Connections on C.R.
Relays at Marietta No. 1 Bank. Phase Se-
quence 3, 2, 1. Vector Rotation
as Shown

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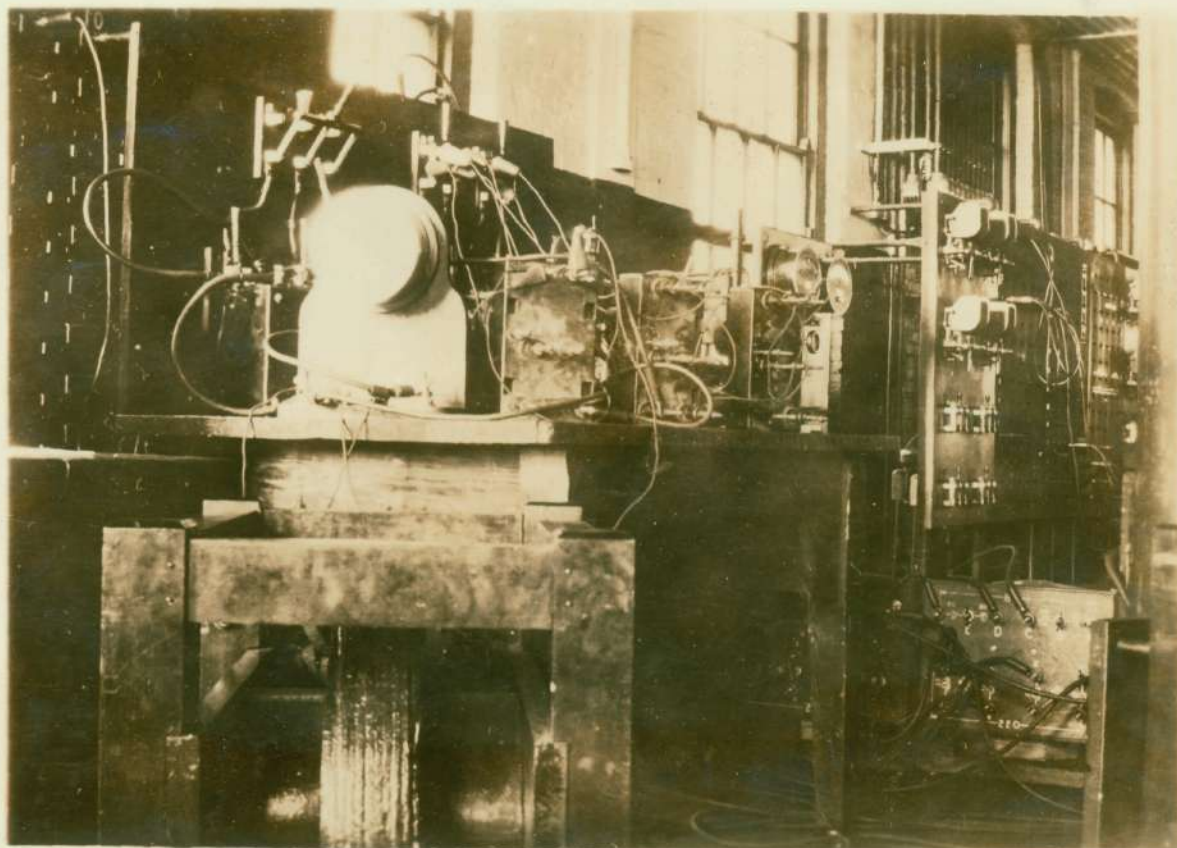
not check anywhere near what it should be. By changing the potential transformer connections to open-delta the operation was satisfactory in every way.



TYPE CR WESTINGHOUSE OVER-
CURRENT DIRECTIONAL RELAYS



TRANSFORMER BANK NO. 1
MARIETTA HIGH TENSION STATION



RELAY TEST APPARATUS

CHAPTER 5

DISCUSSION OF RESULTS

In our introduction we stated that it was our intention to verify existing theory on single phase short circuits and to determine if possible, the limits of its practical application and use.

Our results verify the existing theory for practical connections and assumptions in calculation, and we have achieved a condition which sets a limit upon the use of the present theory, and indicates an avenue of investigation which if followed, would result in defining the exact conditions of application.

The thesis was divided into two main parts as implied in the title. The first part, the investigation of single phase short-circuits as indicated above, resulted in some very interesting information which points the way to further more or less original research.

The second part, the investigation of relay connections and operation, resulted in some valuable important data. checks on existing methods of connection and indicated some innovations in methods of connection.

Test number one in the single phase short-circuit group, shows clearly that for the usual commercial type of hook-up, that the prevalent assumption as to inductive reactance being the only factor limiting current flow on short-circuit is correct. This is accentuated by the fact that the transformers used had highly resistive windings as compared to their inductive reactance and in one bank, the reactance was negligible as compared to the resistance.

The values of short-circuit current were calculated by four methods as indicated in chapter three and the only predetermined values that checked the actual test values were those obtained in part 3 of test 1 where inductive reactance was assumed to be the only factor limiting current flow. This presents a very strong argument in favor of the investigation along this line. It is in line with accepted theory with respect to inductive reactance as the limiting factor on short-circuit.

Test No. 2 in the single phase short-circuit group resulted in some rather mystifying although important data. It indicates clearly that for the type of transformers used on the test, the special experimental low reactance type, the assumption that

inductive reactance is the only factor limiting current flow on short-circuit is erroneous. The predetermined values in no way checked the experimental results. As is seen in chapter three, test number 2, this is due in a great measure to the peculiarities of the transformer hook-up. This test is very important due to the fact that with the apparatus used and the type of hook-up used we have exceeded the limits of the theory for single phase short-circuits.

It is true that the results were obtained from a special case of hook-up and test, but it is the meeting and interlinking of the general case with the special case that usually determines the limiting factors and conditions of any theory and practice.

The results of this test show that further investigation along this line would result in much evidence as to the conditions under which the present theory of single phase short-circuit calculation may be applied with safety and certainty.

The authors regret the lack of time and sufficiently delicate instruments to thoroughly investigate this phase of the problem.

Test number 3 of the single phase short-circuit section was productive of one fact. The three-winding transformer theory for tertiary connections under short-circuit conditions evidently does not hold for the ordinary two winding, split secondary type of transformer when used in this manner. The authors have come to this conclusion after a considerable time has been spent in testing and calculation in an attempt to apply the existing theory or to develop new relationships which would hold. It was with real regret that the authors had to terminate this part of the investigation and proceed with the study of relay connection and operation.

The results obtained in the second part of the investigation, the relay tests, showed conclusively that for accurate predetermination of relay operation, great care must be taken in deriving the type of connection used. Absolute determination of the phase rotation, definite knowledge of instrument and transformer polarities and strict adherence to the diagram of connections as worked out are imperative.

The work with relays showed that the diagrams supplied with relays cannot be relied upon implicitly. The connections for the runs in chapter 4 are correct theoretically and work out most satisfactorily in practice. From the tests it can be seen that if the connections are worked out consistently with polarities and rotation taken into consideration satisfactory operation will be obtained with various types of transformer connections.

In connection with the statement of the engineers of the Georgia Railway and Power Company that trouble had been experienced in the operation of these relays at the Marietta High Tension Station, it would seem from our tests that the trouble must have been due to mechanical causes in the relays inasmuch as our tests indicated that the relays would work under the extreme conditions usually met in practice. The operator at the Marietta station stated that it was sometimes necessary to take a pencil and touch the moving element of the relay so that it would function properly. Consequently the connections as used there are correct and that more consistent results can only be obtained by an improvement in the mechanical design

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of the relays.

The results on the whole were more than satisfactory practically and indicate decisively that there is much investigation and research along this line of endeavor as yet undone.

Westinghouse Induction Type Over-Current and Directional Over-Current Relays

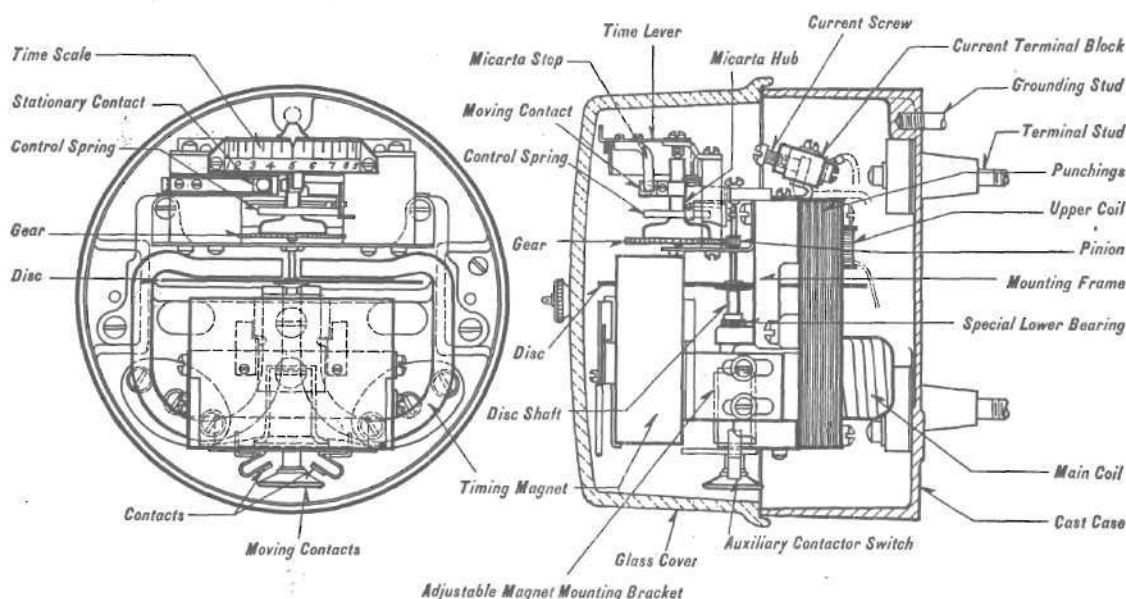


Fig. 21—Front and Side Sectional View of Low-Energy Type CO Over-Current Relay

CONSTRUCTION

Figure 18 shows the Low-Energy Type CO Relay with cover removed while figure 21 shows a cross section view. The construction of the magnetic element, the disc, the case and the cover are exactly the same as the Type CO Relay. The method of mounting the contacts is different, however, inasmuch as they are mounted on a separate shaft which is geared to the main disc shaft. With this arrangement a very small amount of energy is all that is necessary to cause the disc to rotate. The number of turns in the winding of both the main and the auxiliary coils is different from that on the standard energy Type CO Relay. The torque compensator is also omitted and the definite minimum time characteristic is obtained by having the disc run at synchronous speed with excessive overload. This is possible inasmuch as the gearing makes it necessary for the disc to make a number of revolutions before the contacts are closed.

OPERATION AND CHARACTERISTICS

The operation of the Low-Energy Type CO Relay is the same as that already described for the high energy type. Inasmuch as it requires such a low amount of energy for operation it is consequently much more sensitive than the standard type. The gearing makes it some-

what slower in resetting than the standard type of relay.

The inverse time characteristic and the definite minimum time are similar to those of the standard CO Relay. As will be noted by figure 22 showing the time current curves of the low energy relay, the curves are somewhat more inverse and do not flatten out as quickly as those of the standard Type CO.

The relay is also equipped with an internal contactor switch and it may be supplied with either single or double tripping circuits and with either 2 or 4 second minimum time characteristics.

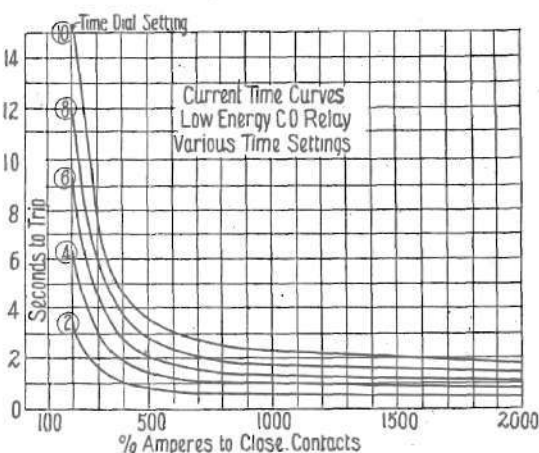


Fig. 22—Current-Time Curves of Low-Energy Type CO Over-Current Relays

Westinghouse Induction Type Over-Current and Directional Over-Current Relays

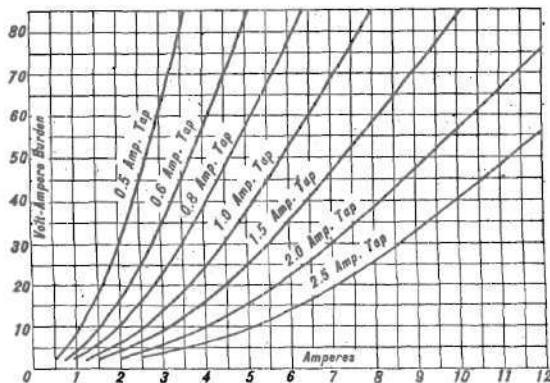


Fig. 23—Characteristic Curves of Low-Energy Type CO Over-Current Relay, Showing the Burden Placed on the Current Transformer with Various Currents in the Relay Windings

INSTALLATION, ADJUSTMENT AND TESTING

The instructions for installing, adjusting and for the care and maintenance of the Low-Energy Type CO Relay are the same as those already given for the standard Type CO. Also the same general test information is applicable.

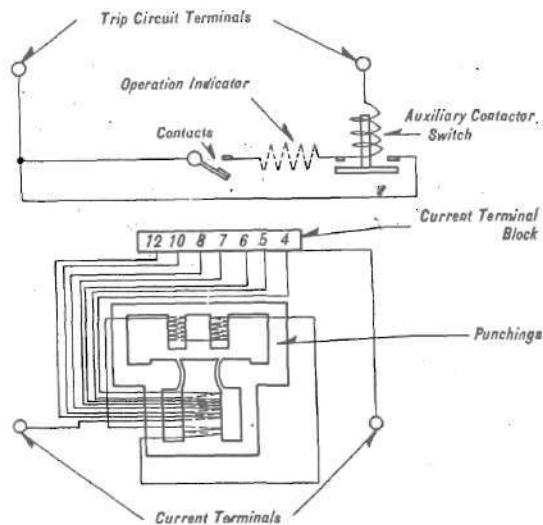


Fig. 24—Diagram of Internal Connections for Low-Energy Type CO Over-Current Relay

The current tap values of the 4 to 12 ampere range are the same as the standard relay, namely, 4-5-6-7-8-10-12 amps. The tap values of the $\frac{1}{2}$ to $2\frac{1}{2}$ amperes range are .5-.6-.8-1.0-1.5-2.0-2.5.

Type CR Directional Over-Current Relay

APPLICATION

The line of Type CR Directional Over-Current Relays is designed to protect or disconnect transmission lines when there is a short circuit or other fault on the system of such a nature that the current flow is excessive in the direction for which the relays are connected to operate. In general practice the direction in which the current flows in order to have the directional relay trip is away from the station bus bars inasmuch as in most applications the relays are connected so as to hold their contacts open as long as the flow is toward the sub-station. The Type CR Relay may be depended upon to discriminate as to the direction of current flow under all conditions of low voltage which are likely to occur in cases of severe short circuits.

Parallel Transmission Lines—The Type CR Relays are suitable for use at the receiving end of lines where a fault on any line will cause the power to reverse and flow back to the point of the trouble on the defective line. Figure 25 shows a typical application of the directional over-current relay for the protection of parallel feeders.

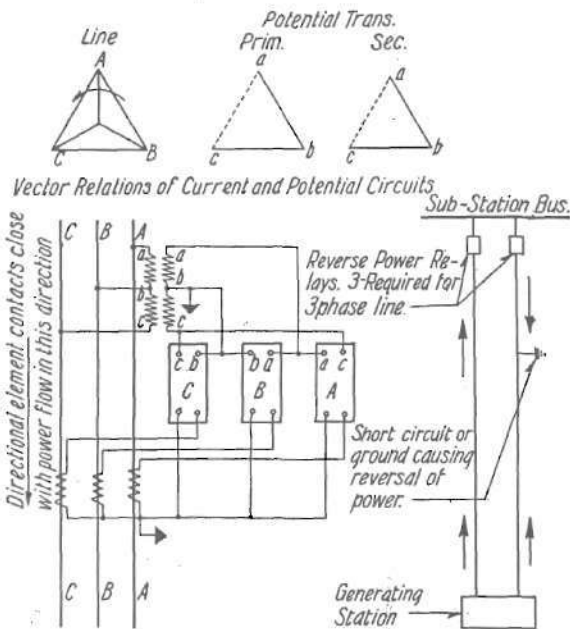


Fig. 25—Ordinary Method of Connecting Type CR Directional Over-Current Relays on Three-Phase System. Voltage Vectors shown. Connections give Current 30° lead at 100% P.F.



Fig. 26—Type CR Directional Over-Current Relay

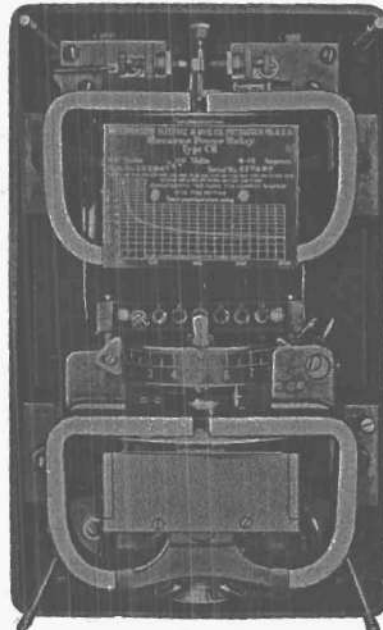


Fig. 27—Type CR Directional Over-Current Relay (Cover Removed)

Ring Systems—A ring system such as shown in figure 28 is similar to the case of two parallel feeders supplying a substation except that each feeder is made to loop through a number of substations. On such a system definite time limit directional over-current relays such as the Type CR must be used. The time limit of each successive relay is increased by a sufficient amount to allow time for the circuit breaker in the preceding substation to open. Relays applied on such a system are usually installed in such a way that at each substation the normal direction of power is assumed to be into the substation. The relays will trip only when the current is flowing out of a given substation and exceeds the amount for which the over-current element of the Type CR Relay is set to close its contact.

Special Application—There are many special applications in which the Type CR Relay is used. Among these might be mentioned the cross connection system of protection as used on parallel feeders shown in figure 29. Another application is the use of the Type CR Duo-Directional Relay for the protection of two parallel feeders. A schematic diagram of this is shown in figure 30.

CONSTRUCTION

Figures 26 and 27 show the general appearance and arrangement of the parts of the Type CR Directional Relays. Each relay consists of two separate and distinct parts, excess current

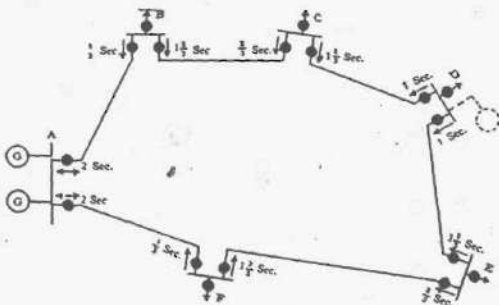


Fig. 28—Typical Ring System Protected by Means of Type CO and Type CR Relays

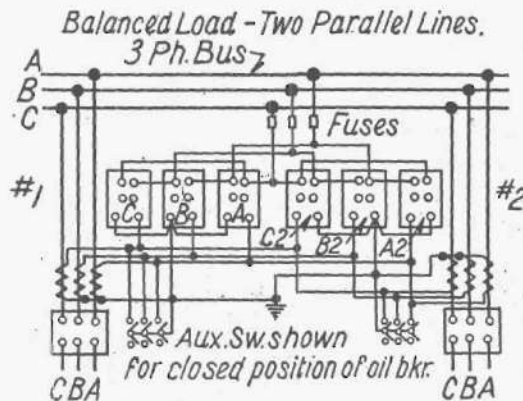


Fig. 29—Diagram of Cross-Connected Type CR Relays for Parallel Line Protection

Westinghouse Induction Type Over-Current and Directional Over-Current Relays

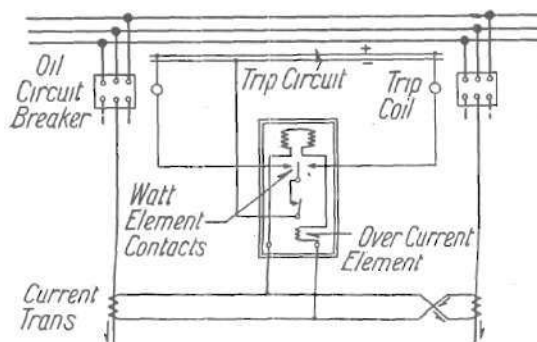


Fig. 30—Diagram of Connections for Type CR Duo-Directional Relays for the Protection of Two Parallel Lines

element and the directional or wattmeter element. The over-current element is identical with the Type CO Overload Relay as already described, and is mounted in the lower part of the case with the wattmeter element mounted directly above it.

Directional Element—The wattmeter or directional element is composed of an electro-magnet, the moving element, contact assembly, and mounting frame and bearings, mounted in the upper half of the relay case. The electro-magnet resembles that of the standard Westinghouse Watthour Meter and operates in exactly the same way as the Watthour Meter element. The current coils are wound on the

two upper poles and the potential coil on the main lower pole.

Moving Parts—The moving parts of the directional element are practically the same as those already described under the Type CO Relay. The disc differs from that of the Type CO inasmuch as there are no holes punched in it and is copper. The special type of ball bearing as used in the over-current element is not used in the directional element but instead a rigid steel shaft with a hemispherical bottom rests on a sapphire cup jewel. At the top of the shaft is an adjustable pivot bearing. This construction gives a means of adjustment for end play and allows very little so that heavy short circuits will not cause undue vibration.

The moving element is carefully balanced and is controlled by a light spring so that its action in closing the directional contacts will be as nearly simultaneous with the reversal of current as possible. With the standard adjustment there should be practically no torque placed on the disc by the spring. The spring is used mainly for a current conductor for the moving contact.

Contact Assembly—The contact assembly consists of a stationary contact screw mounted and a moving contact spring mounted on an insulating sleeve on the disc shaft. The moving contact closes a circuit in one direction or both

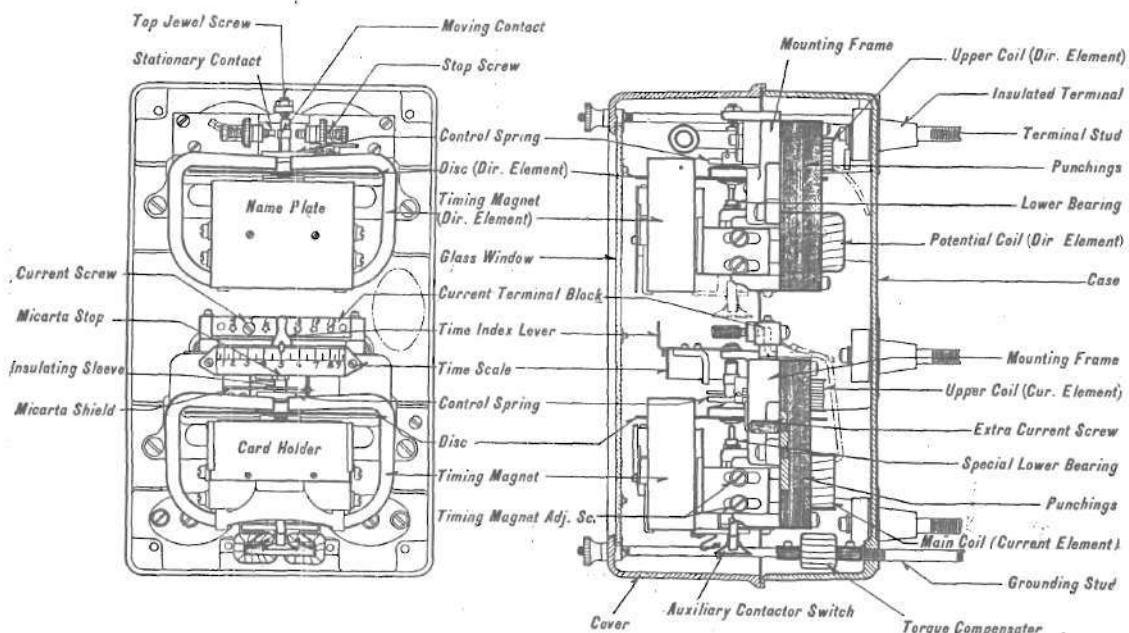


Fig. 31—Front and Side Sectional View of Type CR Directional Over-Current Relay

Westinghouse Induction Type Over-Current and Directional Over-Current Relays

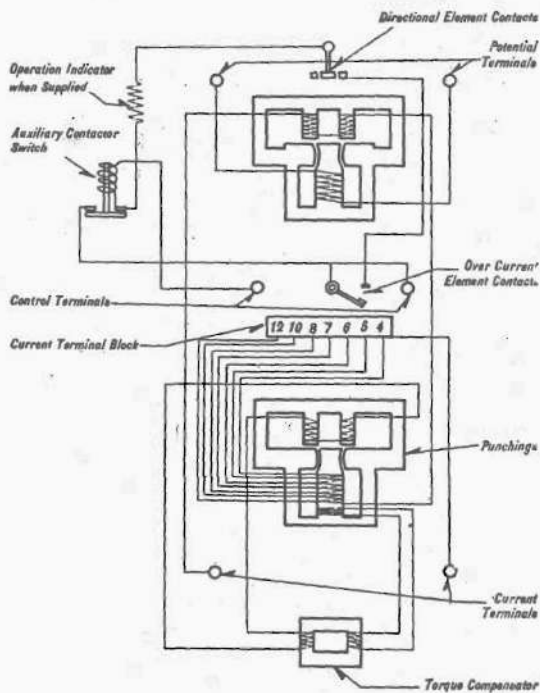


Fig. 32—Internal Wiring Diagram of Type CR Relay Showing Standard Connections With Six Terminals. (Rear View)

directions of travel according to whether it is a uni-directional or a duo-directional relay. Its motion is exceedingly small, being only about $\frac{1}{32}$ of an inch either way. As shown by the wiring diagram in figures 32, 33, 34, and 39 the contacts of the directional element are connected in series with those of the over-current element and the contactor switch as used in the Type CO Current Relay is so connected in the tripping circuit that the contacts are relieved of practically all duty.

Latest Design—In the latest design of the CR Directional Relay as shown in figure 26, the stationary contact or contacts as the case may be are made screw mounted and located in the front of the case instead of at one side as in the former design. The moving contact is spring mounted. In this design the contactor switch is located at the bottom of the case to the rear of the overload element thus insuring it against accidental tripping when the cover is being removed.

It is sometimes desired to install standard CR Directional Relays inasmuch as future additions to the system will make them necessary, but at the time of installation it is desired to have them operate as straight overload relays. With the new design of the

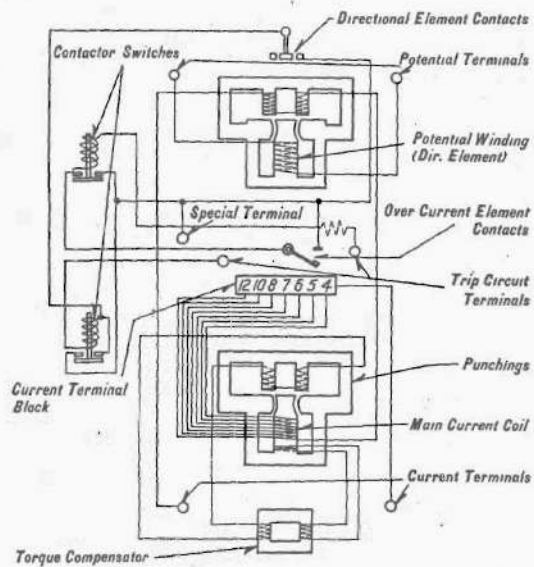


Fig. 33—Internal Wiring Diagram of Type CR Relay with Special Terminal in Trip Circuit between Elements (7 Terminals, 2 Contactor Switches)

Type CR this is easily accomplished inasmuch as the directional element contacts may be locked shut by closing the screw mounted stationary contact firmly against the moving contact. This eliminates the action of the directional element from the action of the relay as a whole.

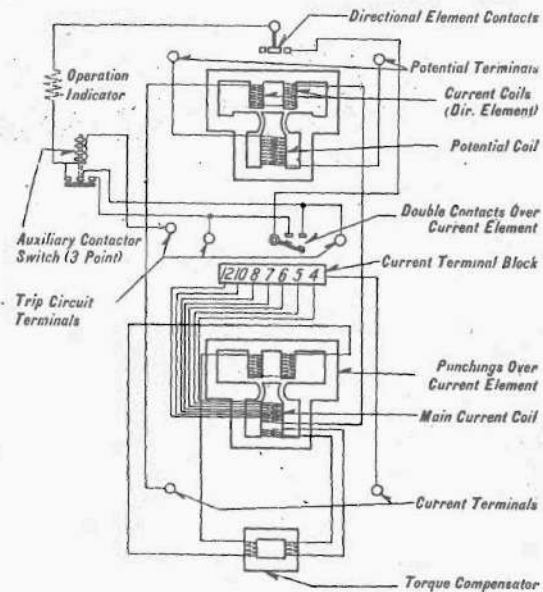


Fig. 34—Internal Wiring Diagram of Type CR Relay with Double-Trip Circuit (7 Terminals)

OPERATION AND CHARACTERISTICS

The directional element of the Type CR Relay is so constructed that it is extremely sensitive and quick acting. It will close its contacts with a reasonable excess current flowing and with a voltage as low as one per cent of normal. The contacts of the directional element will only close, however, with the current flow in the direction for which the relay is connected to act. No amount of excess current flowing in the other direction will operate this element. As stated in the preceding paragraph the spiral spring on the directional element exerts practically no torque on the disc shaft, its main purpose being to conduct the current of the tripping circuit. In the uni-directional relays as soon as there is any current flowing in the proper direction there will be a torque exerted on the disc tending to hold the contacts open. With no current flowing in the line the directional element contact may close, but this is of no consequence, as the overload element contacts will remain open.

INSTALLATION

Caution—As already mentioned, too much care cannot be exercised in the handling of the relays, as, although they are of sufficiently rugged construction to stand all ordinary handling, they are sensitive instruments and will not stand the excessive bumps and knocks to which other apparatus is sometimes subjected.

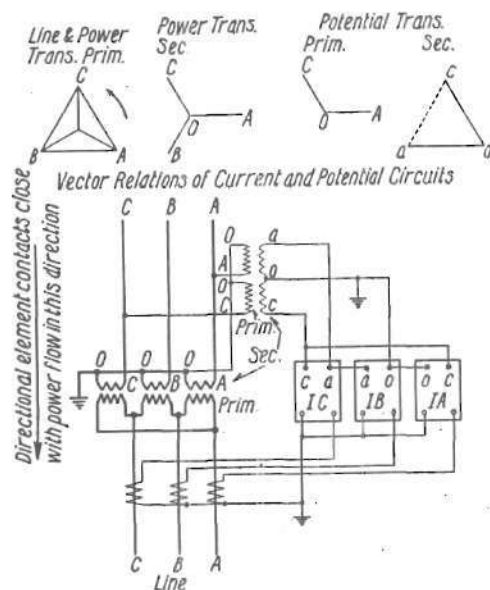
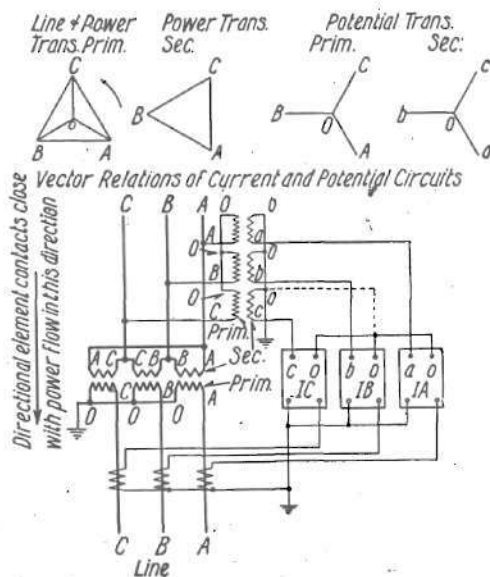


Fig. 35—Type CR Directional Over-Current Relay Connections with Y-Δ Power Transformer between Line and Station. Connections as shown give Current 30° lead at 100% P. F.



This scheme of connections requires three voltage transformers, but enables the standard 125-volt relays to be used.

Fig. 36—Proper Connections for Type CR Direction Over-Current Relay used on Three-Phase System with Δ-Y Power Transformers between Line and Substation.

If the relay is not already mounted on a slate panel when received it should be mounted by means of the terminal studs. Drilling plans for preparing the panel for mounting the relay are either supplied with the relay or may be obtained from the factory upon request.

After the relay has been permanently mounted it should be thoroughly cleaned by means of a small brush and cloth. The cover should be removed and the interior part of the relay carefully inspected for any damage which might have been done in shipment. This inspection should especially include a test of the moving parts to see that they have not become out of alignment and that there is no friction existing. The presence of friction can usually be determined by moving the disc with the hand and allowing it to return to the normal position. The auxiliary contactor switch plunger should also be moved up and down with the finger in order to insure against any sticking or friction.

CONNECTIONS

After the relay has been properly mounted as described above, connections should be made to terminals on the rear of the panel

either according to the diagrams of connections accompanying the relay or according to standard diagram as shown in figure 25. All connections made to the terminals should be well tightened and where it is necessary to make connections where there is no connecting stud all joints should be well soldered. Poor or loose connections are very often the cause of a great amount of trouble.

In applying the Type CR Directional Relays to polyphase systems consideration must be given to the varying effects of short circuits involving two or three or four conductors or to ground on the phase relation of the current and the voltage applied to the relay. The characteristics of the ordinary wattmeter element are such that the disc will reverse its direction or rotation when the phase relation between the voltage and current becomes 90 degrees or greater. As many faults very greatly disturb the relation of the voltage and current, care must be taken to connect the directional relay in such a way that the voltage and current phase relation may never become more than 90 degrees apart.

Connections must therefore be made so that with unity power factor on the line the current in the relay directional element will be

30 degrees ahead of the potential supplying the directional element. This will allow the current to lag a considerable amount during time of short circuit without placing a 90 degree angle between the voltage and current. This will enable the relay to operate properly upon the occurrence of unbalanced short circuits such as results where only two wires of a three phase system are short circuited and also on other faults of a similar nature.

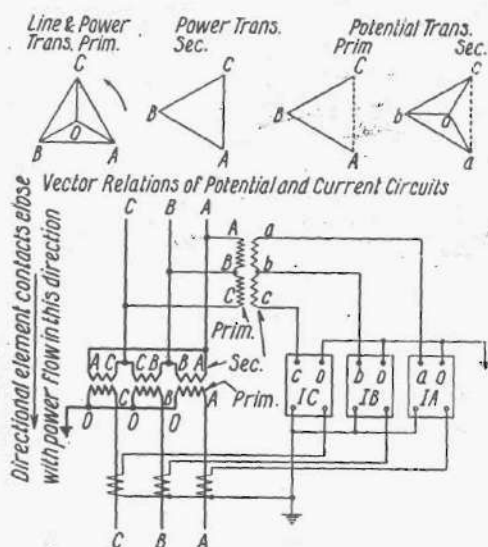
The following methods should be used in checking up the correct connections to the directional element of the relay.

Wattmeter Method—With the power flowing in either direction, if the current is lagging, so that power factor is between 100 and 50 per cent, connect the current coils of a single phase wattmeter in series with the current winding of the relay. Then select a pair of voltage leads which give the highest reading on the wattmeter. The two leads should be connected to the relay potential terminal. Inspect the contact of the directional element, which should be open when the power is flowing towards the bus-bars. If the contacts are closed when the current flows towards the bus bars then the potential leads of the relay should be reversed.

Power Factor Meter Method

A second method is to connect the current coils of a single phase power factor meter in series with the current coils of the relay. A pair of potential leads are then selected which will give 86.6 per cent power factor leading on the power factor meter when the line power factor is 100 per cent. These two leads should be connected to the relay potential terminals. The upper contact should be inspected as before as mentioned in the preceding paragraph and checked for proper operation.

Phase Meter Method—A third method of checking the proper connections of the relay is by means of the Westinghouse Phase Meter. It is a portable instrument built on very much the same principle as a power factor meter but



NOTE—These connections require voltage transformers with 200 volt secondary, the star voltage on the relay in such case being 116-volts. If standard 110-volt secondary transformers are used, special 58-volt relays or extra 58-116-volt step up transformers are necessary.

Fig. 37—Proper Connections for Type CR Directional Over-Current Relay when used on Three-Phase System with Δ -Y Power Transformers between Line and Sub-station. Connections use only Two Voltage Transformers, and as shown give current 30° lead at 100 % P. F.

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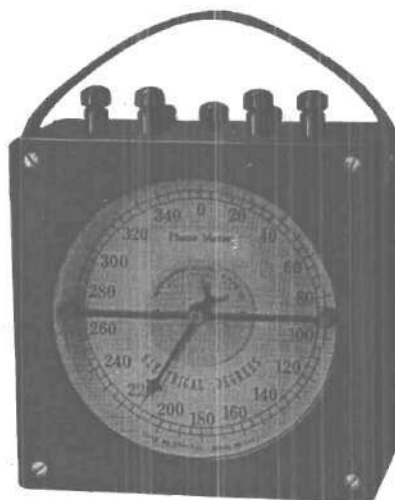


Fig. 38—Portable Phase Indicator for Use in Making Connections

calibrated to read in degrees and show precisely the phase relation between any current and voltage sources to which it may be connected. Full directions for the use of the portable phase meter are supplied with the instrument, which is shown in figure 38.

Characteristics—The operating characteristics of the over-current element are the same as those on the Type CO Relay. The same time current curves therefore apply as shown in figure 11.

With the contacts of the directional element and those of the overload element connected in series three conditions are necessary before the relay will completely close the tripping circuit.

- (1) Excess current must be flowing;
- (2) In the direction for which the relay is connected to operate.
- (3) For a length of time sufficient to close the excess current element contacts.

The sensitivity of the directional element is such that it may close its contacts on momentary surges of current in the reverse direction, but unless the excess current is maintained a sufficient length to operate the over-current element the tripping circuit is not completed. Conversely, the contacts of the overload element may be closed by excess current flowing in the normal direction but the directional element contact will remain open.

Type CR Duo-Directional Relays—The Type CR Duo-Directional Relays as already

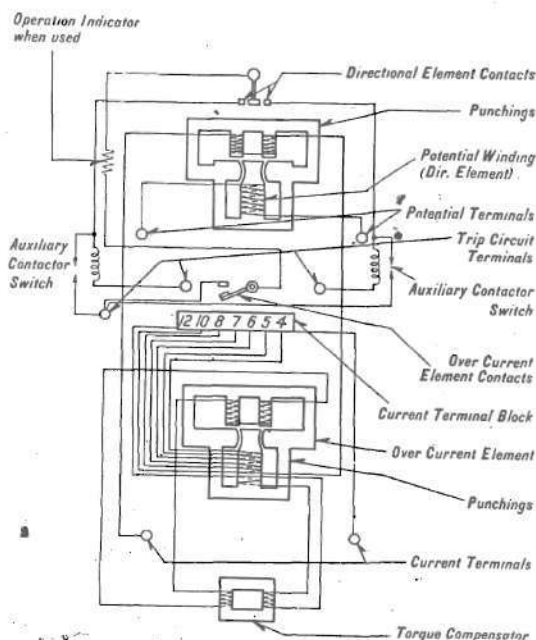


Fig. 39—Internal Wiring Diagram Type CR Duo-Directional Relay. (7 Terminals, 2 Contactor Switches)

mentioned under special applications are used in cross connected relay schemes where practically no current flows in the windings unless trouble exists. This relay is exactly the same as the standard single contact relay except that there is a stationary contact on each side of the moving contact, thus allowing the tripping circuit to be made in either direction. The contact arrangement, spiral spring, and all mountings are exactly the same as in the standard relay. Under ordinary conditions either contact may be closed by the floating of the disc in either direction, but under such conditions the over-current element contact will remain open. After any faulty condition, however, the flow of current will be such that torque will be produced in the directional disc to close the contact in the proper direction and thus have the tripping circuit completed as soon as the over-current element contacts are closed.

CURRENT AND TIME SETTINGS

Current Setting—These settings of the Type CR Directional Over-Current Relay are practically the same as those already described for the Type CO Over-Current Relay. The only possible current adjustment of the CR Relay is that of the over-current element which is obtained by changing the current screw in the contact block located above the element prop-

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er. Full directions for the proper setting of the over-current elements have been given. See pages 8 and 9.

Caution—Care should be taken whenever the current adjustment is being changed that the secondary circuit of the current transformer is not opened. When changing the current screw from one current tap hole to another the transformer secondary circuit may be closed either by shorting the current terminals on the rear of the relay, (the two lower current terminals) or by inserting the extra screw in the tap hole desired before removing the screw from the existing setting. One extra screw for this purpose is supplied in a hole in one of the bosses on which the mounting frame is fastened.

Time Setting—The time setting of the over-current element of the Type CR Relay is exactly the same as that already described for the Type CO. The directional element contacts are so arranged that they close almost instantly when there is a reversal in the flow of current so that all time adjustments for the complete operation of the relay are taken care of by the time adjustment of the overload element.

CARE AND MAINTENANCE

Initial Test—After the relays have been properly installed, they should be given an initial inspection and test to insure that the operation of the relay is going to be as desired. Inspect the moving parts of both the over-current and the directional element and also the plunger of the auxiliary contactor switch to see that no sticking or unnecessary friction exists. The discs of both elements should be turned through their complete travel and it should be noted that they run true, or, in other words, remain at all points in their travel approximately in the center of the air gap through which they pass. The discs are carefully adjusted at the factory so that they rotate exactly in the center of the air gap and such a condition is necessary for the proper operation of the relay.

The plunger of the auxiliary contactor switch should be moved up and down with the finger in order to insure it against sticking. It should be observed that the Type CR Duo-Directional Relay contains two auxiliary contactor switches, one being connected to shunt each of the directional element contacts and the over-current contacts.

Electrical Test—The initial electrical test of the relay varies somewhat with different operating companies. The operation of the directional element, however, should be checked out to insure that it closes the contacts when the current is flowing in the desired direction. This check, of course, can be made by observing the action of the directional element when there is power flowing in the line. For instance, if the directional element is connected to close its contact whenever the current is flowing away from the substation bus bars, then with the current flow towards the substation bus bars the directional element contacts should remain open. With the current flow in the opposite direction the contact should close immediately even upon a very small voltage. The over-current element may be tested as already described under testing in the Type CO Relay. See pages 10 and 11.

Routine Test—In installations of any importance, it is the common practice to subject all relays to periodic test. These tests are usually much the same as the initial test and it is recommended that each test be made to include all the features as described in the initial test. As noted under the testing of the Type CO Relay, it is also recommended that record cards be kept whereon all information gained at each test can be recorded and thus a life record of the relay kept readily accessible.

Inspections and Care—Inasmuch as the working part of all relays are inclosed in a practically dust-proof case, few inspections are necessary other than those which may be made at the time of the routine testing. As the operation of the ordinary protective relay is rather infrequent, and the construction is relatively rugged, little care is necessary after the initial installation is properly made.

ADJUSTMENTS

The following adjustments are those made in the factory when the relay is assembled and the same instructions should be followed out in case occasion arises where any adjustments of the mechanical features of the relay are necessary.

Over-Current Element—The over-current element of the Type CR Directional Over-Current Relay is tested and calibrated in the same way as the Type CO Over-Current Relay. All mechanical adjustment and current time settings are therefore the same for the Type CR

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over-current element as for the Type CO Over-Current Relay. See pages 8, 9 and 10.

DIRECTIONAL ELEMENT

Adjustment of Jewel Screws—The top jewel screws should be turned down far enough to reduce the play of the disc shaft to a minimum. These screws should not, however, be tightened so much that friction is introduced. With some care the jewel screw may easily be adjusted so that no appreciable end play can be detected by pushing up and down on the edge of the disc and at the same time no friction will be present. The lock nut on the jewel screw should be well tightened after any adjustment has been made.

The proper adjustment of the jewel screw is very important and great care should be taken to insure that the disc will vibrate the minimum amount on high current.

Spiral Spring Adjustment—The spiral spring should be so adjusted that the contacts are just barely held open with zero current and voltage.

Contact Adjustment—In the latest design of directional element contacts, the contact stop should be so adjusted that the moving contact arm is in a central position, and then

the fixed contacts should be adjusted so that there is a $\frac{1}{32}$ " gap between the contacts. For the duo-directional type relay, the spring should be so adjusted that the movable contact floats in the middle position and then the fixed contact should be adjusted to give approximately a $\frac{1}{8}$ " gap total.

Electrical Test—The directional element disc should not tend to creep in either direction when 30 amperes is passed through the winding with zero voltage on the potential coil, and the spring disconnected. If the disc creeps in either direction on current alone the position of the magnetic shunts situated above the disc on either side of the mainpole should be changed until the disc stops creeping. This adjustment is manipulated with a screw driver in the same manner as the light load adjuster on the Type OA Watthour Meter. Turning either one of the adjusters in toward the mainpole causes the movable contact to move in the direction that the adjuster is being turned.

With one volt impressed on the voltage coil of the directional element, and 40 amperes or less flowing in the series coil, the contact should close on a reversal of direction of the current flow, and remain open on the normal direction of current flow.

Type CRA Directional Over-Current Relay

The Type CRA Relay consists of the standard Type CR directional element with the Type COA over-current element instead of the standard Type CO over-current element. Its characteristics and operation are therefore exactly the same as the Type COA Relay. Its application is also the same as the standard Type CR Relay where it is desired to have supervision of the current flowing in the relay circuit without going to the extent of supplying separate ammeters for the circuit.

For the calibration of the current indicating elements see description under Type COA Relay. See pages 13 and 14.



Fig. 40—Type CRA Directional Over-Current Relay

Low-Energy Type CR Directional Over-Current Relay

APPLICATION

The Low-Energy Type CR Directional Over-Current Relay consists of the standard directional element and the low-energy Type CO over-current element mounted in the

same case. The relays are made in two standard ranges, each being suitable for a different application as follows:

The relay having a current range of 4 to 12 amperes is used for line sectionalizing to