RELAY PROTECTION
OF
HIGH VOLTAGE POWER SYSTEMS

RELAY PROTECTION OF HIGH-VOLTAGE ELECTRICAL POWER SYSTEMS

by

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FOREWORD

The Protection Engineer of a Power Company might be termed a peculiar type of individual. The engineers design the systems according to the accepted standards and methods of the day; their construction crews erect the individual sections with consummate skill; the whole is carefully inspected and tested. The report reads, "Everything perfectly satisfactory."

Along comes the Protection man. Without so much as a glance at any part of the proposed or prepared layout he calls for the drawings, and is heard to mutter: "Now, when the fault occurs here at this bus......" He does not say if - he says when. He has come with the preconceived notion that sooner or later every part of the system will fail, despite manufacturers' and foremen's declarations of utter confidence. He is, it appears, a confirmed pessimist.

Such an attitude, however, is not opposed to the best interests of his Company. From long experience he has learned that electrical systems cannot be trusted to be fault-proof. Not only has he to contend with faulty apparatus and the like, but there is also the troubling thought that due to abnormal circumstances, part or all of the system will experience unexpected shocks. Part of the latter, up to the economic limit, have been provided for by a factor of safety in the preliminary design; but it is obviously possible that this factor be exceeded.

Granted, then, that failures are liable to occur, it becomes exceedingly important that we do not permit the faults to secure the ascendancy and cripple the supply of power. That defines the duty of the Protection Engineer.

By means of detecting and dissecting devices, always on duty but active only when danger threatens, he makes himself master. As long as affairs go on normally, his assistants stand by. The moment this state of affairs alters, there is a buzz of activity. Those nearest to the scene of trouble size up the situation, and cut from the unaffected section of the system this "sick" part, preventing the spread of the malady. Sometimes even one of his workers may fall down on its job (often through no fault of its own) but its fellows behind it will carry on.

In effect, then, the Protection Engineer is concerned mainly with guarding from injury healthy parts of the system. His primary purpose is to maintain as much of the system in operation as is possible, due regard being paid to economy.

This paper will be divided into three parts. The first will deal with the method of Symmetrical Components, and its application to the calculation of short-circuit currents. Obviously, the engineer must know how to make such calculations.

The second part will deal with Synchronous Machine Reactances and their experimental determination.

The third part will describe the principles and practice of high-voltage system protection, with actual schemes in use as illustrations.

PART I

THE METHOD OF SYMMETRICAL COMPONENTS

Practically every account of the Method of Symmetrical Components that has come to my attention has had in the introductory paragraphs the following historical fact: The Method of Symmetrical Components was discovered by Mr. C. L. Fortescue and presented in a paper before the American Institute of Electrical Engineers at their conventinn in 1918.

Since its inception and presentation, it has found such widespread use that today it is regarded as having "become an indispensible tool for the study of unbalance of all kinds on polyphase systems" designed for the transmission and distribution of electrical energy.

Mr. Fortescue deserves considerable credit for his brilliant discovery. And yet it seems inevitable, at this date, that that method or another with the same ends in view, should have been developed. When some serious difficulty arises - an obstacle that when removed will open the way for greater expansion - the greatest minds set themselves to the task, and eventually a solution is offered. This process has occurred often enough in science and technology.

Such a condition appears to have faced Mr. Fortescue and his contemporaries. Power systems were becoming larger and larger. The demand for continuous service was increasing. And finally, it was common knowledge that from 95 to 99 per cent of the faults on the systems originated as "unbalanced" faults, degenerating eventually to the "balanced" or three phase fault, when protective principles came into operation.

Surely, Electrical engineers could not rest content with the realization that their method of calculation was applicable to such a minute percentage of the total. I say, therefore, that in the light of what had happened to former presumably unsolvable problems, it was inevitable that a method should be developed to yield solutions for "unbalanced" faults.

Faults on a three-phase system, as indicated above, are either "balanced" or "unbalanced". In the case of a three-phase short-circuit, the current and voltage conditions in all three phases are identical; the fault is balanced. Such balance, however, does not exist when the following faults occur: (a) single phase to ground; (b) single phase line to line; (c) two lines to ground. In these cases, the fault is unbalanced.

It is when dealing with these unbalanced faults, or with single-phase loads on a three-phase system, that the Method of Symmetrical Components stands out as the only practical method of dealing with the problem.

The Method of Symmetrical Components depends fundamentally on the fact that any three vectors can be resolved into three sets of balanced vectors. The problem of solving an unbalanced set of vectors thus disintegrates into one of solving three sets of balanced vectors. As a matter of fact, two of these sets consist of balanced three-phase vectors, the third being three vectors which are equal and in phase.

<u>THE OPERATOR "A"</u>

In working with complex quantities, the operator j (equal to $\sqrt{-1}$) is used to rotate through the positive direction a vector without, however, altering its length in any way. More generally, cos θ - j sin θ is an operator which rotates a vector through the angle θ in the positive direction. When $\theta = 90^\circ = \frac{\pi}{2}$, then $\cos\theta - j\sin\theta = j = \sqrt{-1}$.

In the same manner, the operator "a" is one which rotates a vector through 120° in the positive direction without altering its length.

$$a = \cos\frac{2\pi}{3} + j\sin\frac{2\pi}{3} = -0.5 + j\,0.866 \qquad (1)$$

a^2 rotates the vector through 240° in the positive direction without altering its length.

$$a^2 = \cos\frac{4\pi}{3} + j\sin\frac{4\pi}{3} = -0.5 - j\,0.866 \qquad (2)$$

a^3 rotates the vector through 360° without altering the length. Thus $a^3 = 1$, and a is one of the cube roots of unity. $a^4 = a$, and so on. Figure 1 shows the relation between the vectors I, aI, a^2I.

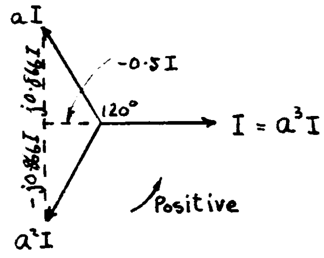


Fig 1.

Adding equations (1) and (2):

$$a + a^2 = -1$$

$$\text{i.e. } 1 + a + a^2 = 0 \qquad (3)$$

In order to proceed with the discussion of Symmetrical Components, consider a three-phase grounded neutral system. The actual currents in the phases a, b, c are respectively I_a, I_b, I_c.

These three currents are considered to be made up of three sets of currents, known formally as positive phase sequence currents, negative phase sequence currents, and zero phase sequence currents. Thus, using the subscripts (1), (2) and (3) for the values respectively, the positive phase sequence current in phase a is I_{a1}; the negative phase sequence current in phase a is I_{a2}, and so on.

The positive phase sequence components of current form a balanced set of three-phase currents, being equal in magnitude but 120° out of phase. The system is called positive because the currents reach their maximum in the order a, b, c. That is, I_{a1} leads I_{a2} by 120° and I_{a2} leads I_{a3} by 120°.

It is important to realize that these three vectors determine a complete unit, and must be treated as such.

Figure 2 shows the positive phase sequence currents.

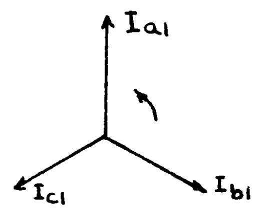


Fig 2

The relations between the three vectors are:

$$I_{a1} = aI_{b1} = a^2 I_{c1}$$
$$I_{b1} = aI_{c1} = a^2 I_{a1} \qquad (4)$$
$$I_{c1} = aI_{a1} = a^2 I_{b1}$$

from (4) and (3) :

$$I_{a1} + I_{b1} + I_{c1} = a^2 I_{c1} + aI_{c1} + I_{c1} = I_{c1}(a^2 + a + 1) = 0$$

Thus, the sum of all the vectors of the symmetrical polyphase system is zero. In other words, there is no positive phase sequence ground current. The conditions for currect flow must therefore be as pictured in Figure 3, where the arrows indicate positive direction of flow of current. Convention regards as positive the direction from source of supply to the fault.

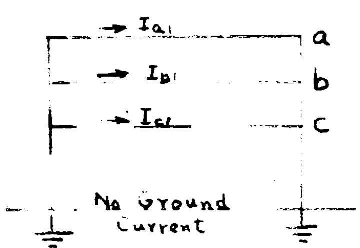


Fig. 3

NEGATIVE PHASE SEQUENCE COMPONENTS

In speaking of negative phase sequence components, the subscript (2) is used. The currents are then I_{a2} , I_{c2} , I_{b2}, and reach their maximum value in the order mentioned. The veetors still rotate in the positive or counter-clockwise direction, are separated 120° and are equal in magnitude.

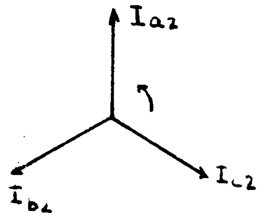


Fig. 4

They are pictured in Figure 4.

Obviously,

$$I_{a2} = aI_{c2} = a^2 I_{b2}$$
$$I_{b2} = aI_{a2} = a^2 I_{c2} \qquad (5)$$
$$I_{c2} = aI_{b2} = a^2 I_{a2}$$

From (5) and (3) :

$$I_{a2} + I_{b2} + I_{c2} = I_{a2} + aI_{a2} + a^2 I_{a2} = I_{a2}(1 + a + a^2) = 0$$

It follows that there is no resultant negative phase sequence ground current. The conditions are indicated in Figure 5, where the arrows indicate positive direction of flow of current.

ZERO PHASE SEQUENCE COMPONENTS

The third and final system of vectors is radically different from the two just discussed. This system consists of three equal vectors, all in phase with each other. The subscript (o) is used to refer to zero phase sequence components.

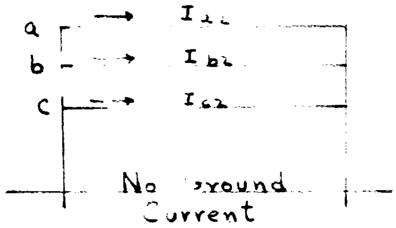


Fig 5

Symbolically, $I_{ao} = I_{bo} = I_{co}$ (6)

Figure 6 shows this system, while Figure 7 shows the currents.

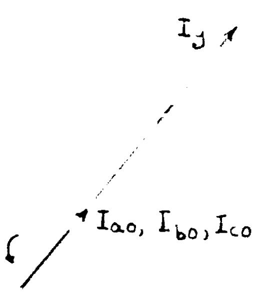


Fig 6

In the case of the positive and negative phase sequence currents, the current in any conductor returns by way of the other two conductors. Here, however, since the currents are all in phase, the only possible path of return is through the ground. The ground current is $I_g = I_{ao} + I_{bo} + I_{co} = 3I_{ao} = 3I_{bo} = 3I_{co}$ since the three phase currents are equal to each other.

The path of the zero phase sequence currents is from the grounded neutral of the generator, say, through the three-phase wires in parallel to the ground fault, and back through the ground to the original point. Only if the path is complete will zero phase sequence currents flow. For example, certain transformers pass these currents while others form an infinite barrier to their flow. A number of transformer connections may conveniently be discussed here. Before doing so, however, it is well to note that a neutral or ground wire along the transmission line may do away with actual ground currents, wholly or in part, depending upon the degree of isolation.

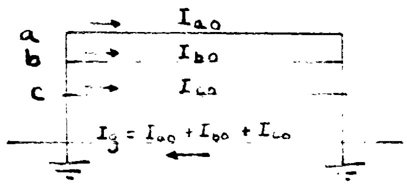


Fig 7

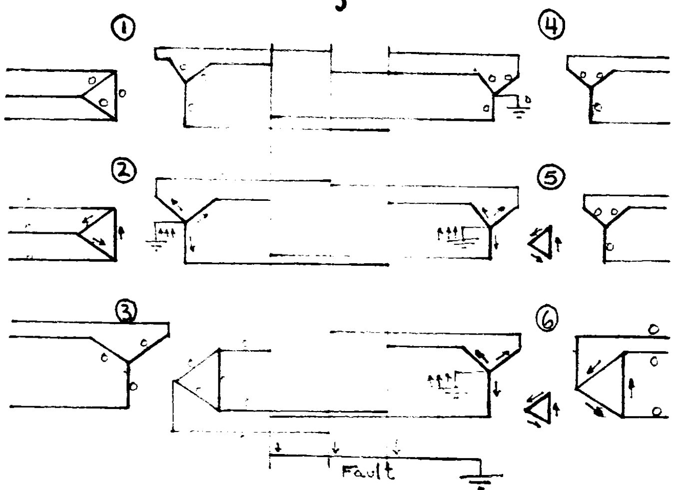


Fig. 8

Six different types of transformers are shown connected to a three-phase bus in Figure 8. Each arrow represents one unit of zero phase sequence current flowing in the positive direction. A zero beside a winding or conductor infers no zero phase sequence current in that particular section. (5) and (6) represent three-winding transformers, each having a delta-connected tertiary.

ZERO PHASE SEQUENCE CURRENTS IN TRANSFORMERS

The reasons for the flow or otherwise of zero phase sequence currents in each of the transformers will be discussed.

Transformers (1) and (3): Because there is no ground connection in the primary of either of these transformers, the path for the zero phase sequence currents is made incomplete. Hence no zero phase sequence currents can flow in the lines leading to these transformers. The connection used on the secondary side in no way influences the truth of this statement.

Transformer (2): The primary side of this Y-delta transformer is grounded, and with the fault on the Y side as shown, zero phase sequence currents flow from the fault through ground and through the transformer to the bus back to the fault. The three units of current in the primary neutral flow from the star point, one unit per winding. The corresponding compensating currents circulate in the delta, as shown. The secondary lines have no zero phase sequence currents, regardless of what is tied to them.

Transformer (4): This example presents an interesting point. Seeing the primary star of the transformer grounded, we might at first thought be led to believe that, as in the previous case, zero phase sequence currents could flow. However, when we come to consider compensating currents, we see that they cannot flow in the ungrounded star secondary. Elementary transformer theory emphasizes the need of neutralizing ampere-turns. Zero phase sequence currents, therefore, do not flow to or from this transformer.

Transformer (5): As far as external line currents are concerned, this transformer behaves exactly as does transformer (2) to the flow of zero phase sequence currents. The ungrounded Y does not permit these currents in that winding. The grounded primary does carry zero phase sequence currents, the compensating ampere turns being supplied by the circulating currents in the tertiary delta winding.

Transformer (6): Although behaving differently internally from transformer (5), this three-winding transformer also has zero phase sequence currents in the primary lines, but none in the secondary. In this case, compensating currents flow in both deltas; the result is that the reactance of the transformer as a whole is altered. The method of discovering the reactance will be dealt with in the paragraphs on the Phase Sequence Networks.

PHYSICAL CONCEPTION OF THE SYSTEMS

It is generally helpful when wrestling with new concepts to resort to actual physical models. This is very common practice in the science of Physics. A satisfactory picture of the significance of the various sequence systems may be had by considering the fields which result from the application of the three sequence currents to the windings of a three-phase machine. The set of three equal stator currents producing a flux wave rotating at synchronous speed with the rotor is positive phase sequence. That set producing a flux wave rotating at synchronous speed in a direction opposite to that of the rotor is negative phase sequence current.

Zero phase sequence current produces no net fundamental air-gap flux, due to their nature, and because they are applied to the windings which are inherently 120 electrical degrees apart.

And now, to present a model for the positive and negative phase sequence currents, consider a set of permanent magnets concentric with the rotor. They are arranged with north and south poles alternating, equal in number to the rotor poles. Rotating the magnets at synchronous speed with the rotor produces on the rotor the effect of positive phase sequence currents. Rotating the magnets at the same speed in the opposite direction produces on the rotor the effect of negative phase sequence currents. Finally, moving the magnets radially toward or away from the rotor, while they are rotating in the first-mentioned direction at synchronous speed, produces the effect of a change in magnitude of positive phase sequence current.

TOTAL CURRENT IN ANY PHASE

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

Thus, the total current in phase a is:

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

Similarly: $$I_b = I_{b0} + I_{b1} + I_{b2} \qquad (7)$$

and, $$I_c = I_{c0} + I_{c1} + I_{c2}$$

The directions for positive flow are shown in Figure 9.

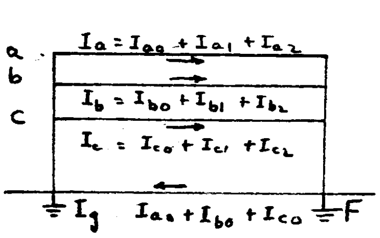


Fig. 9

It is possible to express the value of the current in any phase in terms of the sequence components of current in any other phase. Thus, suppose only I_{a0}, I_{a1}, and I_{a2} were known; I_b and I_c would be determined as follows.

$$I_b = I_{b0} + I_{b1} + I_{b2}$$
$$= I_{a0} + a^2 I_{a1} + aI_{a2} \quad -(8) \quad \text{[from (6),(4),(5), respectively.]}$$
$$I_c = I_{c0} + I_{c1} + I_{c2}$$
$$= I_{a0} + aI_{a1} + a^2 I_{a2} \quad - \quad - \quad (9)$$

The sequence components of phase "a" may now be determined from equations (7), (8), (9).

$$(7) + (8) + (9) = 3I_{a0} = I_a + I_b + I_c - I_{a1}(1+a+a^2) - I_{a2}(1+a+a^2) = I_a + I_b + I_c$$

$$\therefore I_{a0} = 1/3\ (I_a + I_b + I_c) \quad - \quad (10)$$

$$(= I_{b0} = I_{c0})$$

Thus the zero phase sequence current in any phase equals one-third of the sum of the currents in each phase.

$$(7): \quad I_{a1} = I_a - I_{a0} - I_{a2} \qquad (11)$$

$$(8): \quad a^2 I_{a1} = I_b - I_{a0} - aI_{a2} \qquad (12)$$

$$(9): \quad aI_{a1} = I_c - I_{a0} - a^2 I_{a2} \qquad (13)$$

$$(11) + a(12) + a^2(13): \quad I_{a1} + a^3 I_{a1} + a^3 I_{a1}$$

$$= I_a - I_{a0} - I_{a2} + aI_b - aI_{a0} - a^2 I_{a2} + a^2 I_c - a^2 I_{a0} - a^4 I_{a2}$$

But $a^3 = 1$ and $a^4 = a$, and $1 + a + a^2 = 0$

Thus $3I_{a1} = I_a + aI_b - a^2 I_c - I_{a0}(1 + a + a^2) - I_{a2}(1 + a^2 + a)$

$$I_{a1} = 1/3\ (I_a + aI_b + a^2 I_c) \qquad (14)$$

Similarly, $I_{a2} = 1/3\ (I_a + a^2 I_b + aI_c)$ (15)

Using appropriate equations, the components for the other phases are found in exactly the same way.

As already explained, the positive phase sequence and negative phase sequence currents flowing in any conductor of a three-phase system return through the other two conductors, because each component is part of a balanced system, from fundamental Symmetrical Component Theory. Regardless, therefore, of the actual type of short-circuit, whether single phase, three phase, etc., the positive phase and negative phase sequence components always behave as if there were a dead three-phase short circuit. But after applying the Method of Symmetrical Components to the calculation of fault conditions of current (and voltage), it will be found that the net result is that the different components combine to yield total currents which satisfy the conditions of the particular type of short-circuit under consideration.

For this reason, in subsequent short-circuit calculations a three-phase short-circuit will always be shown at the faulted point. Following convention, the actual short-circuit shall be shown by a solid line across the faulted conductors, while a dotted line shall join the others.

RESOLUTION OF VECTORS

The problem to be solved in this section is : given any three vectors (not necessarily equal or balanced), to find the various phase sequence components.

Assume that the three vectors shown in Figure 10 are given by

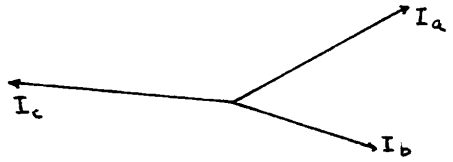


Fig. 10

$$I_a = 10 + j5$$
$$I_b = 6 - j3$$
$$I_c = -10 + j1$$

Now, the vector sum of the these three line currents gives the ground current. In a balanced system, the sum would naturally be zero. Here, however,

$$Ig = I_a + I_b + I_c \qquad (16)$$
$$= 6 + j3$$

From (10):
$$I_{ao} = 1/3\ (I_a + I_b + I_c) = 1/3\ Ig$$
$$= I_{bo} = I_{co} \quad \text{from (6)}$$
$$\therefore\ I_{ao} = I_{bo} = I_{co} = 2 + j1$$

From (14):
$$I_{a1} = 1/3(\ I_a + aI_b + a^2 I_c)$$
$$= 1/3\ \left[(10+j5)+(-0.5+j0.866)(6-j3)+(-0.5-j0.866)(-10+j1)\right]$$
$$= 1/3\ \left[(10+j5)+(-3+j1.5+j5.196+2.598)+(5-j0.5+j8.66+0.866)\right]$$
$$= 5.15 + j6.62$$

From (4):
$$I_{b1} = a^2 I_{a1}$$
$$= (-0.5-j0.866)(5.15+j6.62)$$
$$= 3.16-j7.77$$
$$I_{c1} = aI_{a1}$$
$$= (-0.5+j0.866)(5.15+j6.62)$$
$$= -8.310+j1.15$$

Thus far we have I_{a0}, I_{a1}, I_{b0}, I_{b1}, I_{c0}, I_{c1}. We require all the negative phase sequence components.

From (15): $I_{a2} = 1/3(I_a + a^2 I_b + aI_c)$

$$= 1/3\left[(10+j5)+(-0.5-j0.866)(6-J3)+(-0.5+j0.855)(-10+j1)\right]$$

$$= 1/3\left[(10+j5)+(-3-j5.196-2.598+j1.5)+(5-j8.66-0.866-j0.5)\right)$$

$$= 2.85 - j2.62$$

From (5): $I_{b2} = aI_{a2} = (-0.5+j0.866)(2.85-j2.62)$

$$= 0.84+j3.77$$

$I_{c2} = a^2 I_{a2} = (-0.5-j0.866)(2.845-j2.618)$

$$= -3.69-j1.15$$

SUMMARY OF RESULTS OBTAINED

Phase a	Phase b	Phase c
$I_{a0} = 2 + j1$	$I_{b0} = 2 + j1$	$I_{c0} = 2 + j1$
$I_{a1} = 5.15+j6.62$	$I_{b1} = 3.16-j7.77$	$I_{c1} = -8.31+j1.15$
$I_{a2} = 2.85-j2.62$	$I_{b2} = 0.84+j3.77$	$I_{c2} = -3.69-j1.15$
Totals: $I_a = 10 + j5$	$I_b = 6-j3$	$I_c = -10 + j1$

These values check with those given, and hence show the accuracy of the work.

In order to complete this section, the degree of simplification resulting from a balanced set of vectors will be indicated. The system is shown in Figure 11, and the following equations apply:

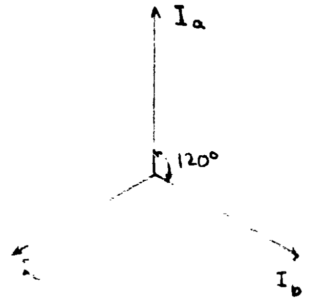


Fig 11

$$I_a = I_a$$

$$I_b = a^2 I_a$$

$$I_c = aI_a$$

Then $I_{a0} = 1/3(I_a + I_b + I_c) = 1/3(1+a^2+a)I_a = 0$

$$I_{a1} = 1/3(I_a + aI_b + a^2 I_c) = 1/3(I_a + a^3 I_a + a^3 I_a)$$

$$= 1/3(1 + 1 + 1)\ I_a = I_a$$

$$I_{a2} = 1/3(I_a + a^2 I_b + aI_c) = 1/3(I_a + a^4 I_a + a^2 I_a)$$

$$= 1/3(1+a+a^2)I_a = 0$$

We see, therefore, that the zero and negative phase sequence components in a balanced three-phase system disappear, leaving only the positive phase sequence component. This should occasion no surprise, for as indicated early in this thesis, previous to the discovery of the Method of Symmetrical Components engineers were equipped with knowledge sufficient only to deal with symmetrical loads or short-circuits. When the new method came into vogue, the old symmetrical quantities became known as positive phase sequence components, but they were old and known quantities re-named. The really new quantities were the negative and zero phase sequence components. If, then, we impose conditions identical with those with which engineers of the old school were familiar, it is obvious that we shall arrive at exactly the same results previously obtained, regardless of the method of procedure or finesse of technique. This is true, of course, only if both the new and old methods are equally accurate. Whether, in this particular case, we decide to name our results simply short-circuit current or positive phase sequence current is after all a matter of the times. The needle of a meter would have reached the same position on the scale in both cases.

This brings to light an interesting problem with which Mr. Fortescue was faced. In working out his more-or-less complex relations, he had to be sure that if symmetrical conditions were imposed at any point in his treatise, these relations would automatically collapse to a set identical with (in results, if not in name) those formerly extant, because these former relations had been definitely proven correct by experimental investigation.

The above theoretical treatment of the set of balanced vestors presents an excellent case in point.

UNBALANCED LOADS

Because of the frequent mention of the invaluable aid afforded by the Method of Symmetrical Components in the study of unbalanced faults, it might appear that the method was confined to the study of faults only. As a matter of fact, it has a wide application in the study of unbalanced loads, where it is found desirable to proceed with such studies. In the ordinary course of events such unbalance is considered to be negligibly small, and few Companies take cognizance of it, other than to realize that in adding new loads, care should be employed to maintain, as nearly as possible, balanced conditions.

THE PROPERTY OF THE INDEPENDENCE OF SEQUENCES

In this section one of the major properties of the Method of Symmetrical Components will be derived. This extremely important property is: in any section of balanced system, positive, negative and zero phase sequence components of current produce only positive, negative, and zero phase sequence voltage drops, respectively.

The section shown in Figure 12 is symmetrical with respect to the impedances: (1) of the phases, (2) between phases, (3) from the phases to neutral. Currents, voltages, and impedances are named

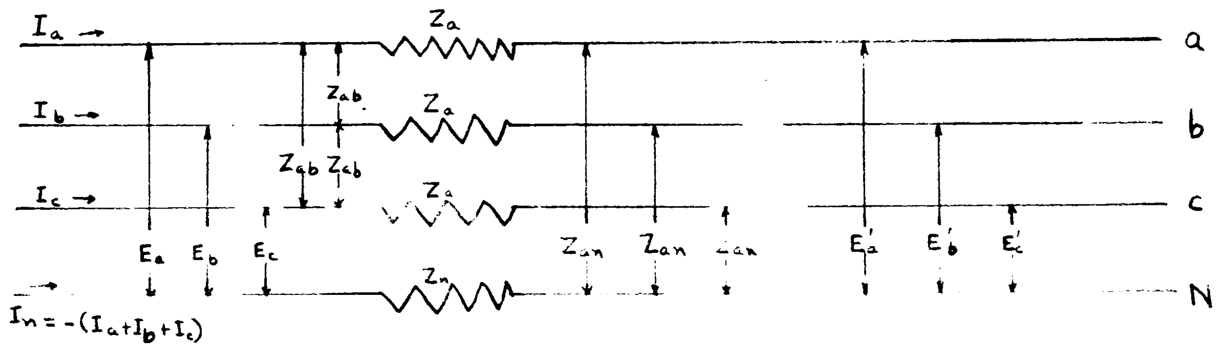


Fig 12

as indicated on the diagram.

The procedure is to determine E_a, E_b, E_c in terms of impedance drops and E'_a, E'_b, E'_c; and then discover the positive, negative and zero phase sequence components of these voltages. Since this latter process has already been carried through for current vectors, it will be worked here symbolically.

$$E_a = E'_a + I_a Z_a + (I_b + I_c)Z_{ab} + I_n Z_{an} - I_n Z_n - (I_a + I_b + I_c)\,Z_{an}$$

$$= E'_a + I_a(Z_a + Z_n - 2Z_{an}) + (I_b + I_c)(Z_{ab} + Z_n - 2Z_{an})$$

Similarly, $E_b = E'_b + I_b\,(Z_a + Z_n - 2Z_{an}) + (I_a + I_c)(Z_{ab} + Z_n - 2Z_{an})$

$$E_c = E'_c + I_c\,(Z_a + Z_n - 2Z_{an}) + (I_a + I_b)(Z_{ab} + Z_n - 2Z_{an})$$

$$E_{a1} = 1/3(E_a + aE_b + a^2 E_c)$$

$$= 1/3\left\{E'_a + aE'_b - a^2 E'_c + \left[I_a + aI_b + a^2 I_c\right]\left[Z_a + (a+a^2)Z_{ab} + (1+a+a^2)(Z_n - 2Z_{an})\right]\right\}^2$$

Simplifying, $E_{a1} = E'_{a1} + I_{a1}(Z_a - Z_{ab}) = E'_{a1} + I_{a1} Z_1$ (17)

Calling $Z_1 = Z_a - Z_{ab}$ = pos.seq.imp.

Similarly $E_{a2} = E'_{a2} + I_{a2} Z_2$ (18)

Calling $Z_2 = Z_a - Z_{ab}$ = neg.seq.imp.

$E_{a0} = E'_{a0} + I_{a0} Z_0$ (19)

Calling $Z_0 = Z_a + 3Z_n + 2Z_{ab} - 6Z_{an}$ = Zero seq.imp.

These equations, (17), (18), (19), prove the theorem, and yield themselves to further interpretation. They show in effect that the system given in Figure 12 may be replaced by three single phase systems, each entirely independent of the others. They are known as the positive phase sequence system, the negative phase sequence system, and the zero phase sequence system. The latter is shown in Figure 13. The impedance for both lines is included in

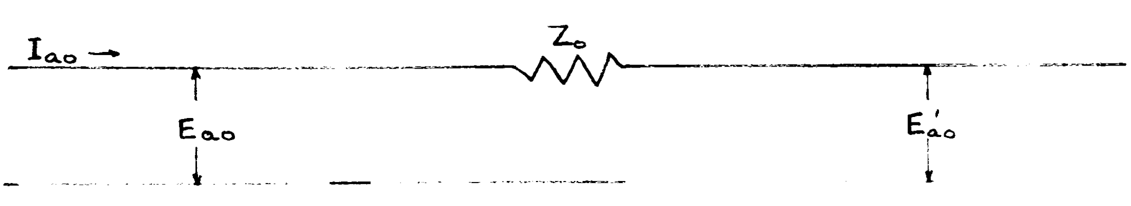


Fig 13

the term Z_0, so that the neutral contains no impedance. When we come to the study of unbalanced faults, we shall see that it is regular procedure first to draw a one line diagram of the system, and then to draw the three sequence diagrams. Working on these single phase systems will be found comparatively simple once they are set up.

It will be noticed that the theorem was proven assuming lumped self and mutual impedances. It may be shown by involved mathematics that the results are true for distributed constants, either inductance or capacitance.

Furthermore, only static apparatus is here considered, but even for symmetrical rotating machines there is no interaction.

<u>THE PHASE SEQUENCE NETWORKS</u>

1. Positive Phase Sequence Network. This network, being the ordinary system network, requires no discussion here. As indicated above, the only new feature about this network is its name. The impedances are the ordinary three-phase impedances, phase to neutral.

2. Negative Phase Sequence Network. Because the negative phase sequence components are balanced three-phase currents, this network is exactly the same as the positive phase sequence network. Furthermore, the negative phase sequence impedance of all stationary apparatus is equal to the positive phase sequence impedance. Unfortunately, this equality generally does not extend to rotating synchronous machinery. The designing engineer explains the cause for inequality, pointing out that there is mutual interaction between windings of different phases lying in the same slot.

As the result of a large number of tests on different machines producing more or less similar results, it has been found that the negative phase sequence transient reactance of a synchronous machine is about 73 per cent of its ordinary transient reactance, and this figure may be found in a great deal of calculations ~~and this figure may be found in a great deal of calculations~~ and literature on the subject. Many writers introduce this number into their calculations without even an explanatory sentence; it is one of the many accepted constants in Electrical Engineering.

3. Zero Phase Sequence Impedance Network. This is the only network involving ground or negative phase sequence currents, and is quite different from the other two, varying on the side of simplicity. Sections of the network in which ground currents cannot flow are omitted. The degree to which any particular system may be affected depends entirely upon its design, that is, upon the generator and transformer connections employed, and whether or not, in the case of star connections, the neutral is grounded. Both the paths and the nature of zero phase sequence currents have already been described. Briefly, the currents in each of the three phases are equal and are also in phase; the path (proceeding opposite to the conventionally positive direction) is from the fault to ground through the three phases in parallel into the ground at one or some or all of the grounded neutrals, and through the ground back to the fault. Because of the parallelism, it is necessary to assume all three phases grounded, since it is only thus that ground currents could get into the phases. Everything works out nicely, however, for in the final result the zero phase sequence current in the actually ungrounded phases are exactly neutralized by positive and negative phase sequence currents in those phases.

Transformer connections which act as closed or open doors to zero phase sequence currents have already been illustrated in Figure 8 and discussed. Figure 14 is a one-line diagram of Figure 8; the conductors containing zero phase sequence current are shown grounded, but where this current cannot flow the branch is left ungrounded at the end, indicating infinite impedance to zero phase sequence current. Figure 15 is copied from Figure 14, omitting

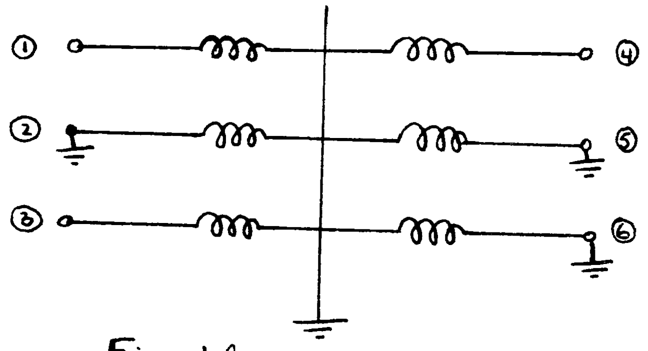


Fig. 14

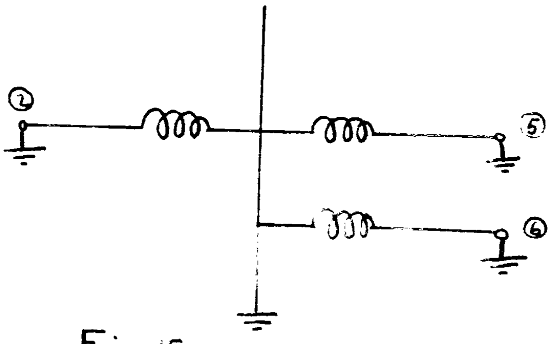


Fig. 15

the branches not carrying zero phase sequence currents.

In order to get some impression of the approximate value of zero phase sequence reactance of a generator, it will suffice to say merely that it is small, varying between 15 and 60 per cent of the direct subtransient reactance (defined later in this paper).

ZERO PHASE SEQUENCE RESISTANCE.

Thus far nothing has been said of resistance, because most frequently resistance is neglected in calculations. However, it is susceptible to the same treatment as reactance.

The zero phase sequence resistance of a conductor is its ordinary resistance. An apparent exception exists: if the conductor is in the neutral, then its zero phase sequence resistance becomes three times its ordinary value. In order to understand this, it is important to realize that resistances (and reactances) are expressed as ohms per phase. The voltage drop across each one is produced by the current per phase. When placed in the neutral, the current rises to three times, i.e., $3I_{ao}$, so the drop becomes $3I_{ao}R_n$, where R_n is the neutral resistance and this drop must be duplicated in the zero phase sequence network. Thus, in order to replace R_n by three equal resistances of combined value R_n, substitute for the R_n three $3R_n$'s in parallel, as in Figures 16 and 17. The same argument applies to neutral reactance.

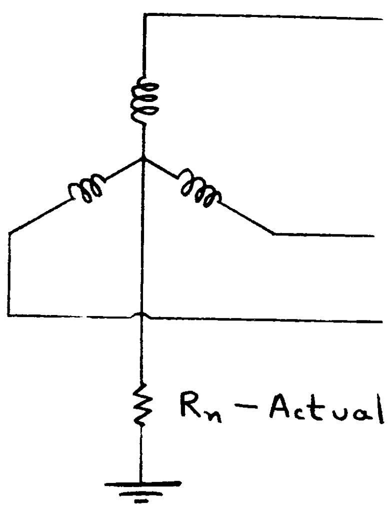


Fig 16

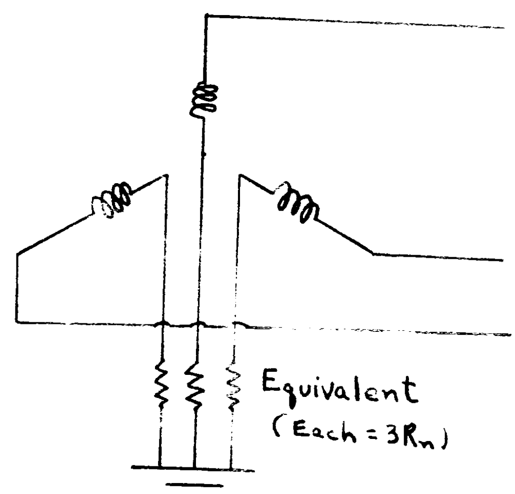


Fig 17

ZERO PHASE SEQUENCE REACTANCE OF A TRANSMISSION LINE

It is impossible in a paper of this nature to give more than a relatively cursory account of the difficulty of obtaining the constants to calculate the zero phase sequence reactance of a transmission line. This subject has occupied the close attention of many able American and European reaearch workers and investigators, and to this day is not a closed one by any means.

The difficulty arises from the fact that the return path of the zero phase sequence currents is through the ground, wholly or in part, depending upon the non-existence or presence of ground wires. Now the electrical properties of our earth are far from constant, varying from place to place and from time to time at any one place. The earth cannot be considered homogeneous, which fact complicates the problem of discovering the current distribution in the ground. Other important factors in this study may be ore beds, surface, or under-surface streams, railroad tracks, metal pipes, building foundations, sand beds, and the like.

The formulas developed by Carson of the Bell Telephone Company seem to be as popular as any. Carson makes two assumptions, namely that the earth is infinite in extent (which seems to be highly justifiable) and that the earth has uniform resistivity (which, as we are led to conclude from the last paragraph, is not strictly true). His theoretically derived results check experiment rather well in other than short lines.

In the ordinary case of three conductors, the zero phase sequence reactance is:

$$X_0 = 0.0140 \; f \log_{10} \frac{H}{R_0} \quad \text{ohms per mile per phase} \qquad (20)$$

as derived by R.D. Evans (Bibliography, No.8) where

F = frequency in cycles per second

H = distance below conductors at which the ground current is assumed to flow, i.e., the equivalent depth of the earth return.

R_0 = equivalent geometric mean radius of the conductor group (explained below)

Carson's investigations yielded the following relationship between the earth conductivity and the equivalent depth of the earth return:

$$H = \frac{6.843 \times 10^{-3}}{\sqrt{\lambda f}} \qquad (21)$$

Where λ = earth conductivity in abmhos per c.c.

We get, upon substitution,

$$X_o = 0.0140f \log_{10} \frac{6.843 \times 10^{-3}}{R_o \sqrt{\lambda f}} \qquad (22)$$

R_o is calculated from the configuration of the conductors, and is a constant for any particular job. f also is fixed. λ is obtained by experiment.

It should be noticed that although there may be some considerable error in the found value of λ, the value of X_o may not be out very much, because the value of λ is subjected to two error-reducing processes, namely square root and then logarithm.

An approximate notion of the value of λ, and how it varies with location may be had from the tests in United States and Canada made by E. B. King. The values obtained as the result of over 30 tests varied between 200×10^{-14} to 0.1×10^{-14} abmhos per c.c. The results showed, however, that 75 per cent of the values of λ are in the range from 100×10^{-14} to 10×10^{-14} abmhos per c.c.

EQUIVALENT MEAN RADIUS (R_o)

The equivalent mean radius of a transmission line is the radius of a single conductor which could replace the line so far as its reactance with ground is concerned, with the further assumption that no flux exists within this new conductor.

The equivalent mean radius of a single solid non-magnetic round conductor is shown in texts on Transmission Lines to be $0.779r$, where r is its actual radius.

The equivalent mean radius of a group of 3 conductors of radius r and spacings A,B,C between the different conductors is

$$R_o = \sqrt[3]{0.779\, r \times (ABC)^{2/3}} \qquad (23)$$

The equivalent spacing of a transmission line is

$$S = \sqrt[3]{ABC} \qquad (24)$$

Therefore, $R_o = \sqrt[3]{0.779\, r S^2}$ (25)

The equivalent mean radius of two 3-phase lines is conveniently treated as two groups in parallel, thus:

$$R_{o2} = \sqrt{R_o D} \qquad (26)$$

Where D = geometric mean distance between the groups.

From actual tests, W. W. Lewis of the General Electric Company has proposed the following equation as being sufficiently accurate for all practical purposes:

$$x_o = 4x, \qquad (27)$$

x being the ordinary three-phase reactance, one conductor to neutral.

APPLICATION OF THE METHOD OF SYMMETRICAL COMPONENTS

The fundamentals of the method of symmetrical components have been presented. In order to complete the discussion, the method will be applied to the solution of problems of the type for which it is so eminently suited. These problems will, of course, consist mainly of the determination of required currents flowing in the branches of the system network as the result of variously located faults of all types.

NETWORK ANALYSIS

Before proceeding to a demonstzation of methods of calculating short-circuit currents, the methods of solving complicated networks will be shown. Such networks arise in the major problem.

All forms of analytical solution of networks are based on the solution of a set of simultaneous equations formed by the application of Kirchoff's laws. These laws are:

(1) The sum of the currents flowing toward or away from any junction is zero.

(2) The sum of the e.m.f.s acting in a closed circuit is equal to the sum of the voltage drops in the several parts of the circuit.

The solution of these equations becomes very long and tedious for complicated networks. For this reason, and also to facilitate checking, several methods are employed to reduce the quantity of labor.

The first step in the solution of any network is the construction of the simplest possible single line diagram, marking the circuit constants of every part. Next, determine the equivalent reactance or impedance of the network between the source of power and location of the short-circuit, performed either by the simplification of the network, or by the application of network theorems. Finally, calculate the total short-circuit current at the fault, and in the branches, if required.

The present discussion deals with the second step mentioned in the preceding paragraph, namely the determination of equivalent reactance or impedance by simplification of the network.

Six methods present themselves, involving:

(1) Series circuits
(2) Parallel "
(3) Symmetry
(4) Three-winding transformers
(5) Star-delta transformations
(6) Superposed solutions.

1. SERIES CIRCUITS - Series impedances of the same power factor, as in Figure 17, should be replaced by an equivalent impedance equal to the sum of the individual impedances.

Fig 17

$$Z = Z_1 + Z_2 + Z_3 + \cdots \qquad (28)$$

2. PARALLEL CIRCUITS - Parallel impedances of the same power factor should be replaced by an equivalent impedance Z where (Figure 18)

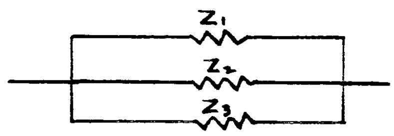


Fig 18

$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \cdots \qquad (29)$$

The current in each branch is inversely proportional to the ratio of the impedance of that branch to the total impedance, Z.

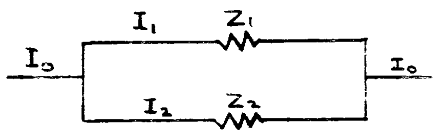


Fig. 19

If the power factors are not equal, there is a particular method of calculation which gives the division of current between the branches as a step in the determination of the equivalent impedance.

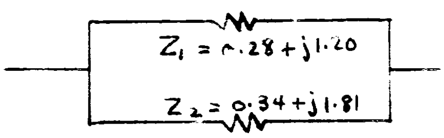


Fig 20

Consider the circuit in Figure 19. By Kirchoff's Laws:

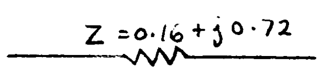


Fig 21

$$I_1 + I_2 = 0 \quad \text{and} \quad I_1 Z_1 - I_2 Z_2 = 0$$

$$\frac{I_1}{I_o} = \frac{Z_2}{Z_1 + Z_2} \quad \text{and} \quad \frac{I_2}{I_o} = \frac{Z_1}{Z_1 + Z_2}$$

The equivalent impedance is $Z = \dfrac{Z_1 Z_2}{Z_1 + Z_2} = \dfrac{I_1}{I_o} Z_1 = \dfrac{I_2}{I_o} Z_2$

As illustration, values of impedance are assumed in Figure 20.

$$Z_1 + Z_2 = 0.28 + j1.20 + 0.34 + j1.81 = 0.62 + j3.01 = a + jb$$

$$a^2 + b^2 = \overline{0.62}^2 + \overline{3.01}^2 = 9.44$$

$$\frac{1}{Z_1 + Z_2} = \frac{1}{a + jb} = \frac{a - jb}{(a+jb)(a-jb)} = \frac{a-jb}{a^2+b^2} = \frac{0.62 - j3.01}{9.44} = 0.66 - j0.319$$

$$\frac{I_1}{I_o} = \left(\frac{1}{Z_1 + Z_2}\right) Z_2 = (0.66 - j0.319)(0.34 + j1.81) = 0.599 + j0.010$$

$$\frac{I_2}{I_o} = \left(\frac{1}{Z_1 + Z_2}\right) Z_1 = (0.66 - j0.319)(0.28 + j1.20) = 0.401 - j0.010$$

$$Z = \frac{I_1}{I_o} Z_1 = (0.401 - j0.010)(0.28 + j1.20) = 0.155 + j0.723$$

Figure 21 thus becomes equivalent to Figure 20.

3. SYMMETRY - The network should be examined to determine if there are points at the same potential. If such points are found, any branch that exists between these points may be omitted since it carries no current, and the points connected directly together. In general, any branch may be omitted which carries no current or whose current is negligible because of very high impedance.

In a great many cases, these three methods suffice to yield the final equivalent impedance. The total current is then obtained, and working back step by step, the current division in the branches is obtained by straight ratio and proportion.

4. STAR-DELTA TRANSFORMATION - When the above methods have been applied and the system is still complicated, the next step is to replace certain groups of impedances by groups of equivalent impedances where this will aid further simplification of the network.

The external characteristics of the delta and star are identical for the fundamental frequency if (Fig.22):

$$A_1 = \frac{B_1 B_3}{B_1 + B_2 + B_3}$$

$$A_2 = \frac{B_1 \ B_2}{B_1 + B_2 + B_3} \qquad (30)$$

$$A_3 = \frac{B_2 \ B_3}{B_1 + B_2 + B_3}$$

$$B_1 = \frac{A_1 A_2 + A_1 A_3 + A_2 A_3}{A_3}$$

$$B_2 = \frac{A_1 A_2 + A_1 A_3 + A_2 A_3}{A_1} \qquad (31)$$

$$B_3 = \frac{A_1 A_2 + A_1 A_3 + A_2 A_3}{A_2}$$

The principles of the star-delta transformation are readily extended to cover the case of a star with any number of branches. Consider the case of the four-point star in Figure 23.

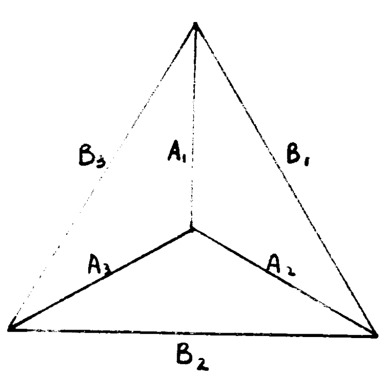
$$\text{Let } \Delta = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D}$$

Then $Z_{12} = \Delta \ AB$ $\qquad Z_{41} = \Delta \ DA$

$Z_{23} = \Delta \ BC$ $\qquad Z_{13} = \Delta \ AC$

$Z_{34} = \Delta \ CD$ $\qquad Z_{24} = \Delta \ BD$

22



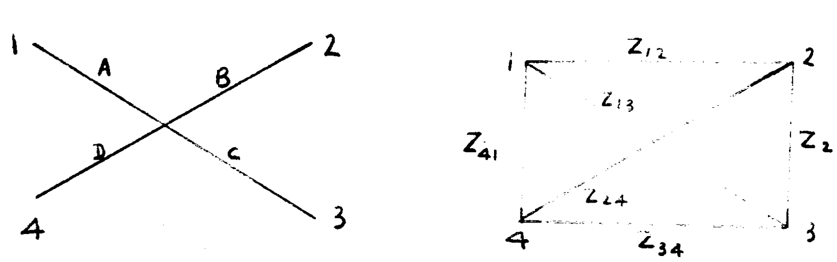


Fig 23

It might appear that this transformation results in an equivalent general network which is more complicated than the original because there are more branches. But it should be remembered that the junction point of the original star is eliminated. The network, of which the star was a portion, may lend itself to easy simplification by the new transformation.

5. THREE-WINDING TRANSFORMERS - A three-winding transformer is represented in a one-line diagram by an equivalent circuit: three star-connected impedances which do not involve inductive coupling.

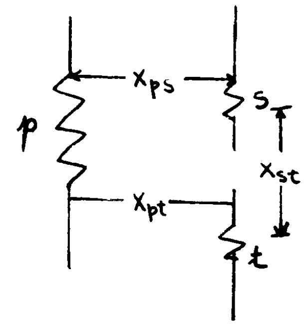


Fig. 24

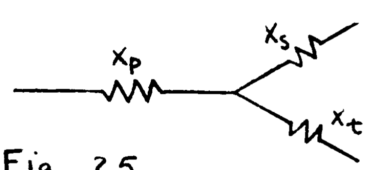


Fig 25

Fig. 24 represents a three winding transformer, and Fig. 25 is its equivalent circuit.

x_{ps} = reactance, primary to secondary

x_{pt} = " , " " tertiary

x_{st} = " , secondary " "

Now

$$x_p + x_s = x_{ps}$$
$$x_p + x_t = x_{pt} \qquad (32)$$
$$x_s + x_t = x_{st}$$

Combining,

$$x_p = \tfrac{1}{2}(x_{ps} + x_{pt} - x_{st})$$
$$x_s = \tfrac{1}{2}(x_{ps} + x_{st} - x_{pt}) \qquad (33)$$
$$x_t = \tfrac{1}{2}(x_{pt} + x_{st} - x_{ps})$$

The equivalent reactance of any one branch may be positive, negative, or zero.

6. SUPERPOSED SOLUTIONS - A further aid which may be employed to simplify the work is the superposed solution. This method is particularly applicable to linear networks with meshes in series, and also to problems requiring solutions of a large number of points. Any two solutions of the given network for different combinations of loads and sources may be superposed to yield a solution for a third combination of loads and sources.

THREE PHASE SHORT-CIRCUITS

Only positive phase sequence currents flow in this type of short-circuit. The network is the ordinary network, and the impedances are the ordinary three phase impedances, phase to neutral.

As an example of a three phase short-circuit calculation, the 220 KV. system of the Hydro Electric Power Commission will be considered. Short circuit KV-A's for various faults will be calculated. The system is shown in Figure 26 in condensed form, and is not to scale.

The following information is given (see also that on Fig.26):

All reactances are in per cent on a 10,000 KV-A base.(Neglect values given in red for the present calculations. They are inserted here for reference in the phase to phase short-circuit calculations).

GENERATOR AND TRANSFORMER REACTANCES, %

Station	Generator		Transformer
Paugan	9.5	7.1	1.86
Chats	12.34	9.3	2.13
Masson	10.2	7.6	1.8
Beauharnois	4.8	3.6	(6.27 L.V.to L.V. (2.85 " " H.V.
Leaside	Condensers *9.5	7.1	(1.50 220 KV (1.28 110 KV (1.01 13.2 KV (2.50 220 KV to 13.2 KV

*I find that this value is incorrect; it really should be 12.8%. This would change my final results by a slight amount, if at all.

Leaside Transformer reactance values are equivalent values. Reactance of Generators is transient in each case.

Transient L.V.Infeed at Leaside = 1,000,000 KV-A approx.

Reactance of lines:

Leaside - Paugan	-	1.65%
Leaside - Chats	-	1.44%
Paugan - Chats	-	0.21%
Paugan - Gatineau	-	6.73% complete

The following calculations are made for faults at Masson and Beauharnois (neglect red values):

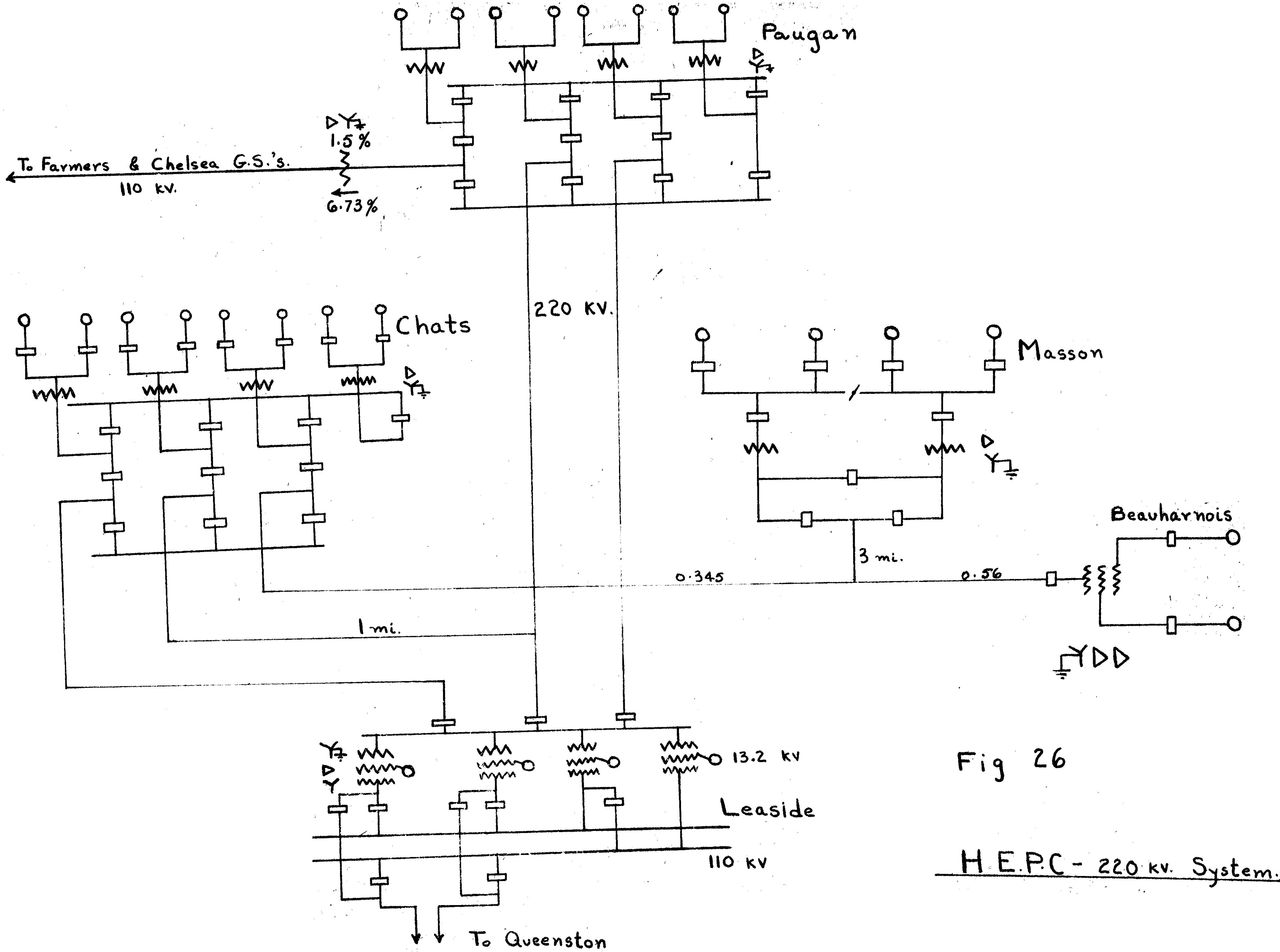


Fig 26

H.E.P.C - 220 kv. System.

[Follow p. 27]

Paugan:

Generator reactance = 9.5%   7.1

Transformer " = 1.86%

Combined reactance of 2 generators= 4.75%   3.55

Total for 2 generators and transformer = 4.75+1.86= 6.61%   5.41

Four such sets in parallel give reactance of station= 1.65%   1.35

Chats:

Reactance of 1 mile line is neglected.

Generator Reactance = 12.34%   9.3

Combined reactance of 2 machines in parallel = 6.17%   4.65

Transformer reactance = 2.13%

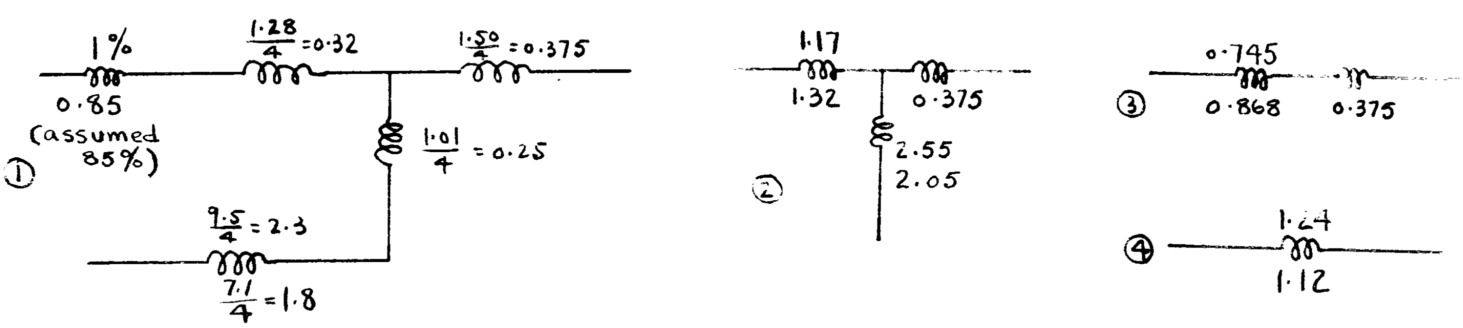
Total per unit of 2 generators and transformer= 8.30%   6.78

Four such sets in parallel give reactance of station= 2.07%   1.69

Leaside:

Since it is given that the transient L.V.infeed at Leaside = 1,000,000 KV-A, it may be considered that the reactance from the L.V.bus to Queenston,etc. = 1%

The following steps are adopted in order to arrive at the reactance value from the H.V.bus to Queenston,etc.= 1.24%



Beauharnois:

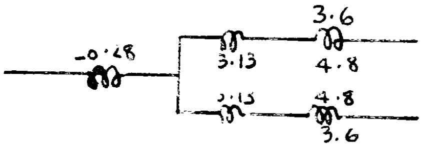
Generator reactance = 4.8%   3.6

$x_p + x_s = x_{ps} = 2.85$ $x_p = \frac{1}{2}(x_{ps} + x_{pt} - x_{st}) = -0.28$

$x_p + x_t = X_{pt} = 2.85$ $x_s = \frac{1}{2}(x_{ps} + x_{st} - x_{pt}) = 3.13$

$x_t + x_s = x_{st} = 6.27$ $x_t = \frac{1}{2}(x_{pt} + x_{st} - x_{ps}) = 3.13$

The equivalent star makes the station reactance diagram:



Equivalent reactance of station= $\frac{1}{2}(3.13 + 4.8) - 0.28 = 3.68\%$ 3.08

Masson: Reactance of 3 mile line is neglected.

Generator reactance = 10.2% 7.6

Reactance of two generators in parallel = 5.1% 3.8

Reactance per unit of two generators and transformer = 5.1+1.8= 6.9 5.6

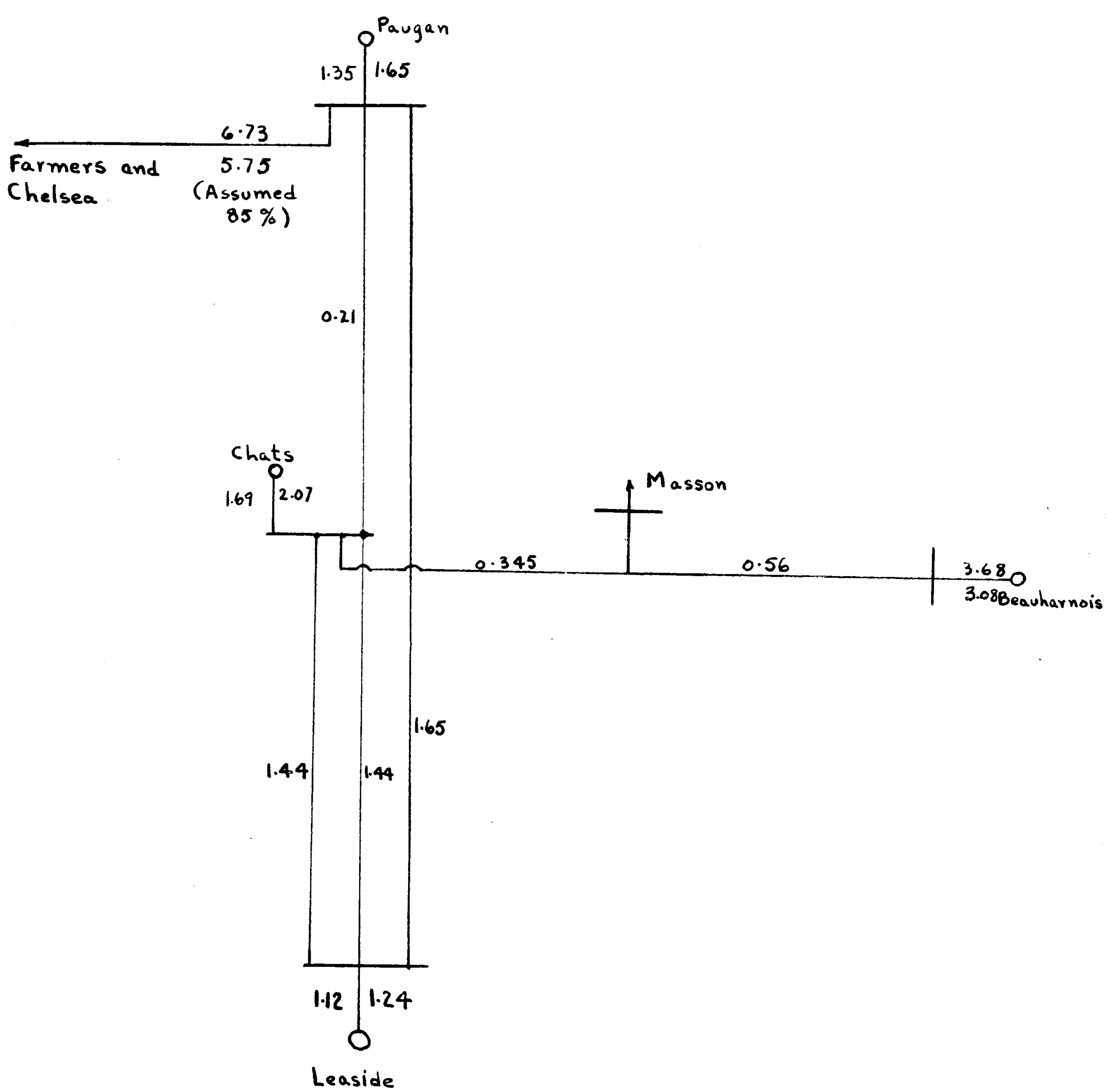
Reactance of two such units in parallel = 3.45% 2.8

Reactance of four generators in parallel = 2.55% 1.9

Reactance of two transformers in parallel = 0.9%

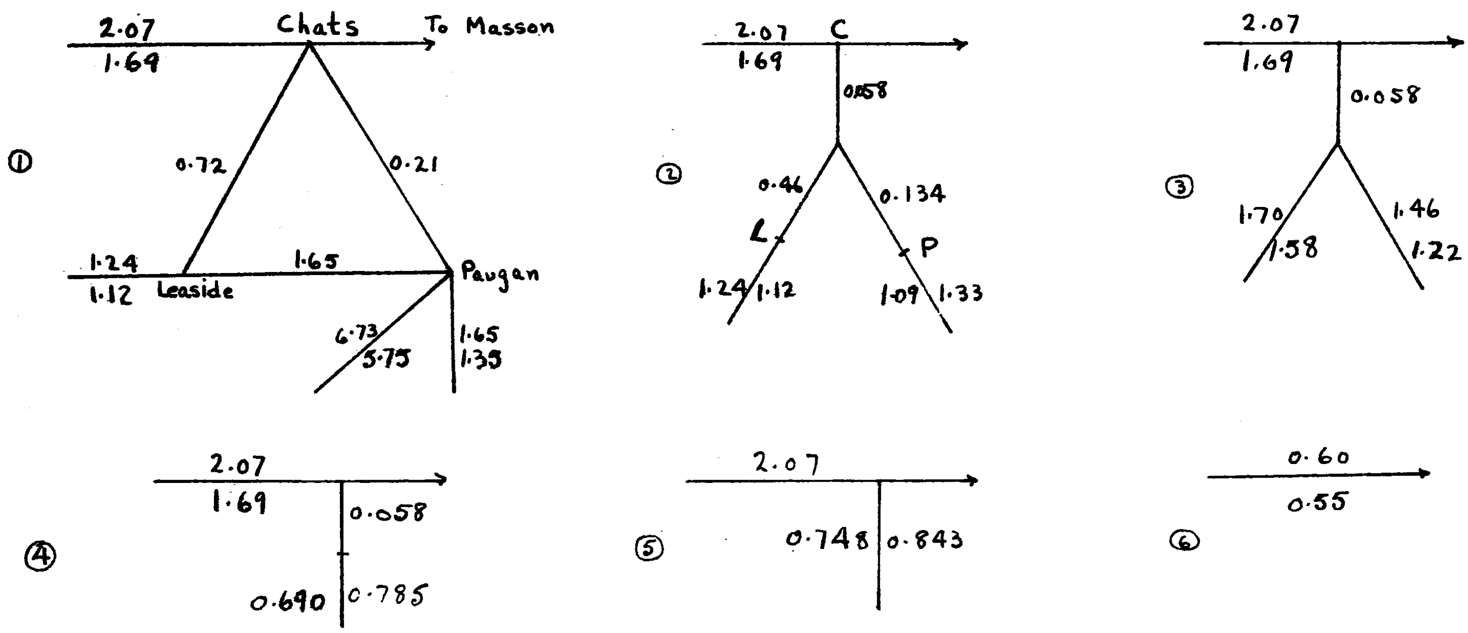
Total reactance of station this way again = 3.45% 2.8

REACTANCE DIAGRAM OF SYSTEM

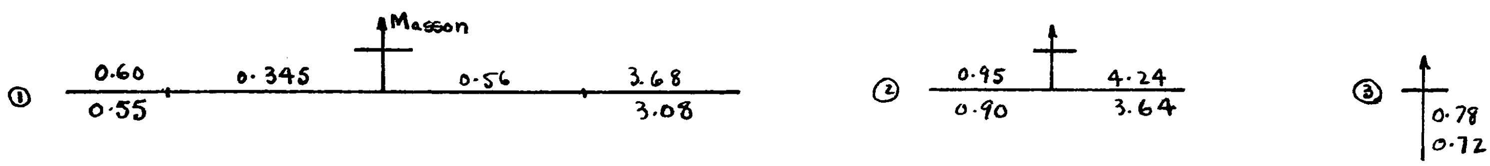


Calculation of Equivalent Reactance.

Chats, Leaside, and Paugan are in delta; reduction is as follows:

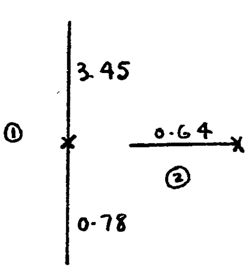


The system diagram now becomes:



That is, the equivalent reactance to the Masson H.V. bus = 0.78%. 0.72

A. Case of fault on the Masson H.V. bus.



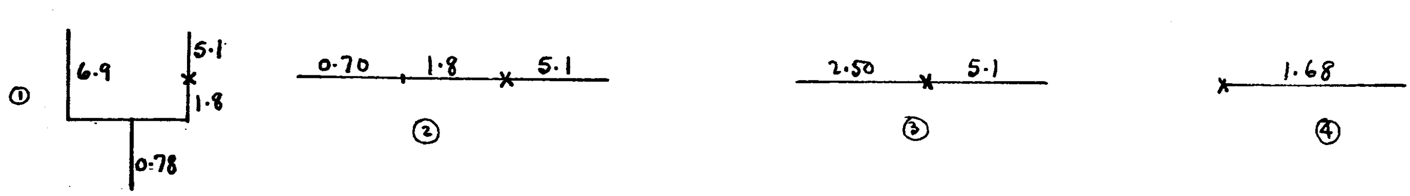
Reactance of station (L.V. tie switch open or closed) = 3.45%

Equivalent reactance to fault = $\frac{3.45 \times 0.78}{3.45 + 0.78} = 0.64\%$

Short-circuit KV-A = $\frac{100}{0.64} \times 10{,}000 = 1{,}560{,}000$

B. Case of fault on the Masson L.V. bus with tie switch open.

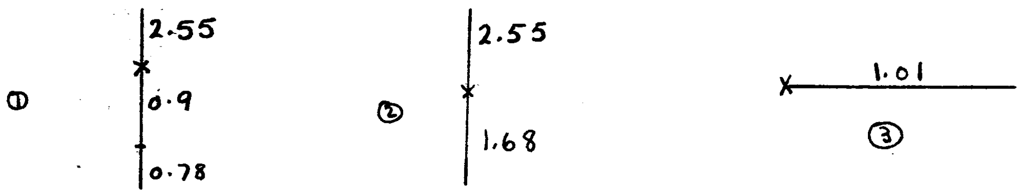
Reactance diagram and its simplification is shown.



Short-circuit KV-A = $\frac{100}{1.68} \times 10{,}000 = 5{,}95{,}000.$

C. Case of fault on the Masson L.V. bus with tie switch closed.

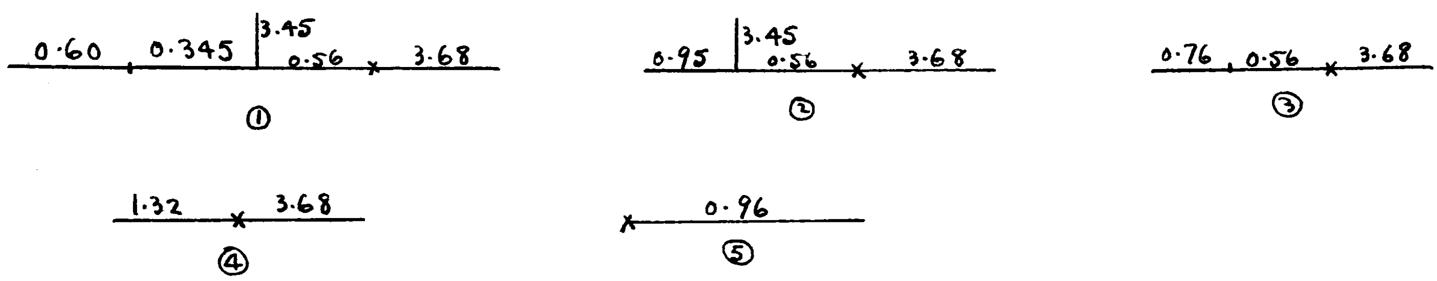
Reactance diagram and its simplification is shown.



Short-circuit KV-A = $\frac{100}{1.01}$ x 10,000 = 993,000

D. Case of fault on the Beauharnois H.V. bus.

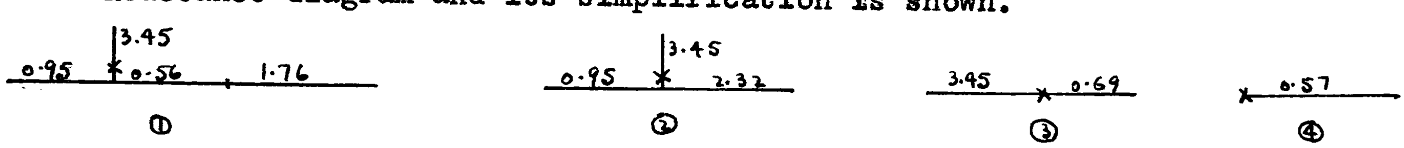
Reactance diagram and its simplification is shown.



Short-circuit KV-A = $\frac{100}{0.96}$ x 10,000 = 1,041,000

E. Case of fault on Masson H.V. bus, assuming four generators and two 3- winding transformers at Beauharnois.

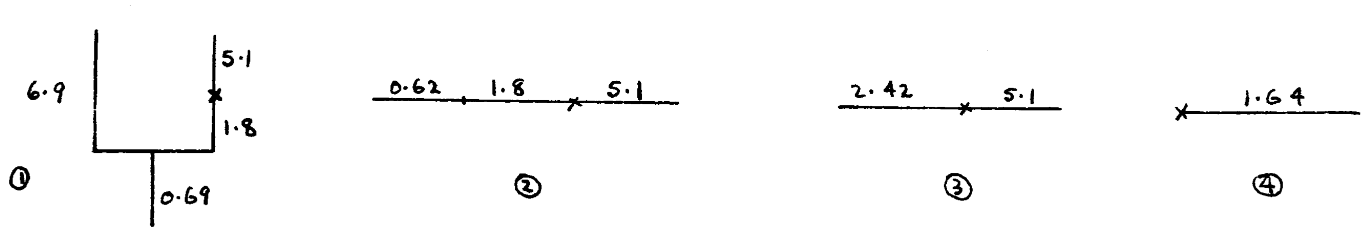
Reactance diagram and its simplification is shown.



Short-circuit KV-A = $\frac{100}{0.57}$ x 10,000 = 1,750,000

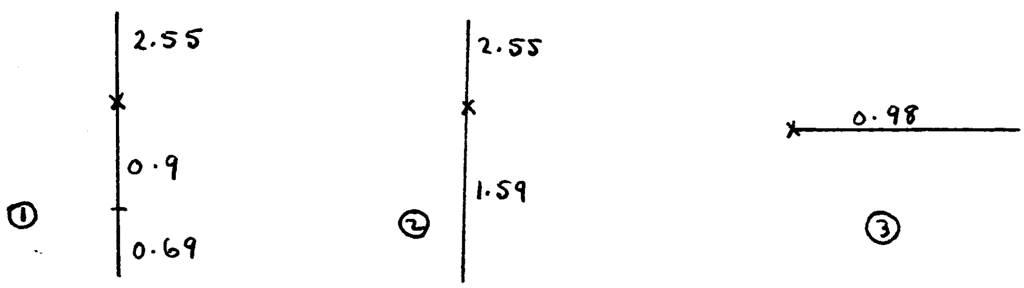
F. Case of fault on Masson L.V. bus with tie switch open, assuming four generators and two 3-winding transformers at Beauharnois.

Reactance diagrams shown.



Short-circuit KV-A = $\frac{100}{1.64}$ x 10,000 = 610,000

G. Case of fault on Masson L.V. bus with tie switch closed, assuming four generators and two 3-winding transformers at Beauharnois.



Short-circuit KV-A = $\frac{100}{0.98}$ x 10,000 = 1,020,000

H. Case of fault on H.V. bus at Beauharnois, assuming four generators and two 3-winding transformers at Beauharnois.

Reactance diagrams shown.

Short-circuit KV-A = $\frac{100}{0.75}$ x 10,000 = 1,327,000

SUMMARY:

Fault on Station	Bus	Masson L.V. Tie switch	Beauharnois station	Short-circuit KV-A	Case.
Masson	H.V.	———	2 gens.& 1 trans.	1,560,000	A
"	"	———	4 gens.& 2 trans.	1,750,000	E
"	L.V.	open	2 gens.& 1 trans.	595,000	B
"	"	"	4 gens.& 2 trans.	610,000	F
"	"	closed	2 gens.& 1 trans.	993,000	C
"	"	"	4 gens.& 2 trans.	1,020,000	G
Beauharnois	H.V.	———	2 gens.& 1 trans.	1,041,000	D
"	"	———	4 gens.& 2 trans.	1,327,000	H

PHASE TO PHASE SHORT-CIRCUITS:

Because the negative phase sequence components of current are identical in nature with the positive phase sequence components, the circuits involved in this type of short-circuit are exactly the same as in the case of the three-phase short-circuit.

The negative phase sequence impedance of all stationary apparatus, including lines, is equal to the positive phase sequence impedance. This equality does not extend further to the case of synchronous machinery.

The experimental procedure adopted to measure these negative phase sequence reactances is given in a subsequent chapter of this thesis. Tests show that, in general, the negative phase sequence reactance is about equal to the positive phase sequence sub-transient reactance. A summary of the results obtained by S.H. Wright in the A.I.E.E. Transactions for December 1931 indicates equality almost throughout. Good engineering practice, however, rules that calculations should always be made on the safe side; and inasmuch as theory shows that equality need not exist, it is better to assume that the negative phase sequence reactance of a generator is equal to 75 per cent of its positive phase sequence transient value. This value, or perhaps the value 73, appears very regularly in the literature dealing with short-circuit calculations, but because most of the articles on the subject are written with a strong injection of text-book or you-learn-from-me flavor, I hazard the guess that the real reason for the prevalence of that odd number 73 is as summed up in the Relay Handbook Supplement: "The value of 73 per cent has been used in this Supplement chiefly to point out that the values may be different, and to give solutions where they are different."

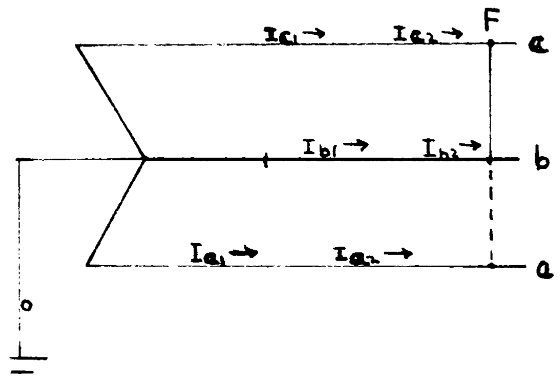


Fig 27

For two reasons I include phase to phase short-circuit calculations: first, because this chapter as a whole is in the nature of a demonstration; second, for the reason mentioned above, namely to keep on the safe side.

In the case of a line to line short-circuit, since the ground is not involved, $I_{ao}=I_{bo}=I_{co}=I_g=0$. Assuming the short-circuit to be between phases b and c, then

$$I_a = I_{a1}+I_{a2}+I_{ao} = 0.$$

But $I_{ao} = 0$. Then $I_{a1} = -I_{a2}$, which was obvious from Fig.27.

Mr. Bekku (see Bibliography) has developed a fundamental relation applicable to the present problem.

$$I_{b1} = \frac{100\ I_n}{Z_1+Z_2} \qquad \text{(34)}$$

where Z_1 and Z_2 are the positive and negative phase sequence impedances in per cent on the same KV-A base as I_n. In our case, we are neglecting resistance so that Z is replaced by X, and we are interested in short-circuit KV-A. The formula then becomes

$$\text{Short-circuit KV-A} = \frac{100\sqrt{3}}{X_1+X_2} \times \text{KV-A base chosen,} \qquad \text{(35)}$$

where the reactances are in per cent on the chosen KV-A base to the point of short-circuit. The $\sqrt{3}$ arises from the relation $I_b=\sqrt{3}\ I_{b1}$.

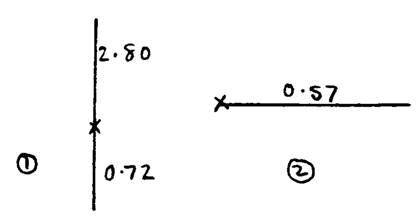
The values of X_2 for the generators on the H.E.P.C. system are shown in red in the table on page (27). X_2 is taken equal to 75 per cent of X_1, the values already given.

The calculations parallel those made for the three-phase short-circuits. The values are inserted in red, from page (23) to page (30), and yield the interesting (but not unexpected) result that the equivalent reactance to the Masson H.V. bus is now just six-hundredths of one per cent lower than the previous value; that is, the positive phase sequence reactance to the bus is 0.78%, and the negative is 0.72%. This is a decrease of about $7\frac{3}{4}$%.

We learn from this calculation, then, that if the system is somewhat extensive and interconnected, the positive and negative phase sequence reactance may be written equal with a degree of accuracy comparable to the accuracy with which the system constants are known.

Several cases of fault will be worked for comparison with the three-phase faults.

A. Case of fault on the Masson H.V. bus.



Reactance of station = 2.80%

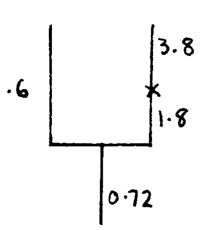
Equivalent reactance to fault = $\frac{2.80 \times 0.72}{2.80 + 0.72}$ = 0.57 %

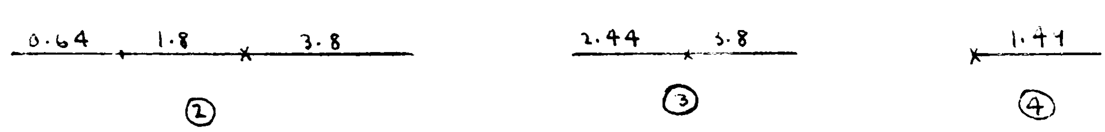
Short-circuit KV-A = $\frac{100\sqrt{3}}{0.57 + 0.64} \times 10000$ = 1,430,000,

applying formula (35) and the value of X_1 from page 30.

B. Case of fault on the Masson L.V. bus with tie switch open.

Reactance diagram and its simplification is shown.

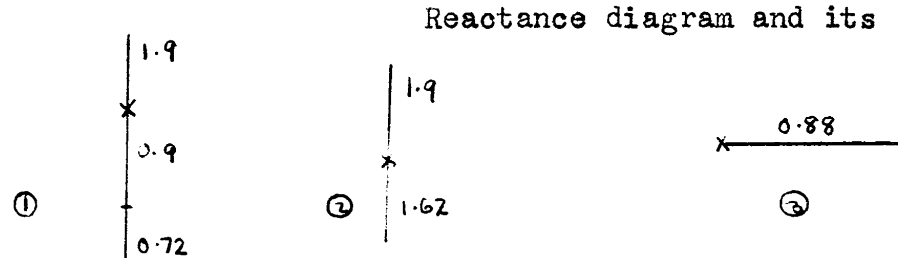




Short-circuit KV-A= $\frac{100\sqrt{3}}{1.49 + 1.68} \times 10,000$ = 546,000

C. Case of fault on Masson L.V. bus with tie switch closed.

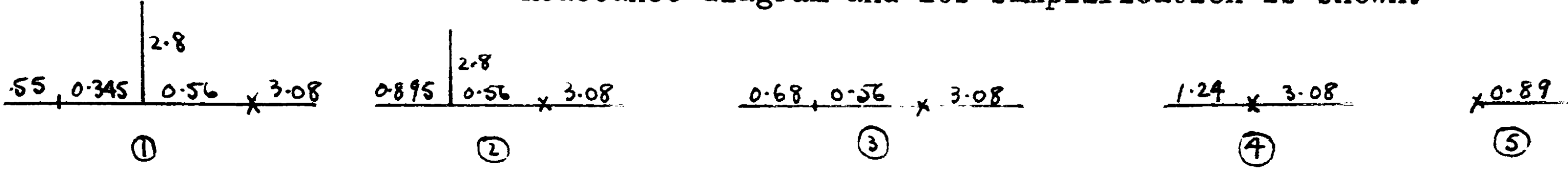
Reactance diagram and its simplification is shown.



Short-circuit KV-A = $\frac{100\sqrt{3}}{0.88 + 1.01} \times 10,000$ = 915,000

D. Case of fault on the Beauharnois H.V. bus.

Reactance diagram and its simplification is shown.



$$\text{Short-circuit KV-A} = \frac{100\sqrt{3}}{0.89 + 0.96} \times 10,000 = 936,000$$

COMPARISON SUMMARY.

Fault on Station	bus	Masson L.V. tie switch	Beauharnois station	Short-circuit KV-A 3-phase	2-phase	Case
Masson	H.V.	———	2 gens& 1 trans.	1,560,000	1,430,000	A
"	L.V.	open	"	595,000	546,000	B
"	"	closed	"	993,000	915,000	C
Beauharnois	H.V.	———	"	1,041,000	936,000	D

LINE-TO-GROUND SHORT-CIRCUIT.

In setting up the network for this type of problem, it is found to be quite different from the former two. The nature of the network depends entirely upon the transformer and generator connections, and whether they are grounded or not. This has already been discussed under the title Zero Phase Sequence Networks.

The difficulty of ascertaining the value for the zero phase sequence reactance of transmission lines has also been indicated. In the calculations to follow, equation (27), namely $X_o = 4X$, will be applied.

When there is a lack of definite knowledge, the value for the zero phase sequence reactance of synchronous machinery may be taken as 25 per cent of the positive phase sequence reactance. This value is probably quite close to the correct one. The generators at Masson are supposed to have the following reactance values on a 28,000 KV-A base (according to a report I saw):

$X_+ = 30\,\%$; $X_o = 8\,\%$

In this particular case, x_o is 26.7 per cent of x_ϕ.

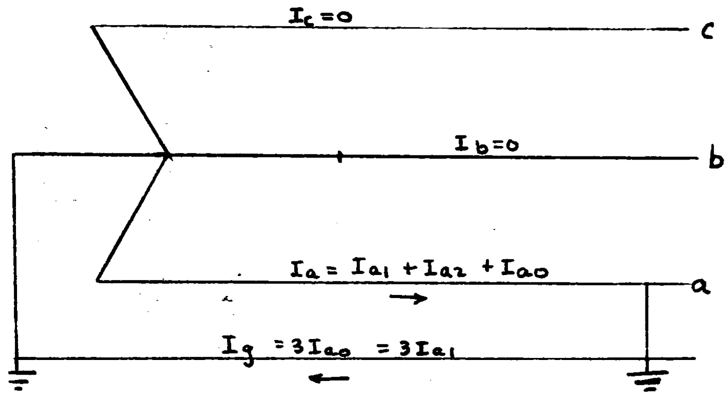


Fig 28

Fig. 28 shows the current flow in this type of fault.

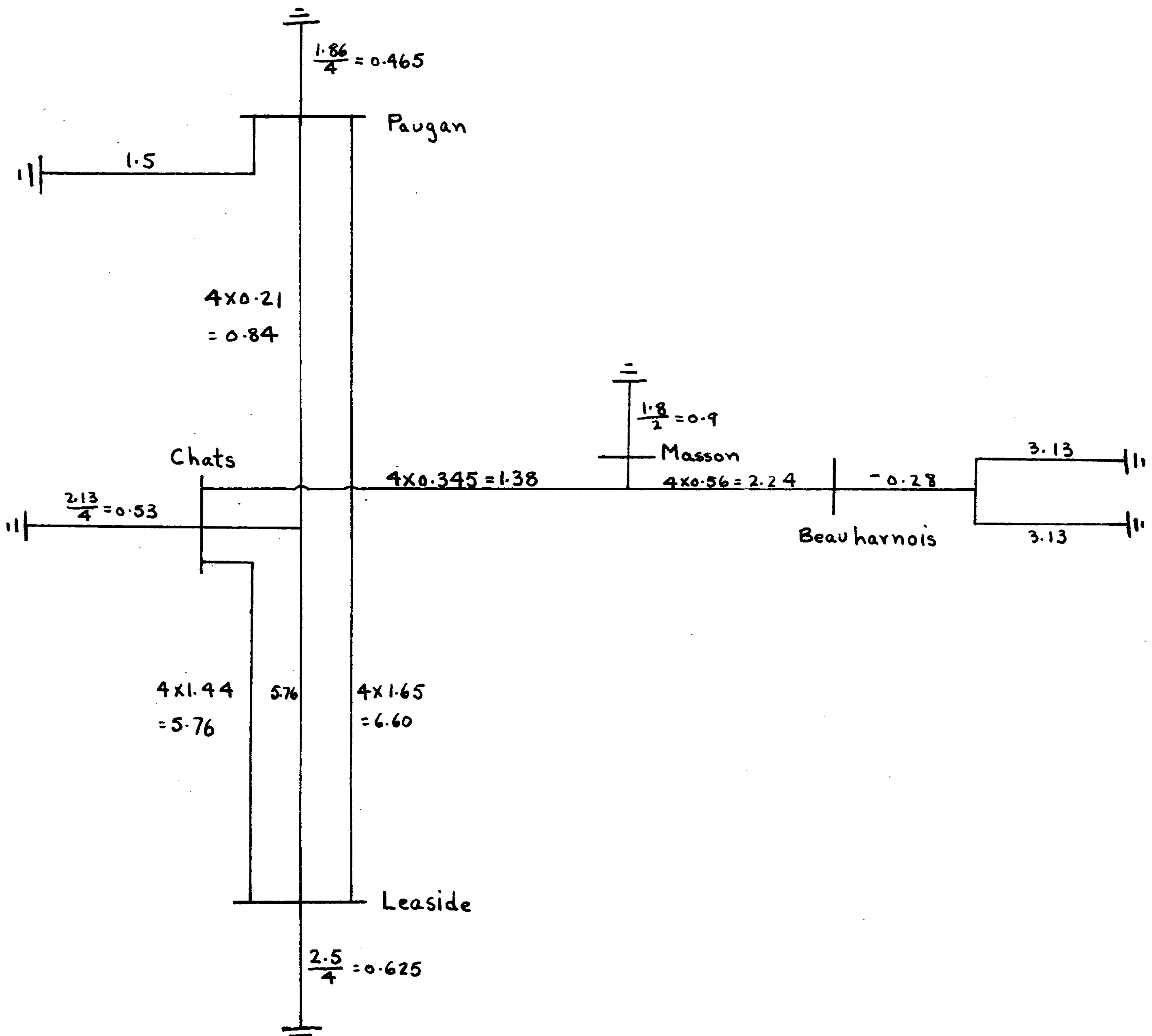
The formula for short-circuit KV-A is now:

$$\text{Short-circuit KV-A} = \left(\frac{3 \times 100}{x_\phi + x_2 + x_0}\right) \times \text{KV-A base chosen} \quad (36)$$

where the x's are in per cent on the chosen KV-A base. The 3 arises from the relation $I_a = I_g = 3\ I_{a1}$ (Fig.28).

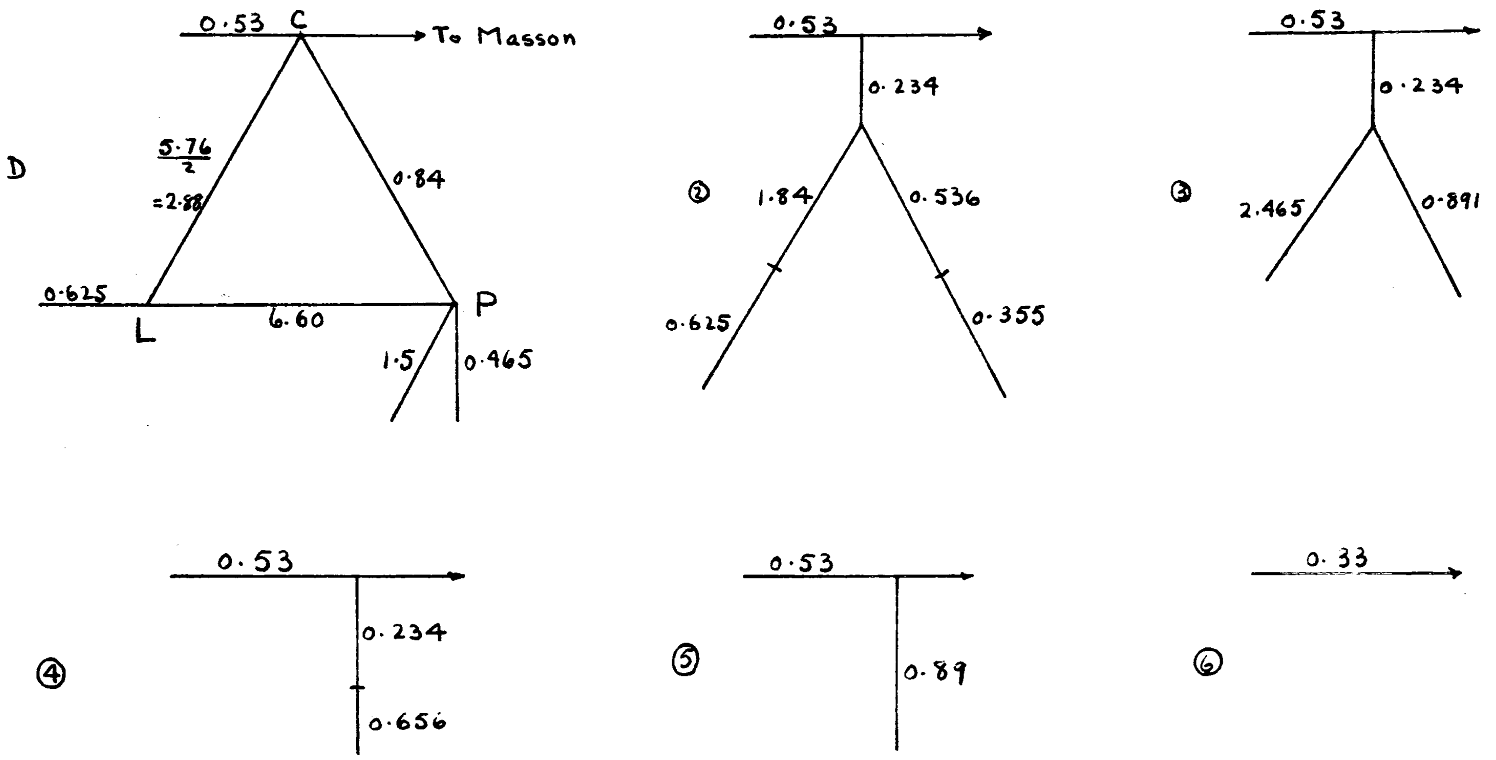
The solution of the KV-A resulting from a ground fault on the Masson H.V. bus will be attempted next.

ZERO PHASE SEQUENCE NETWORK.

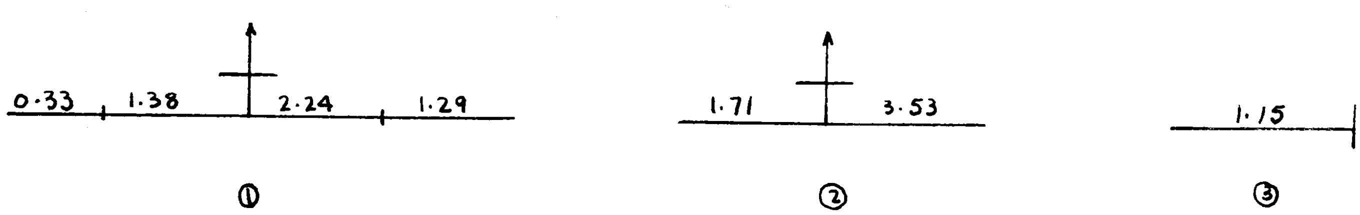


CALCULATION OF EQUIVALENT REACTANCE.

Chats, Leaside and Paugan are in delta; reduction is as follows :

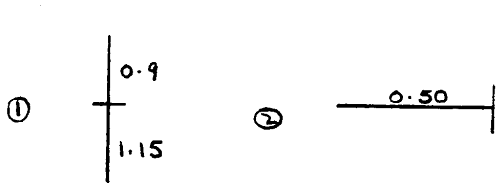


The system now becomes:



That is, the equivalent zero phase sequence reactance to the Masson H.V. bus = 1.15 %

Short-circuit KV-A resulting from a line-to-ground fault on the Masson H.V. bus



$$= \frac{3x100}{0.57 + 0.64 + 0.50} \times 10,000$$

$$= 1,755,000$$

TWO-LINE-TO-GROUND SHORT-CIRCUITS.

The Southern California Edison Company uses many of the latest and best methods of system protection on their 220 KV system, including the application of carrier currents, and yet they do not protect against phase-to-phase faults.

The records show that their system is well protected by using ground fault methods of detection. For this reason it is logical to feel that both line-to-line and two-line-to-ground faults will be exceedingly rare on this system, also operated at 220 KV. This follows from the evident fact that a two-line-to-ground short-circuit may be considered as a line-to-line short-circuit superimposed upon a line-to-ground short-circuit. Inasmuch, however, as phase-to phase fault calculations were made, results for this type of fault on the Masson H.V. bus will be obtained for the purpose of comparison.

If the short-circuit is between phases b and c and ground, then, according to the Relay Supplement,

$$Ia_1 = \frac{100\ I_n(x_2+x_o)}{x_1\ x_2+x_1\ x_o+x_2 x_o}$$

$$Ia_2 = \frac{-100\ I_n x_o}{x_1 x_2+x_1 x_o+x_2 x_o} \qquad \text{——— (37)}$$

$$Ia_o = \frac{-100\ I_n x_2}{x_1 x_2+x_1 x_o+x_2 x_o}$$

where x_1, x_2 and x_o are in per cent on the same KV-A base as I_n, and are respectively equal to 0.64, 0.57 and 0.50.

$$I_n = \frac{10,000}{\sqrt{3} \times 220} = 26.25 \text{ amperes.}$$

Applying formulas (37):

$$I_{a1} = \frac{100 \times 26.25\ (0.57+0.50)}{0.64 \times 0.57+0.64 \times 0.50+0.57 \times 0.50} = \frac{2625 \times 1.07}{0.97} = 2900 \text{ amps.}$$

$$I_{a2} = \frac{-100 \times 26.25 \times 0.50}{0.97} = -1355 \text{ amps.}$$

$$I_{ao} = \frac{-100 \times 26.25 \times 0.57}{0.97} = -1545 \text{ amps.}$$

The total currents are

$$I_a = I_{a1}+I_{a2}+I_{ao} = 2900-1355-1545 = 0$$

$$I_b = I_{ao}+a^2 I_{a1}+aI_{a2} = -1545+(-0.5-j0.866)2900-(-0.5+j0.866)1355$$

$$= -2318-j3695 \text{ amperes.}$$

$$I_c = I_{ao}+aI_{a1}+a^2 I_{a2} = -2318+j3695 \text{ amperes.}$$

$$I_g = I_b+I_c = -4636 \text{ amperes.}$$

We also know that $I_g = 3\ I_{ao} = 3 \times (-1545) = -4635$ amperes, which provides a numerical check.

Absolute value of current in either phase b or c is equal to

$$\sqrt{(2318)^2 + (3695)^2} = 4350 \text{ amperes.}$$

This is the maximum current to be interrupted by any phase of the three-phase circuit breaker, and on this basis, the

$$\text{Short-circuit KV-A} = 4350 \times \frac{220\sqrt{3}}{} = 1,660,000$$

RECAPITULATION.

The short-circuit KV-A from a fault on the Masson H.V. bus, assuming two generators at Beauharnois are as given hereunder, for types of fault indicated.

Type of fault	KV-A	Currents.
Three phase short-circuit	1,560,000	4100
Phase to Phase short-circuit	1,430,000	3750
One Phase to Ground short-circuit	1,755,000	4600
Two Phase to Ground short-circuit	1,660,000	4350

DISCUSSION.

It may be well to point out that in all the calculations the fault was regarded as a dead short-circuit, that is , it was assumed there was no impedance present at the point of fault. Also, resistance was neglected throughout. For these reasons, the results obtained are to be taken as maximum values. If the circuit-breakers are designed for these values of KV-A, then a reasonable factor of safety is automatically provided.

It is customary to rate a switch in KV-A. Thus if a three-phase switch is rated at 120,000 KV-A, it means that the switch will interrupt,without damage to itself, $\frac{120,000}{\sqrt{3} \times 220} = 314$ amperes per phase on a 220 KV system.

Since it is really the current that does the damage, it is expected that the current on any phase will not exceed 314 amperes. If unbalance occurs, so that the current in one phase increases to 500 amperes, while the currents in the other two phases decrease from 314 to a corresponding value, then even though the KV-A is just equal to that previously interrupted, nevertheless the switch is in grave danger of being destroyed. To interrupt 500 amperes, the rating should be $500 \times 220\sqrt{3} = 190,000$ KV-A. It is important to realize that it is just as difficult for a switch to rupture a current of 500 amperes on one phase only as 500 amperes on each of the three phases.

We see, then, that in order to rate a switch in KV-A, it is first necessary to determine the maximum current per phase that will be interrupted, and then convert to KV-A. In all of the above calculations, these maximum currents per phase were found in each case; but because there was no particular need for knowing these currents in all but the last case, they were not worked out: they were immediately converted to KV-A.

In this system, it appears that a single-line-to-ground fault produces the largest current in any conductor. The rating of the switch capable of interrupting this current works out to be 1,755,000 KV-A.

It is interesting to discover how little the values of circuit-breaker rating vary from each other. The largest value is only 23% greater than the smallest.

PART 2

SYNCHRONOUS MACHINE REACTANCES

At this time of writing there is no accepted standard set of definitions for synchronous machine reactances. Several committees have been appointed to prepare such a set, and have presented proposed definitions. It seems likely that in the near future the American Institute of Electrical Engineers will take action on these committee reports, with the probable result that a new American set of definitions will come into existence.

For a long period of time, the theory of synchronous machines recognized two reactances: transient and synchronous. Transient reactance was the reactance of the generator which was effective in limiting the current at the first instant of short-circuit before armature reaction had sufficient time to exert its influence. Synchronous reactance was the reactance which limited the current to its final steady value after the establishment of stable conditions.

In the last few years the theory has undergone a great deal of refinement. A major factor in this development was the application of the Method of Symmetrical Components to the theory of synchronous machines. The magnitude of the influence will become apparent when the names of the new reactances are studied.

MODERN MACHINE REACTANCES

As a result of the development in the theory, the two reactances named above have been replaced by eight well-known ones and dozens of others, less understood and probably less important. As far back as January 1928, the literature on electrical machinery had already mentioned thirty-one varieties of reactance; and a good many more have appeared since. Out of this chaos there will arise, it is to be hoped, a solid structure containing standard and recognizable quantities.

In the meantime, the eight more-or-less well known reactances will be discussed. These are tabulated below with their symbols:

ARMATURE REACTANCES

x_d : direct synchronous, positive phase sequence

x_q : quadrature synchronous, positive phase sequence

x'_d : direct transient, positive phase sequence

x'_q : quadrature transient, positive phase sequence

x''_d : direct subtransient, positive phase sequence

x''_q : quadrature subtransient, positive phase sequence

x_2 : negative phase sequence

x_0 : zero phase sequence

DIRECT AND QUADRATURE VALUES

The first thing to understand is the difference between the "direct" and "quadrature" values of the several positive phase sequence reactances. These terms are introduced to take into account the difference in effects of armature reaction directly over the poles and between the poles. The positive phase sequence current is resolved into two components. One magnetizes in the axis of the poles; the other in the inter-polar space. Thus, each positive phase sequence reactance may be obtained for each of two axes of magnetization - the direct and the quadrature axes.

The "direct" values of reactance occur when the axes of the poles line up with the axes of the resultant magnetic field produced by the three-phase currents in the armature. In this position, (Fig. 29), it is easily seen that the reluctance of the magnetic path through the armature and field structures is a minimum. It follows that the magnetizing current will be a minimum, and for this reason the reactance - the ratio $\frac{E}{I}$ - will

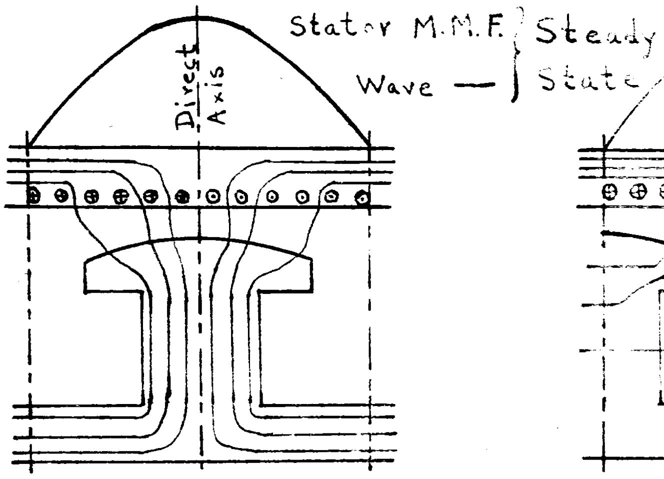


Fig 29

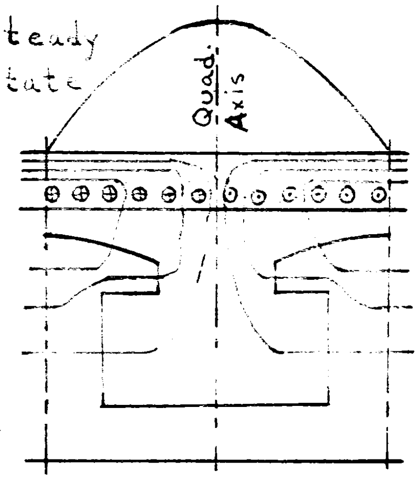


Fig. 30

be a maximum.

In Figure 30 the rotor has been advanced so that the pole axes are midway between the axes of the magnetic field produced by armature reaction. The conditions are now reversed. The reluctance is a maximum, the field current is a maximum, and the reactance becomes a minimum.

The three "quadrature positive" values of reactance are used where very accurate analyses are required, such as for example, in torque angle characteristics and stability calculations. They are not used in short-circuit calculations.

DIRECT AXIS SYNCHRONOUS REACTANCE

In August, 1932, the A.I.E.E. published a "Report on Proposed American Standard Definitions of Electrical Terms." The quoted definitions given below (in the appropriate places) are contained therein, and are given here for the purpose of clarifying, illustrating, and summarising the material preceding each.

"Direct-Axis Synchronous Reactance - The direct-axis synchronous reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental direct-axis component of armature current, to this component of current under steady state conditions and at rated frequency."

This corresponds to the old Synchronous Reactance.

The definition of Quadrature-axis Synchronous Reactance is not given. In fact, no quadrature components are defined in that report.

TRANSIENT CHARACTERISTICS

The old Transient Reactance has been replaced by four reactances as a result of the new and more comprehensive theory. They are x_d'' , x_d' , x_q'' and x_q' , where the two primes stand for subtransient.

Probably the easiest way to understand the difference between transient and subtransient is to study a short-circuit current oscillogram.

Figure 31 shows the particular case of a symmetrical wave. One

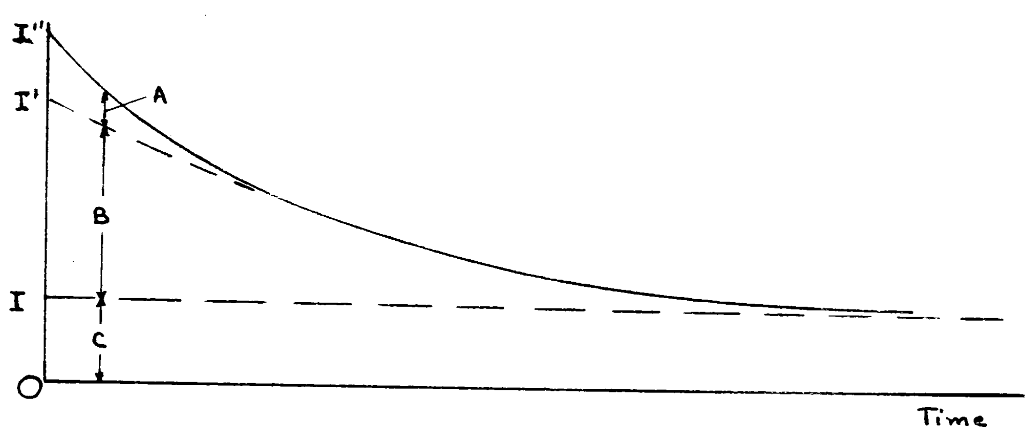


Fig 31

envelope only is shown. The subtransient, transient and sustained current values are marked I", I' and I respectively and serve to yield the corresponding reactances.

The value for I' is found by projecting back to the vertical axis the envelope of the curve, neglecting the first few cycles, as shown. Having done this, the fault current may now be considered as made up of three parts. The first is the rapidly-decaying component, marked A. the second is the more-slowly decaying componet, marked B. The third and final component of the short circuit current is the sustained value, marked C. Putting it into mathematical form, the current at any time "t" is

$$i = C + Be^{-\alpha t} + Ae^{-\beta t} \qquad (38)$$

where A, B, C, α, β are constants to be determined from the oscillogram, and e is the Naperian base of logarithms. This equation cannot be considered to be obvious, but experiments have shown that the components decay approximately exponentially.

If equation (38) is true, and A, B, and C are in per cent, then

$$x''_d = \frac{100}{A + B + C} \quad \text{and} \quad x'_d = \frac{100}{B + C}$$

This is not the usual method of determining these values.

Theory readily explains the cause of the difference between the transient and sub-transient values. If there were no good conducting material in the generator other than that in the armature and field windings, then there would be no difference in these two values. But this condition rarely exists. Most salient pole machines are now equipped with damper windings; and a turbine generator has a mass of iron in the rotor circuit. For the purpose of this discussion, these conductors are classed as "additional" rotor circuits.

Now let us see what happens when a short-circuit is suddenly thrown upon an unloaded machine. For a brief instant the flux-linkages in every rotor circuit remains constant. But the armature current has grown enormously, and its effect is to demagnetize these circuits. In order that the constancy of flux-linkages be maintained, the currents in these rotor circuits increase. This induced d.c. current is responsible for the initially greater short-circuit current as compared with the sustained value.

Now, if there are several rotor circuits, including additional ones, it is safe to expect that the induced d.c. currents in some will die away more rapidly than in others. As a matter of fact, this actually happens. The induced currents in the additional circuits die away very rapidly, in a few cycles, leaving the true transient current. Hence the reason for the method of projection of obtaining I' at the very instant of short-circuit.

If additional rotor circuits are present, then the really important value to know at the instant of short-circuit is the subtransient value, obtained by projecting the envelope of the first few cycles back to the current axis.

So we see that when a sudden short-circuit is thrown onto a generator, it is the subtransient reactance which determines the initial symmetrical current. In a few cycles (20 for turbo-generators, 6 for other machines) the subtransient reactance ~~dies down~~ increases to the transient reactance, and this in turn ~~dies down~~ increases, but much more slowly as a rule, to the final sustained value.

The rate of decay of the subtransient is a function of the damper resistance. The rate of decay of the transient is a function of the armature and field leakage inductance and the field resistance.

For machines equipped with damper windings, the value of the subtransient quadrature reactance is different from the corresponding synchronous value. But the transient is very likely to be equal to the synchronous. This follows from the fact that there is no really effective winding in the quadrature axis, even if a damper winding is placed in the poles. It is simply a physical fact. We should expect, then, that

$$x_q' = x_q \qquad (39)$$

ASYMMETRICAL WAVES

In actual practice, it is extremely unlikely that one will succeed in obtaining a symmetrical oscillogram, because it means short-circuiting the terminals at the instant of maximum voltage; they will almost always be asymmetrical, as shown in Figure 32.

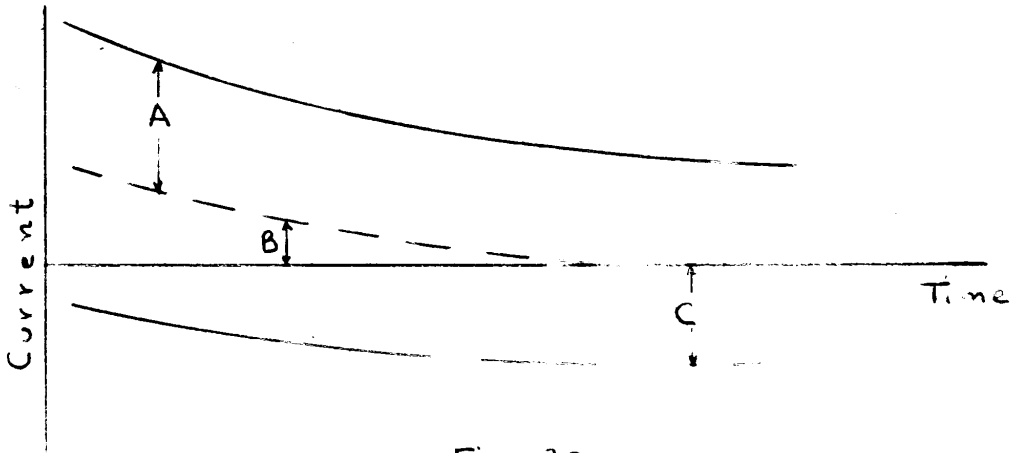


Fig 32

In such a case, the value of the short-circuit current is first considered to consist of two major components. In order to get them, the mid-point curve - shown dotted - is drawn. Then A is called the symmetrical a.c. component, and is dealt with as described above, while B is the asymmetrical or d.c. component. C is the sustained value. The current represented by B is actually d.c., except in the case of a machine without damper windings, in which case there will probably be a large second harmonic.

DIRECT-AXIS TRANSIENT REACTANCE DEFINED

"The direct-axis transient reactance is the ratio of the fundamental component of reactive armature voltage,due to the fundamental direct-axis component of symmetrical armature current, to this component of current under suddenly applied load conditions and at rated frequency, the value of current to be determined by the extrapolation of the envelope of the symmetrical current wave to the instant of the sudden application of the load, neglecting the high-decrement currents during the first few cycles."

This definition repeats in concise terms the matter already given. It is undoubtedly the best definition offered so far, and yet is certainly far from definite in meaning. Give the same oscillogram to five men and there will probably be five values of transient current revealed. They will probably be in close agreement, but the agreement will not be exact. This arises, of course, from the introduction of the human element into the problem of ascertaining the value. I speak from experience when I point out the difficulty. Any method that depends upon graphics is bound to be more or less inexact. The difficulty is aggravated in the case where the asymmetrical component is not far different from the symmetrical: in such a case it is a real problem to try to decide where the asymmetrical component reaches zero.

DIRECT-AXIS SUBTRANSIENT REACTANCE.

"The direct-axis subtransient reactance is the ratio of the fundamental component of reactive armature voltage, due to the initial value of the fundamental direct-axis component of symmetrical armature current, to this component of current under suddenly applied load conditions and at rated frequency."

The same trouble, to a considerably lesser extent, exists in this case, because again the envelope must be projected back to zero time. However, in this case there are two aiding features. First, the envelope extends very near to the current axis; second, the difficulty of deciding where the envelope ends is not present as in the previous case because it ends at the top of the first wave.

This concludes the discussion of the positive phase sequence reactances.

NEGATIVE PHASE SEQUENCE REACTANCE, x_2

If we were presented with a box having three electrical terminals, and were asked to determine its negative phase sequence reactance (on the assumption that the contents had negligible resistance), it is obvious that we would apply negative phase sequence voltage to the terminals, and measure the current and voltage per phase. Then the reactance of the box would be the ratio voltage to current.

It is the same story as obtaining the resistance of a conductor by causing a direct current to flow through it, and measuring the voltage drop from end to end of the conductor. The resistance is the ratio of the voltage drop to the current flowing.

We do not know what is in the box above. Let us assume it is a synchronous generator. Then when negative phase sequence voltage is applied to the terminals, the current in any phase contains negative phase sequence current of the fundamental frequency, but also contains a positive phase sequence third harmonic current. If the opposite process is undertaken, namely the "application" of a sinusoidal wave of current per phase, then the terminal voltage will have a third harmonic across each phase. Thus we see that one, and only one, of two conditions of "purety" may exist. Either the current or the voltage may be a pure sine wave. It can be shown that the value of the negative phase sequence reactance is different for each of these cases; in certain cases the ratio of one to the other has been as large as 5, though usually they are not far apart in value.

EFFECT OF TERMINAL CIRCUIT.

The question now arises: under what circumstances will the current be fundamental, and when will the voltage be fundamental? The answer is: the current will be maintained fundamental when the reactance of the terminal circuit is large. That is to say, such a condition will be approached when the external reactance is large. And the voltage will be maintained fundamental in the cases of double-line-to-neutral and line-to-line short circuits.

The above statements result from the following mathematical analysis.

When negative phase sequence voltage is applied to the generator, the fundamental value of current is approximately equal to $\frac{1}{2}\left(\frac{1}{x_d''}+\frac{1}{x_q''}\right)$

Thus $$x_2 = \frac{2x_d''\,x_q''}{x_d''+x_q''}$$

Suppose now that the voltage was applied to the machine through an external reactance x. The total reactance is

$$\frac{2(x_d''+x)\ (x_q''+x)}{x_d''+x + x_q''+x}$$

and $$x_2 = \frac{2(x_d''+x)\ (x_q''+x)}{x_d''+x_q''+2x} - x$$

$$= \frac{2x_d''x_q''+2x_d''x+2x_q''x+2x^2-x_d''x-x_q''x-2x^2}{x_d''+x_q''+2x}$$

$$= \frac{2x_d''x_q''+x(x_d''+x_q'')}{x_d''+x_q''+2x} \qquad \text{(40)}$$

If now x becomes very large, x_d'' and x_q'' and also $x_d''\,x_q''$ become relatively negligible in (40), so that

$$x_2 = \frac{x(x_d''+x_q'')}{2x} = \frac{1}{2}(x_d''+x_q'') \qquad \text{(41)}$$

This is the case of the fundamental current with a third harmonic across each phase.

For the case of a sustained single-phase line-to-line short-circuit—— or the equivalent case of a line-to-line fundamental voltage —— the fundamental component of current may be shown to be

$$\frac{\sqrt{3}\ e}{x_d+\sqrt{x_d''\ x_q''}}$$, where e is the voltage before the short occurred. But in Part 1 of this thesis, the current for this type of short-circuit was shown to be limited by the sum of the positive and negative phase sequence reactances (see (34)). Translating into symbols for this finer investigation, the current is

$$\frac{\sqrt{3}\ e}{x_d+x_2}.$$

Evidently $$x_2 = \sqrt{x''_d \, x''_q} \qquad \text{———————————— (42)}$$

This is the case for fundamental voltage and a third harmonic component of current.

If equation (42) is correct, then by adding an external reactance, x per phase, to the circuit and including it in this equation , we should again get equation (41).

Adding x in, the reactance of the complete circuit is

$$\sqrt{(x''_d + x)\ (x''_q + x)}$$

The effective reactance of the machine is then

$$x_2 = \sqrt{(x''_d + x)(x''_q + x)} - x$$

$$= \sqrt{x''_d x''_q + x(x''_d + x''_q) + x^2} - x$$

Now, the binomial theorem is

$$(y+h)^m = y^m + my^{m-1} h \ \frac{m(m-1)}{1 2} \ y^{m-2} h^2 + \ldots\ldots$$

Letting $y = x^2$, $h = x''_d x''_q + x(x''_d + x''_q)$, and $m = \frac{1}{2}$,

and substituting, we get

$$x_2 = x + \tfrac{1}{2}x^{-1}\left\{x''_d\, x''_q + x(x''_d + x''_q)\right\} + \frac{\frac{1}{2}(-\frac{1}{2})}{2}\, x^{-3}\left\{x''_d\, x''_q + x(x''_d + x''_q)\right\}^2 + \ldots\ldots - x$$

$$= x\left[1 + \frac{1}{2}\left\{\frac{x''_d\, x''_q}{x^2} + \frac{x''_d + x''_q}{x}\right\} - \frac{1}{8}\left\{\frac{x''_d\, x''_q}{x^2} + \frac{x''_d + x''_q}{x}\right\}^2 + \ldots\right] - x$$

Again consider x so large that x''_d and x''_q are relatively negligible. Then $x''_d\ x''_q$ and powers of x''_d and x''_q are also negligible.

$\therefore\ x_2 = x + \frac{1}{2}(x''_d + x''_q) - x$, dropping out negligible values

$= \frac{1}{2}(x''_d + x''_q)$, as before in (41).

The usual interpretation for negative phase sequence reactance is as given in equation (41), and thus indicates: (1) the existence of fundamental current rather than fundamental voltage; (2) the existence of external reactance. These two conditions are dependent — one infers the other. Item (2) is the real reason for this interpretation of negative phase sequence reactance, because almost always there is external reactance to the point of fault.

There should be no great feeling of discomfort from the thought that maybe the external reactance is so small that the geometric rather than the algebraic mean of x_d'' and x_q'' should be used, that is, equation (42) should have preference over (41). For even if x_d'' and x_q'' are quite different, the means may not differ appreciably.

In a salient pole machine without dampers, the two reactances differ considerably. Reasonable values are $x_d'' = 35\%$ and $x_q'' = 75\%$.

$$\frac{1}{2}\left(x_d'' + x_q'' \right) = \frac{1}{2}\left(35 + 75 \right) = 55\%$$

$$\sqrt{x_d'' \; x_q''} = \sqrt{35 \times 75} = 51\%$$

Even in this extreme case the two differ by only 4%. The conclusion, therefore, is that x_2 may quite safely be regarded as the algebraic mean of x_d'' and x_q'' .

NEGATIVE PHASE SEQUENCE REACTANCE DEFINED.

"The negative phase sequence reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental negative phase sequence component of armature current, to this component of armature current at rated frequency."

ZERO PHASE SEQUENCE REACTANCE, x_0 .

In any table of typical constants for a three-phase synchronous machine, the values given for the zero phase sequence reactance have such wide ranges of variation that rarely, if ever, is an average value offered as being close enough to apply to any machine of the designated type. A typical foot-note explaining this variation is: "x_0 varies so critically with armature winding pitch that an average value can hardly be given." Besides varying with pitch, it also depends somewhat on the breadth factor.

Zero phase sequence reactances are, in general, much smaller than the positive and negative values.

If the armature windings were perfectly (or infinitely) distributed over the armature periphery, so that each phase produced an exact sine wave of m. m. f. then the superposition of the three phases having equal instantaneous currents would result in complete cancellation. This means that there would be no resultant armature m. m. f. and consequently zero reactance.

But this is an ideal and incorrect picture. Chording causes a departure from this condition, as does the phase belt width, and the zero phase sequence reactance is a function of this departure.

Another way of describing the variation is this: when fundamental zero phase sequence current is applied to a synchronous machine, a slot flux is produced which varies widely with the winding pitch. With short pitch windings, the flux is decreased by the presence, in the slots, of conductors carrying current in opposite directions. This slot reactance is thus very sensitive to pitch; it is a minimum at 2/3 pitch. At this pitch also the air-gap m. m. f. disappears. Hence, the zero phase sequence reactance is very small.

A physical conception of the conditions obtaining at full pitch and at 2/3 pitch may be had from Figs. 33 and 34. In Fig. 33, a full pitch is indicated.

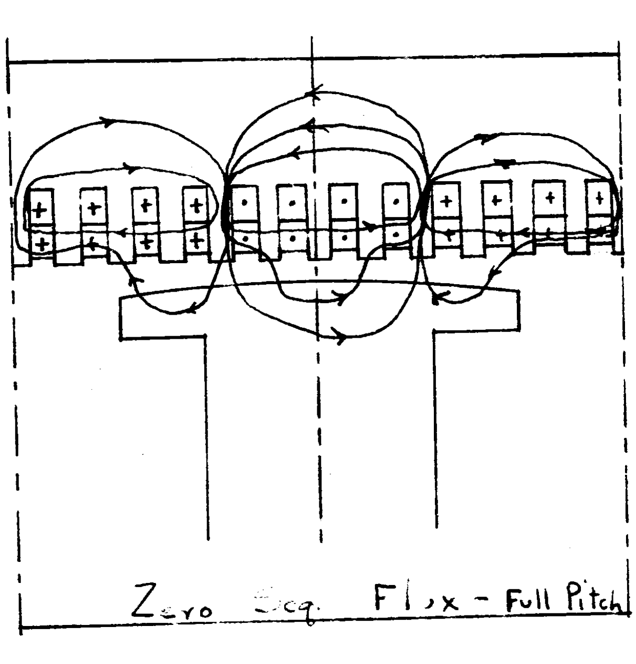


Fig 33

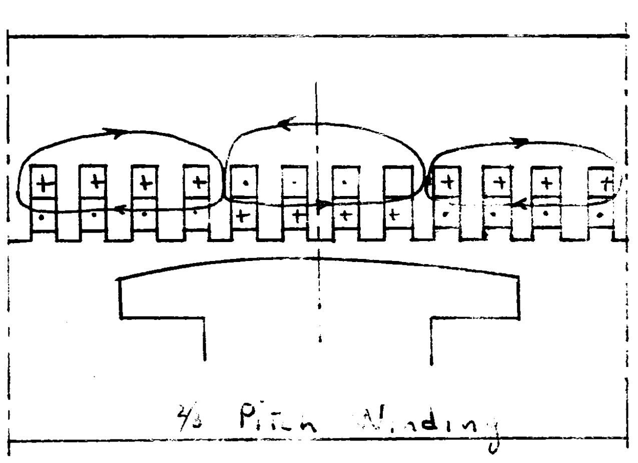


Fig 34

Currents "down" (into the paper) are marked with a cross, according to convention. Applying the Corkscrew Rule, the direction of the zero phase sequence flux is found and marked by an arrow-head. It is seen that a considerable amount of flux finds its way across the air-gap into the pole. At full pitch the flux is a maximum, and so is the reactance.

In Fig. 34 the winding is 2/3 full pitch. The flux is greatly reduced, and none crosses the air-gap. This is the condition for minimum reactance.

ZERO PHASE SEQUENCE REACTANCE DIFINED.

"The zero phase sequence reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental zero phase sequence component of armature current, to this component of current at rated frequency."

A final point regarding fundamental and harmonic currents will be mentioned. When fundamental zero phase sequence current is applied to a generator, a pulsating third harmonic m. m. f. in the air gap is produced. So that while it is true that there is no armature-reaction m. m. f. due to fundamental zero phase sequence currents, it is a fact that there is a third harmonic m. m. f. of three times the number of pairs of poles on the rotor, because the third harmonic currents are in time phase.

There is strong evidence of the existence of this m. m. f. when running a delta-connected machine (not with 2/3 pitch) under short-circuit. The evidence takes the form of unusually high losses and field coil temperatures. The obvious interpretation is that there is an appreciable third-harmonic circulating current. There is a means of predetermining the magnitude of this current. The third-harmonic voltage of the open delta must first be calculated. Then the current which will flow when the delta is closed is the ratio of this voltage to three times the third-harmonic zero phase sequence reactance; $i_3 = \frac{e_3}{3x_{o3}}$, where the subscript 3 refers to third- harmonic. Very nearly, $x_{o3} = 3x_o$. So that the circulating third-harmonic current is (very nearly) $i_3 = \frac{e_3}{9x_0}$.

EFFECT OF SATURATION ON MACHINE CONSTANTS.

An analysis of the performance of a synchronous machine is an extremely difficult and involved one unless the degree of saturation is considered negligible. Happily, in a majority of cases this assumption is very near truth. Nevertheless, there is always the feeling that the effect of saturation may really be relatively large. The effect of saturation is to lower the value of reactance. An example of this effect is made by Mr. Wright in one of his papers. The subtransient reactance of a turbine generator for a dead short-circuit with no external impedance is given as 14.5 per cent; and for a short-circuit with external impedance, the value is 16.5 per cent. In the latter case, the external impedance drops the short-circuit current, and this results in less saturation.

It has been found that saturation effects are different for (1) different machines and (2) different constants of any one machine. "In other words, machine constants are not truly constant."

The modern practice is to specify one value of the constant only, but there appear to be different conventions for each of the constants.

For the case of synchronous reactance, unsaturated values are used, to conform with former definitions.

For the case of transient, subtransient and negative reactances, the values specified are those obtaining from a dead three-phase and line-to-line short-circuit, respectively, from rated voltage at no load. The value so obtained is named the saturated value.

For the case of zero phase sequence reactance there is no ambiguity, because saturation effects for zero phase sequence currents in the range usually encountered are small.

MEASUREMENT OF THE REACTANCES.

Thus far Part 2 has dealt with a description and discussion of the eight most important reactances. The remainder of this Part will deal with methods of measuring these quantities as described and defined above, and will contain results of such measurements made in the A. C. Laboratory at McGill University.

The tests were conducted by two other graduate students, T. Stanley and D. Burnham, and myself.

APPARATUS AND MACHINES.

The name-plate on the machine tested bears the following information:

Westinghouse A. C. Generator

S. O. Number 43A17

Serial 2376796

50 KV-A; 220 volts; 131 amperes per terminal;1200 r.p.m.; 6 poles; damper windings; armature star connected with neutral brought out; 3 - phase; 60 cycles.

It is driven by a direct-coupled D.C. Shunt-wound motor rated at 62.5 H.P.

For several tests a supply of alternating current was required. This was provided by a similar machine except that it has no neutral terminal. Its serial number is 2376798.

A three-element vibrating - mirror type of oscillograph was employed to obtain short-circuit records. It is shown in accompanying photographs.

Three non-inductive current shunts were required to avoid saturation effects. We built these ourselves by mounting doubled conductors onto round wooden blocks, three to four inches in diameter. This winding was made tight and secure by a liberal application of tape.

Meters, switches, rheostats, a tachometer, and a frequency meter complete the list.

The various measurements will now be described in turn.

1. DIRECT-AXIS REACTANCES.

Measurement of Synchronous Reactance, x_d .

(1) By the No-Load Saturation and Short-circuit current curves. The no-load saturation and short-circuit curves for the alternator were obtained in the usual way. The values read are tabulated below, and are plotted in Fig.35.

No-Load Saturation	
E_n	I_f
17.3	0.5
32.3	1.0
49	1.5
62	2.0
72	2.5
79	2.75
83	3.0
91	3.25
95	3.5
102	3.75
107	4.0
111	4.25
115	4.5
120	4.75
124	5.0
128	5.25
131	5.5
137	6.0
144	6.5
149	7.0
157	8.0

Short-Circuit Current	
I_A	I_f
41.5	1.5
54	2
70	2.5
84	3
99	3.5
113	4
127	4.5
141	5
156	5.5
169	6
182	6.5
194	7

E_n is volts to neutral; I is in amperes.

There are two ways of getting x_d .

The first is to follow the old A. I. E. E. definition, in which case

$$x_d = \frac{a}{b} = \frac{4.7}{3.9} = 1.20 \text{ ohms.}$$

The second is to take the ratio c to d of Fig. 35, so that

$$x_d = \frac{c}{d} = \frac{152}{131} = 1.16 \text{ ohms.}$$

It is desirable to convert the ohmic values to per cent. A convenient way of doing this is to employ the factor "normal ohms". Normal ohms of a machine is that number of ohms at rated machine voltage corresponding to 100% impedance on the machine KV-A base. It is readily computed as the ratio of rated line-to-neutral voltage to rated line current.

$$\text{Normal ohms} = \frac{127}{131} = 0.97$$

$$x_d = \frac{1.20}{0.97} \times 100 = 123.7\%$$

$$\text{or} \quad x_d = \frac{1.16}{0.97} \times 100 = 119.5\%$$

$$\text{Mean } x_d = 121.6\%$$

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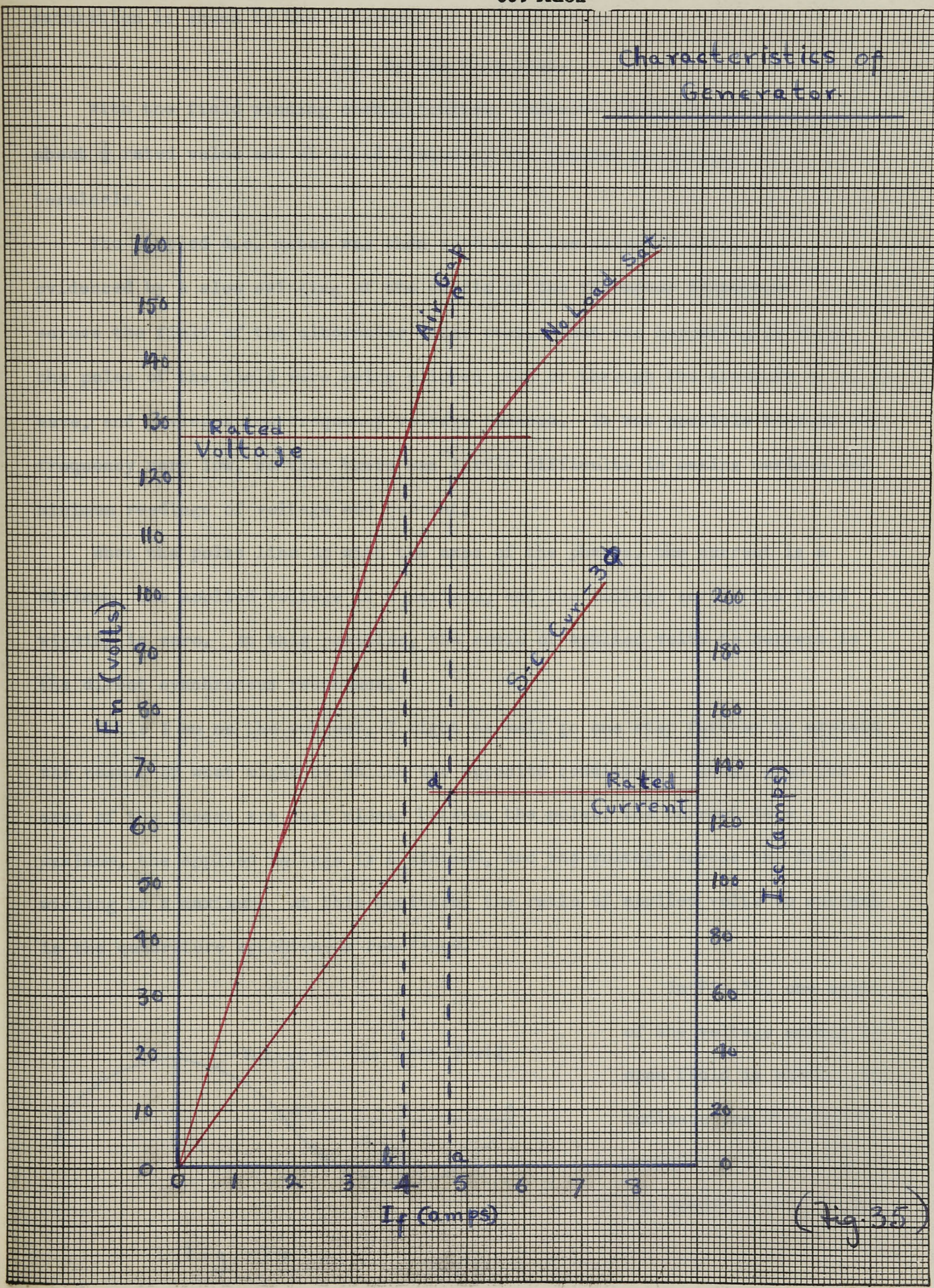

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The convention of calculating this reactance on the basis of no saturation is shown by the reference of all quantities to the air-gap line.

(2) By the Slip Test.

With the field winding open-circuited, balanced three-phase voltage of about $\frac{1}{4}$ rated value and at rated frequency was applied to the generator terminals.

The coupled d.c. motor was then run at a low value of slip, as evidenced by a slow swinging of the needle of the voltmeter connected across the field of the alternator under test. What was happening is this: the poles of the field were being slipped past or through the armature m. m. f. wave, and having a low frequency voltage induced. It was possible to make this frequency very low, so that there was little difficulty in making maximum and minimum readings of voltage and current.

When the poles line up with the axes of the phases, the current is a minimum, the applied voltage is a maximum, and the voltage across the field winding is zero. At this position, the ratio of applied volts to current is the direct synchronous reactance.

While I am on the subject, I might as well go one step further to explain the result of what might be called the opposite conditions. Thus, when the axes of the phases are just midway between the poles, the current is a maximum, the applied voltage is a minimum, and the voltage across the field winding is a maximum. At this position, the ratio of applied volts to current is the quadrature synchronous reactance.

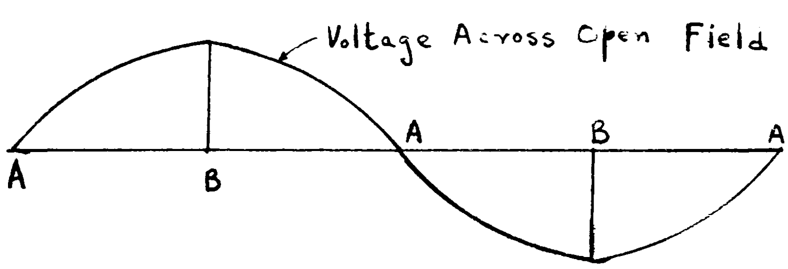


Fig 36.

In Fig.36, one cycle of the voltage across the open field is shown. The A's indicate the direct-axis positions; the B's indicate the quadrature-axis positions.

Follow p. 59

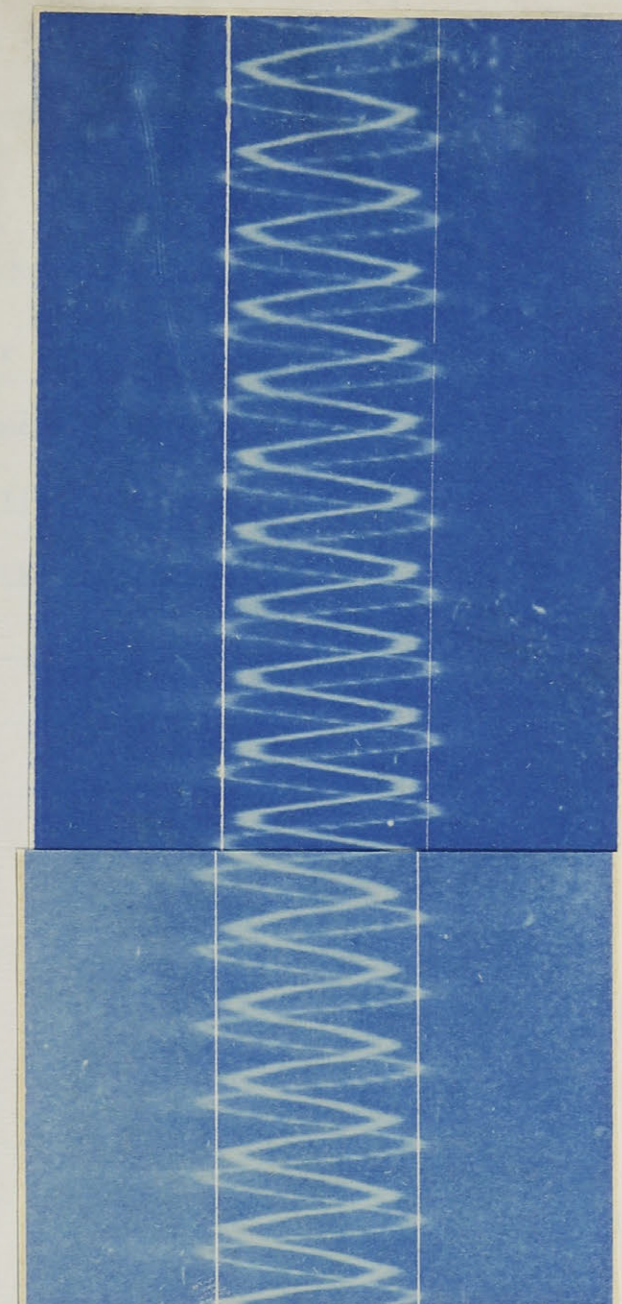


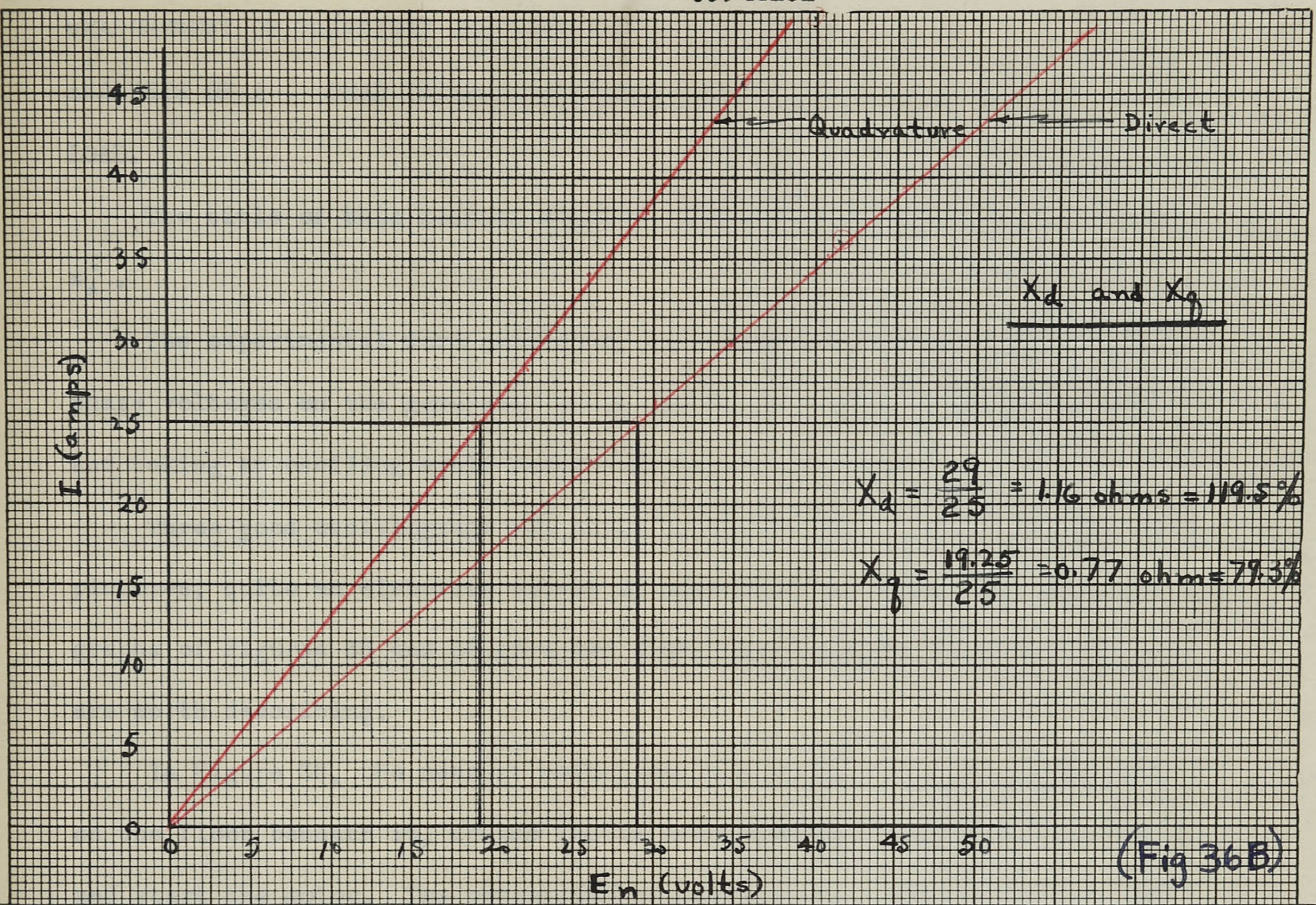
Fig. 36-A

The meter readings taken are tabulated below. x_q is included for future reference. An oscillogram of this test is shown in Fig.36A. The parallel lines are drawn to show off more clearly the variation in magnitude of the waves, the heavier of which is current.

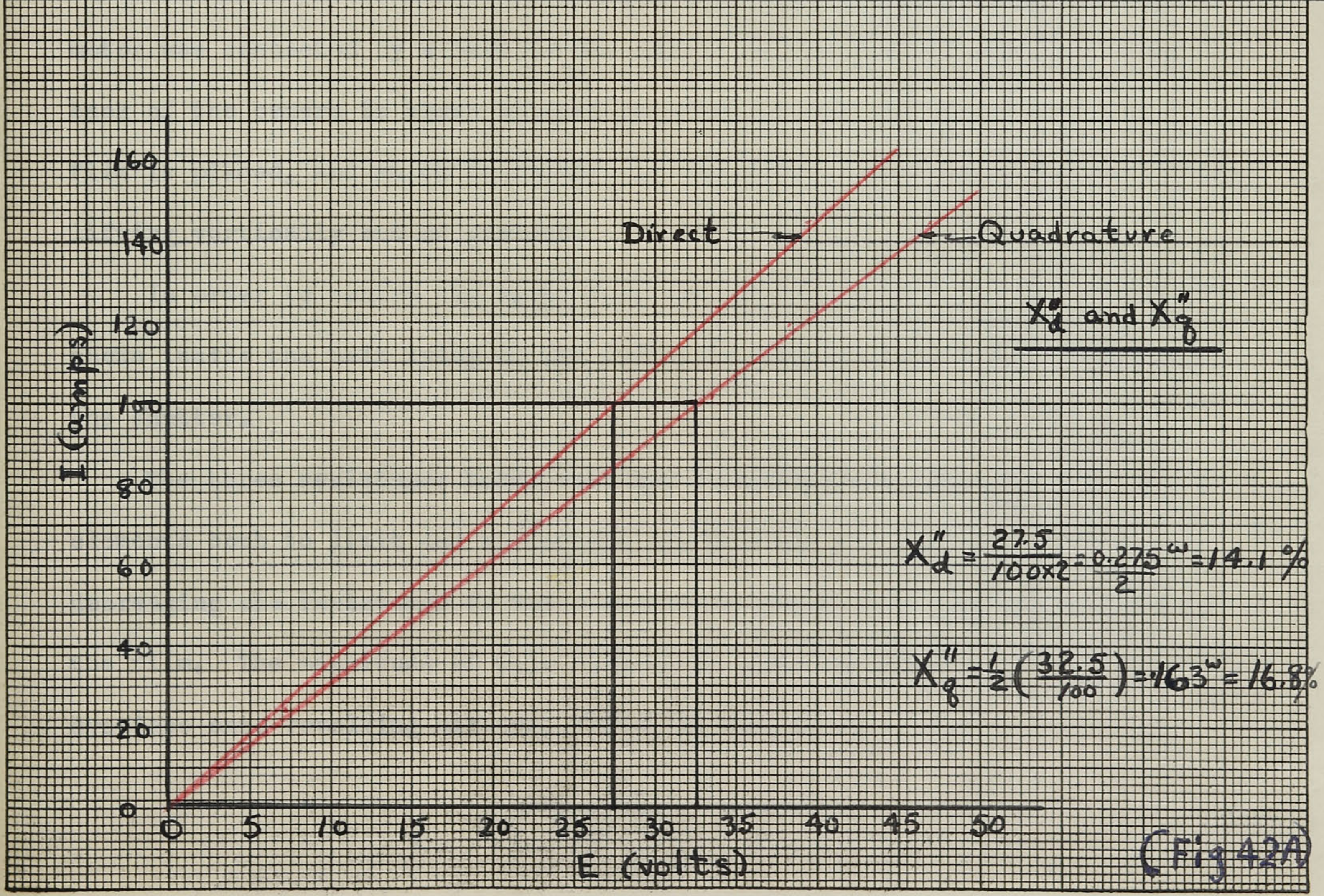
~~The meter readings taken are tabulated below. X is included for future reference. An oscillogram of this test is shown in Figure 36A. The parallel lines are drawn to show off more clearly the variation in magnitude of the waves, the heavier of which is current.~~

SLIP TEST			
I	E_n	x_d	x_q
45.7	35.4		0.775
36.0	41.5	1.15	
49.6	34.9		0.702
35.2	40.7	1.16	
34.0	26.0		0.765
26.2	30.1	1.15	
43.5	33.8		0.776
34.2	40.0	1.17	
49.8	38.6		0.775
39.4	45.5	1.15	
37.8	29.6		0.782
29.6	34.8	1.17	
28.2	22.2		0.786
22.5	26.2	1.16	
	Mean :	1.16	0.77
		$= \frac{1.16x100}{0.97}$	$= \frac{0.77x100}{0.97}$
		= 119.5 %	= 79.3%

Follow p. 60



(Fig 36B)



(Fig 42A)

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These results are obtained graphically in Figure 36B.

MEASUREMENT OF TRANSIENT AND SUBTRANSIENT REACTANCES, x_d' AND x_d'', BY THE ANALYSIS OF A DEAD THREE-PHASE SHORT-CIRCUIT FROM RATED VOLTAGE AT NO LOAD.

The title of this section suggests the method adopted to find x_d' and x_d''.

The experimental work consisted, in brief, of throwing sudden three-phase voltages on the generator while running at rated speed and voltage and taking an oscillographic record of the current wave.

Three good oscillograms are shown in Figure 37. In order to get these pictures, quite an elaborate set-up of apparatus was required. The photographs of Figures 38 and 39 give two views from opposite sides. The features are worth describing.

In Figure 38, the nearest switch was connected, through a potentiometer on the floor beneath it, to the little motor beside it, and was used to stop and start the motor. The potentiometer was used for speed control. The motor was connected by a belt to the camera end of the oscillograph. The back of the camera is shown removed in order to show the drum upon which the film is placed, and which is rotated by the motor. The camera is removed by lifting vertically out of grooves.

In order to centre the spots from the three elements, the celluloid scale, shown inside the belt lying on the table, is slipped down these grooves to the shutter.

The three resistance boxes were put in series with the oscillograph elements both to limit and to control the current through the elements. By decreasing the resistance it was possible to obtain a greater deflection on the film. The magnitude of this deflection could be seen by looking down the eyepiece onto revolving mirrors, driven by the second pulley.

Follow p. 61

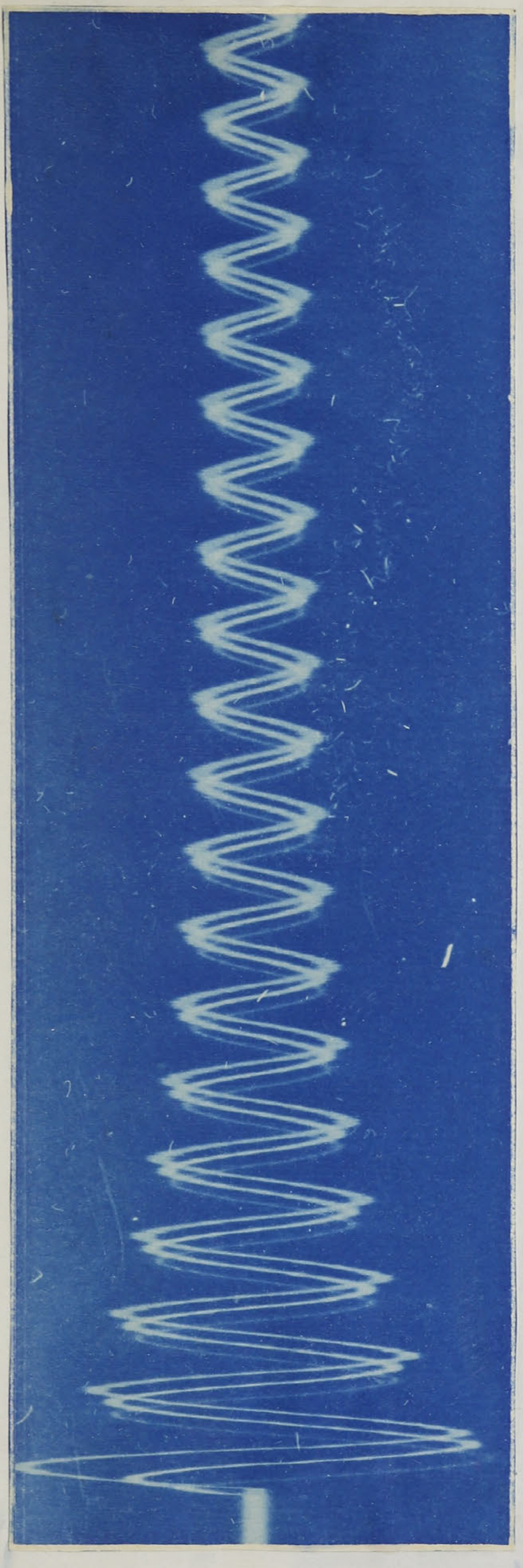

Fig. 37 —(1)

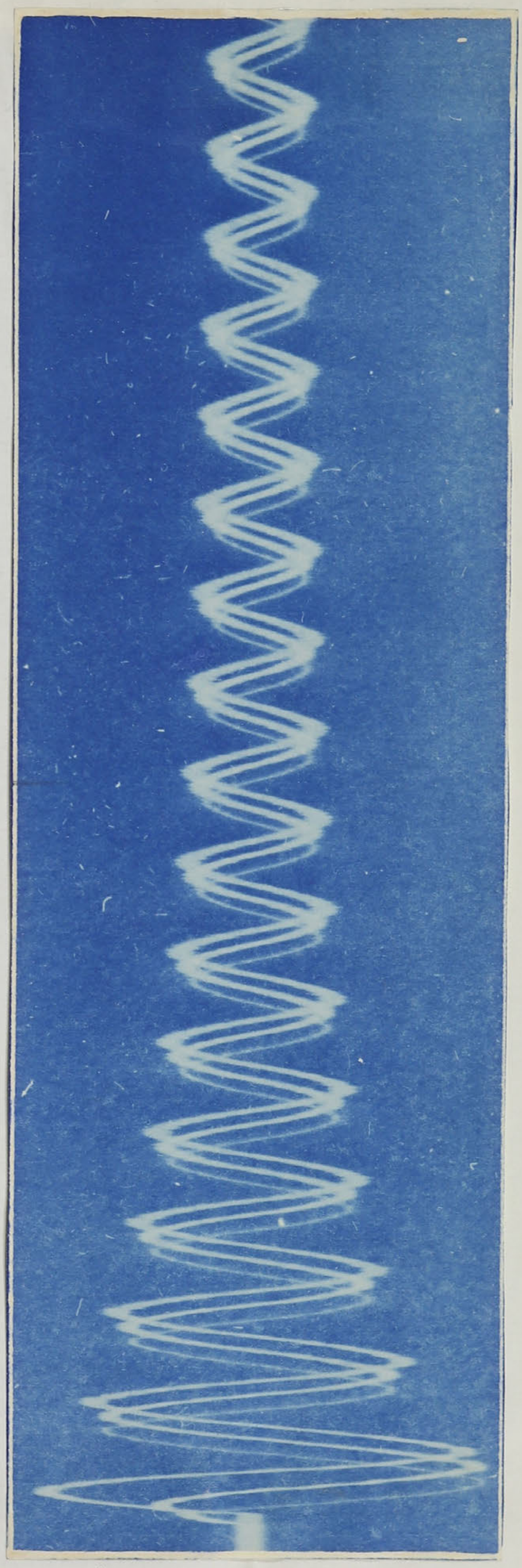

Fig. 37 —(2)

Follow p. 61

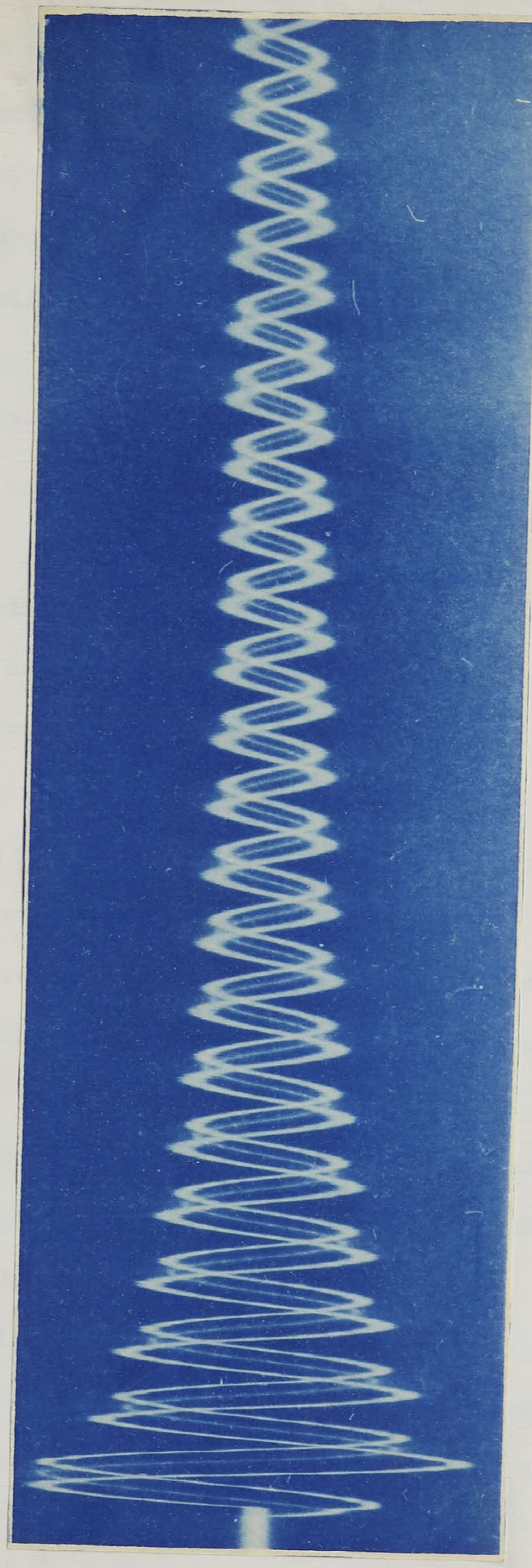

Fig. 37 — (3)

On the further table in Figure 38 may be seen the three non-inductive shunts, meters and switches. A better view is given in Figure 39.

Three meters are shown. That on the left is an ammeter, that in the middle is a voltmeter, and that on the right is a field ammeter. The switch on the extreme left was connected in shunt with the ammeter, and was closed before imposing short-circuits to prevent damage to the meter.

The bulb inside the oscillograph was rated at six volts, but was expected to carry 10 volts for an instant to give a good picture. The function of the little white double-throw switch at the rear end of Figure 39 was to supply these two voltages, from batteries on the floor, to the bulb.

The big double-pole switch to the right of this white switch was the short-circuiting switch. By pulling down to the nearer contacts, all three phases were shorted simultaneously. This switch was carefully cleaned and lined up to minimize the danger of arcs. The switch at the extreme right of the photograph was in the generator field circuit. A small section of the 62.5 H.P. motor is seen just above this switch.

For this picture, the cover of the three elements was removed, and the frames enclosing the minute mirrors are shown covered with cotton to prevent oil from seeping down.

The procedure adopted to obtain a picture was as follows:

First a bridge was set up, and the resistance of each of the three elements accurately measured.

Then six volts was applied to the bulb, the scale was slipped into place, and the reflected spots centred. The scale was then removed, the shutter closed and the loaded camera slipped into place.

Follow p. 62

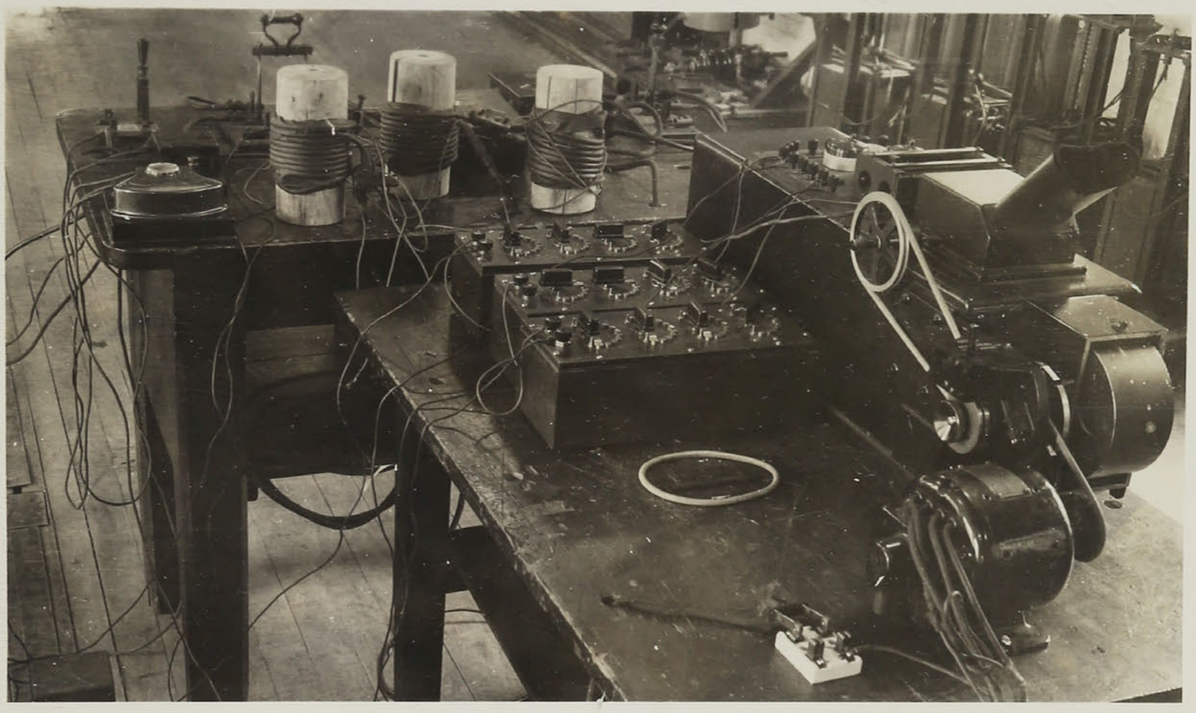

Fig. 38

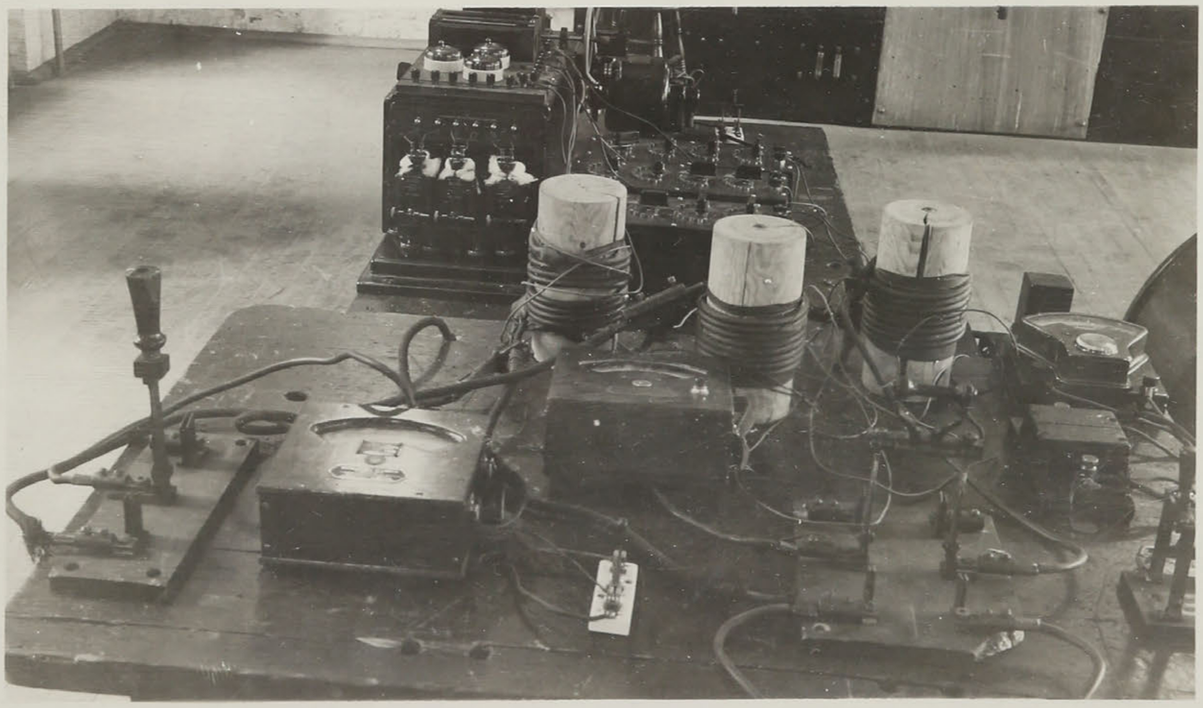

Fig. 39

The generator was driven at rated speed and excited to normal voltage, and suddenly short-circuited. The magnitude of the deflection so obtained was noted by looking at the revolving mirrors, and adjusted by means of the resistance boxes. It was found confusing to view all three phases at once, so that two of the mirrors were blocked temporarily with cotton. Then several short-circuits were viewed to adjust for maximum asymmetry. The resistance of the element whose behavior was being studied was added to the resistance indicated by the appropriate resistance box to get a sum of, say, 180 ohms. Then, if the other two elements had resistances of 10 and 12 ohms, the resistance boxes were set at 170 and 168 ohms, respectively. The purpose of this procedure was to assure equal magnitudes of deflection from all three of the elements, but it assumed that the voltage drops across the three shunts were equal. This may or may not have been true. We attempted to design the shunts to have identical properties, but had no means of accurate test. I have no doubt that the percentage variation was negligible. The error was certainly less than that possible from a decision as to the position of the envelope of the oscillogram.

Having fixed the magnitudes of deflection, the light was turned off and the camera shutter opened. The camera motor was started and brought up to as high a speed as possible in order to spread out the wave; the speed was of the order of 750 r.p.m. The speed and voltage of the generator was checked. Then the operator (each one of us had a turn) closed the ammeter shunt switch, and seized the handles of the bulb switch and short-circuiting switch.

In order to get a good picture it was important that the bright light be on at the time of short-circuit. And in order to save the bulb, it was important that the bulb switch be left closed for an exceedingly brief period. It was felt that with a little practice these requirements could be satisfied by manual manipulation of the switches as satisfactorily as by the application of elaborate mechanical devices.

The procedure, therefore, was: (1) to slam the bulb switch down onto the 10-volt contact, (2) a brief instant later to slam down the short-circuiting switch, and (3) an instant later to lift the bulb switch. The generator field circuit was then opened at the operator's leisure.

Then the camera motor was shut down, the camera removed and the film developed. Three of the best oscillograms are included in Figure 37.

ANALYSIS OF OSCILLOGRAM

There are two ways of getting x'_d and x''_d from the oscillograms, one by projection as discussed above, and the other by analysing the curve in the following manner. The discussion refers to any one phase.

Two envelopes and the mid-point curve are drawn. This provides information for the computation of the following two factors, referring to the symmetrical and asymmetrical components respectively.

The factor for the symmetrical component times the distance between envelopes converts this distance to per unit r.m.s. current; it equals $\frac{1}{2\sqrt{2}} = 0.354$ times the asymmetrical component factor, described next.

The factor for the asymmetrical component times the distance from the mid-point curve to the zero-current line at any instant converts this distance to per unit current (which is $\frac{1}{100}$ of the value in per cent). It equals the ratio: amperes per unit distance of deflection over rated r.m.s. current.

In order to obtain the initial value of the asymmetrical component, it is remembered that the decay is approximately exponential. For this reason the logarithms of the asymmetrical components are plotted on a time base, as in Figure 38. Extrapolation gives the initial value, A. This

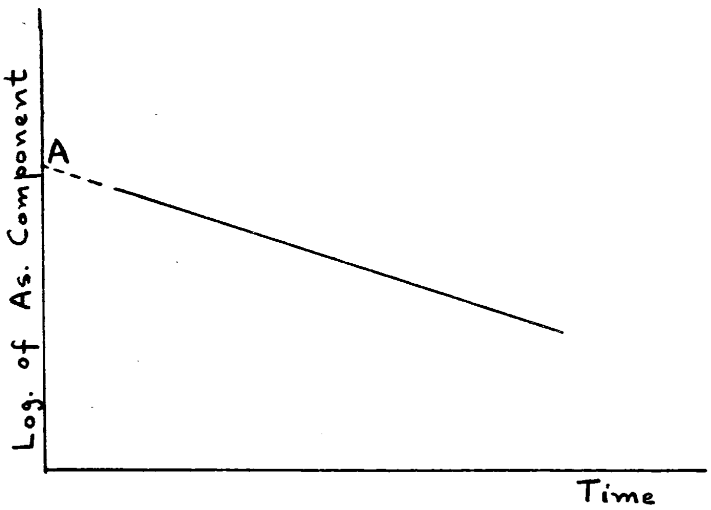

Fig 38

value is not a constant, since it depends entirely on the instant of short-circuit. In order to get the maximum value, the graphical method illustrated in Figure 39 is used. A,B,C are initial values of the asymmetrical component for the three phases. OM is the maximum possible asymmetrical component. This assumes a sine wave, which is about true in the machine under test, as may be seen from the wave shape in Figure 39A. The top of the wave is flattened a bit while the irregularities are due to the teeth.

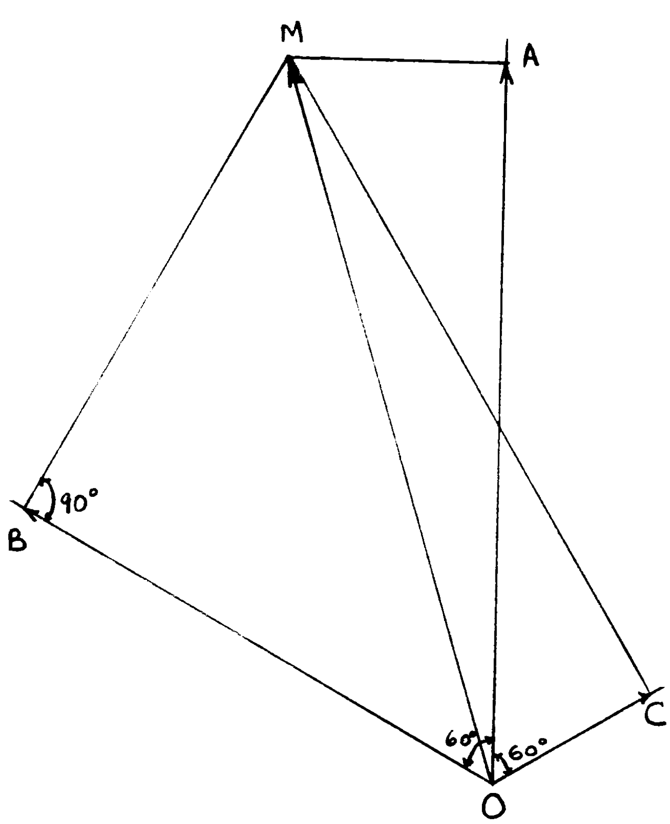

Fig. 39

The average of the per unit r.m.s. values of the symmetrical components is plotted as in Figure 40, and the initial value taken as $\frac{OM}{\sqrt{2}}$. X''_d is then the ratio of rated voltage to this value of current.

Follow p. 65

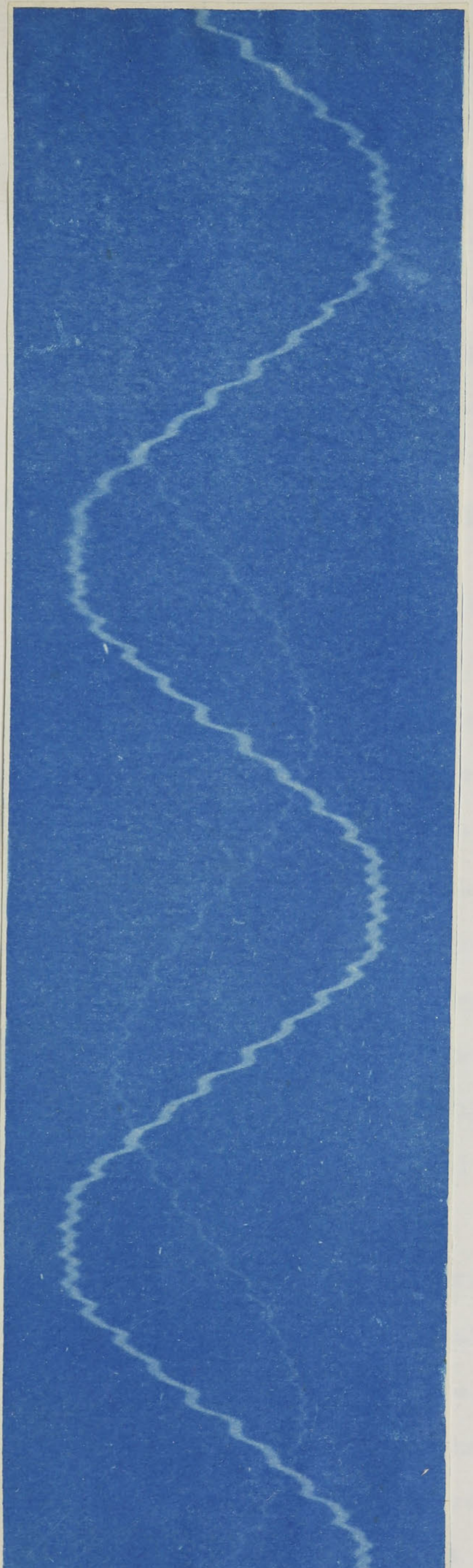

Fig. 39-A

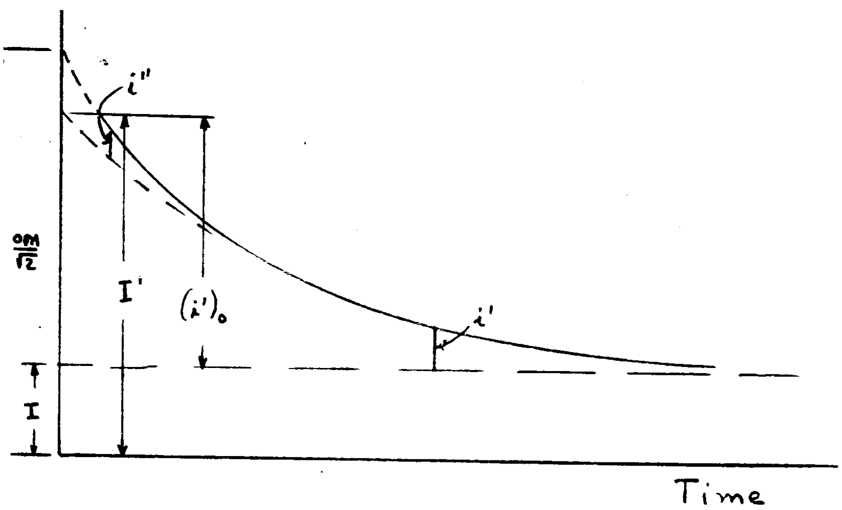

Fig 40

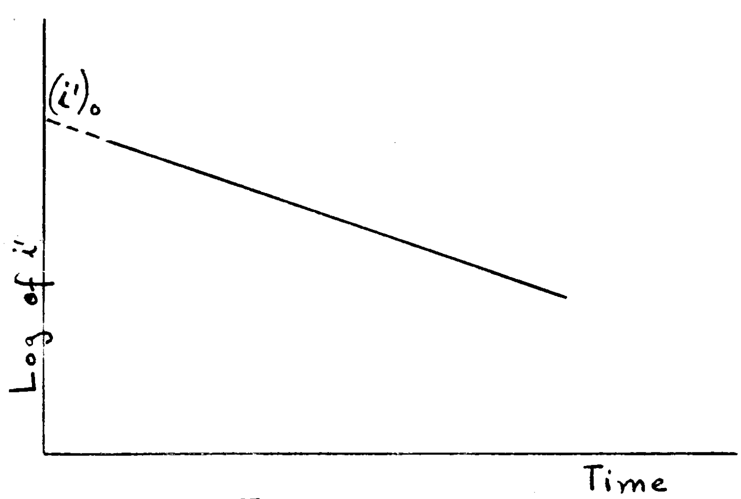

Fig. 41

X'_d is the ratio of voltage to current neglecting the first few cycles of rapidly decaying current. Figure 41 is re-plotted from Figure 40, using the logarithmic value of i'. Extrapolation gives $(i')_o$, which is placed into Figure 40.

$I' = (i')_o + I.$ and therefore

$$x'_d = \frac{\text{voltage before short-circuit}}{I'}$$

In applying this method, two major assumptions are made. The wave of current is assumed symmetrical from the instant of short-circuit. The asymmetrical component of current is assumed to die away exponentially. Both of these assumptions are justified, but neither is correct. In our work the latter assumption seemed utterly wrong, for the curves for Figure 38 and 41 were almost anything but straight lines.

This method requires an exceedingly high degree of graphical skill and judgment. In the case of our curves it is my opinion that the method is not a good one - not nearly good enough, at any rate. For although we all applied ourselves vigorously to the solution of the oscillograms by this method, only in one case was a reasonable value (reasonable as compared with the results of other tests for the same quantities) obtained.

Mr. Stanley succeeded in getting these values:

$$x''_d = 13.5\%$$

$$x'_d = 15.8\%$$

The other results varied from these values by 50 to 200%. Probably a great deal of practice would produce better values, but I doubt if there ever would be any close agreement. It is commonly recognized that oscillographic and graphic methods of calculation are not accurate, but serve to give a very approximate value. In some special instances, of course, it happens that the degree of accuracy falls within the limit of the accuracy of the known quantities, in which case it is a highly satisfactory method.

Because of these difficulties, I consider it as satisfactory to judge the zero time values for the three curves by projection. The values are then as follows (steady state current being 152 amperes):

Curve	Amperes	x'_d	Amperes	x''_d
1	825	15.9	950	13.8
2	875	15.0	1000	13.1
3	800	16.4	925	14.1

Since the averages of these values compare very favorably with those obtained by Mr. Stanley, this thesis will present his values in the explicit summary near the end of this Part as best values.

SUBTRANSIENT REACTANCE, x''_d, FROM LOCKED LINE-TO-LINE TEST

This is a second method of obtaining x''_d. The experiment is relatively easy to carry out, the only unusual feature being that the rotor has to be rotated through very small distances at a time, such as 5°. Figure 42 shows

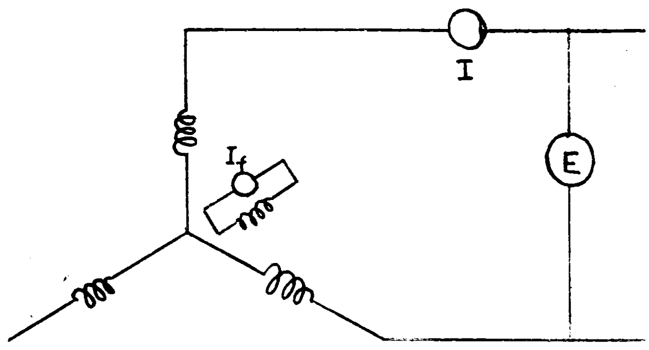

Fig 42

the connections. Single phase voltage, E, was applied to two terminals of the generator, with the rotor still, and the field winding shorted through an ammeter.

The current, I, was made about $\frac{1}{4}$ rated value. Then the rotor was moved by hand through small angles, the three meters being read for each position. This was done for about $1\frac{1}{2}$ pole pitches. That position which gave a maximum ratio of I_f/E was marked as the direct-axis position, while that which gave $I_f = 0$ was marked the quadrature-axis position.

Then for each of these positions a new set of readings were taken with various voltages applied in order to get a mean value of x''_d, and incidentally x''_q. This mean value was considered more accurate than the one value obtained in determining the positions of the two axes.

The data gathered is given below. Quadrature values are included here for future reference. The direct and quadrature positions are 9 and 14, respectively.

LINE-TO-LINE LOCKED ROTOR

	Position	E v	I_f α	I α	I_f/E
	1	13.9	0.19	42.0	.0137
	2	13.2	.38	43.4	.0288
	3	12.6	.51	43.8	.0405
	4	12.2	.62	44.1	.0507
	5	12.1	.615	44.0	.0508
	6	12.9	.48	43.4	.0372
	7	13.2	.39	43.0	.0296
	8	13.8	.235	42.8	.0176
Quad.→	9	13.8	0.0	43.0	0.0
	10	13.6	.16	43.0	.0117
	11	13.1	.42	43.4	.0321
	12	12.6	.53	43.8	.0422
	13	12.1	.635	44.0	.0524
Direct→	14	12.0	.645	44.0	.0538

IN POSITION 14 - DIRECT-AXIS VALUE

E v	I_f α	I α	E/I= $2x''_d$	x''_d ω
7.2	0.37	24.5	0.294	.147
9.2	.48	32.8	.280	.140
10.9	.57	39.6	.275	.138
13.8	.73	50.2	.275	.137
16.5	.86	59.0	.280	.140
23.0	1.10	75.3	.306	.153
24.1	1.25	86.5	.279	.139
27.4	1.45	99.0	.277	.137
33.8	1.76	124.0	.273	.136
39.5	2.07	145.0	.273	.135

Mean: 0.137 ω

$= \frac{0.137 \times 100}{.97}$

= 14.1%

IN POSITION 9 - QUADRATURE-AXIS VALUE			
E ^{V}	I_f $^{\alpha}$	I $^{\alpha}$	$\frac{1}{2}(E/I) = x''_q$ $^{\omega}$
10.1	0	30.5	0.165
16.7		51.2	.163
24.2		73.8	.164
28.6		87.3	.164
33.5		101.8	.165
38.2		119.5	.160
46.8		144.5	.162
		Mean:	.163 $^{\omega}$

$$= \frac{.163 \times 100}{.97}$$

$$= 16.8\%$$

These results are also obtained graphically in Figure 42A (on same sheet as Figure 36B).

II QUADRATURE-AXIS REACTANCES

SYNCHRONOUS REACTANCE, x_q

The unsaturated (following convention) value of x_q is obtained by the slip test, as already described on page 59. The average of the tests give

$$x_q = 0.77 \text{ ohm}$$

$$= \frac{0.77 \times 100}{0.97} = 79.3\%$$

TRANSIENT REACTANCE, x'_q.

It has already been explained that due to the fact that there is no really effective winding in the quadrature axis even if a damper winding is placed on the poles, equation (39) holds. That is $x'_q = x_q$, for salient-pole machines.

$$\therefore \; x'_q = 79.3\%$$

SUBTRANSIENT REACTANCE, x''_q

The method of measuring this value has also been described in the section dealing with the direct-axis value of the subtransient reactance - pages 68 and 70 . The result given there is $x''_q = 16.8\%$

III ZERO PHASE SEQUENCE REACTANCE, x_o

LOCKED ZERO PHASE SEQUENCE REACTANCE TEST

This is one of two methods for measuring x_o. The connections employed are shown in Figure 43. Voltage E is applied across one phase with the rotor still and the field winding short-circuited. The current, I, is made approximately equal to rated current. The ratio E to I gives x_o very nearly, since the negative phase sequence resistence is assumed to be zero.

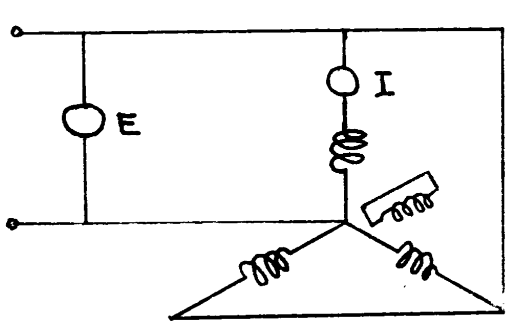

Fig 43

The following values were read:

LOCKED ZERO- SEQUENCE TEST		
E ^{v}	I $^{\alpha}$	x_o = E/I $^{\omega}$
2.80	60.1	.0466
4.00	85.5	.0463
4.20	90.0	.0468
4.60	100.0	.0460
5.15	111.5	.0463
5.60	120.0	.0467
6.06	131.0	.0463
6.25	133.0	.0470
		Mean x_o = .0464 $^{\omega}$ = 4.8%

X_o FROM SUSTAINED DOUBLE LINE-TO-NEUTRAL SHORT-CIRCUIT

This is the second method for measuring x_o, developed by S.H.Wright. With the connections shown in Figure 44, $x_o = \frac{E}{I_n}$, provided that the zero phase sequence resistance is negligible. This method does not require an external source of power supply, but the generator must be driven by its prime mover at rated speed.

The values obtained by test are tabulated.

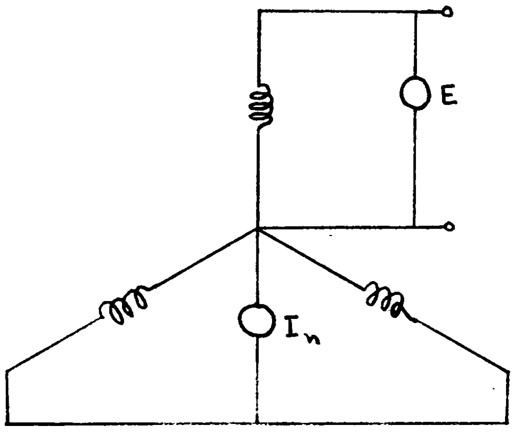

Fig 44

SUSTAINED DOUBLE LINE-TO-NEUTRAL SHORT-CIRCUIT		
E ^{V}	I_n $^{\alpha}$	$x_0 = \frac{E}{I_n}$ $^{\omega}$
4.75	66	.0721
5.80	80	.0725
7.30	100	.0730
8.00	110	.0730
8.70	120	.0730
9.55	130	.0730
10.25	140	.0732
11.55	158	.0732
13.10	178	.0738
14.70	198	.0742

Mean value

of $x_0 = .0732^{\omega}$

$= 7.5\%$

IV NEGATIVE PHASE SEQUENCE REACTANCE, x_2

x_2 FROM AVERAGE OF x_d'' AND x_q'' .

In the theoretical discussion of x_2 , starting on page 50 , exhaustive investigation indicated that x_2 could be taken as the average of x_d'' and x_q'' so that

$$x_2 = \tfrac{1}{2}(x_d'' + x_q') = \tfrac{1}{2}(14.1 + 16.8)$$

$$= 15.5\%$$

(Note: $\sqrt{14.1 \times 16.8} = 15.4$)

x_2 FROM SUSTAINED LINE-TO-LINE SHORT-CIRCUIT

Figure 45 is a representation of the connections used.

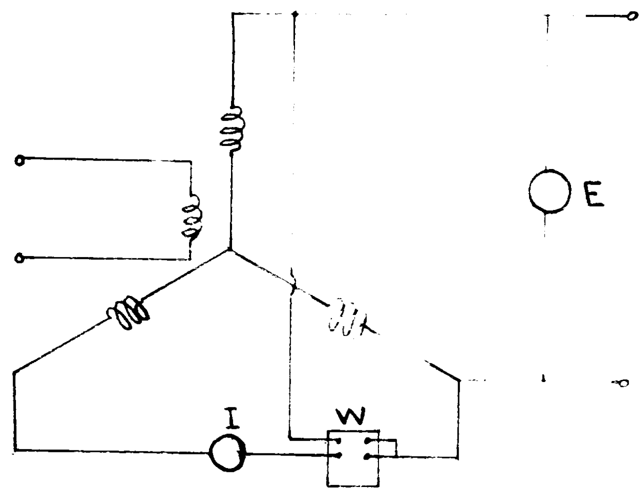

Fig 45

Since, according to convention, the negative phase sequence current should equal rated current, the armature current was varied around $\sqrt{3}$ times normal current.

Theory shows that

$$x_2 = \frac{E}{\sqrt{3}I} \cdot \frac{W}{EI} = \frac{W}{\sqrt{3}I^2}$$

If negative phase sequence resistance is negligible, then the following simplification results:

$$x_2 = \frac{E}{\sqrt{3}I}$$

The data obtained is tabulated below.

SUSTAINED LINE-TO-LINE SHORT-CIRCUIT				
W (KW)	I (A)	E (V)	x_2 (ω)	
....	......	.....	$E/\sqrt{3}I$	$W/\sqrt{3}\ I^2$
4.82	160	37.5	0.136	0.109
3.75	142	33.5	0.136	0.108
3.15	131	30.9	0.136	0.106
2.55	118	27.8	0.136	0.110
1.75	102	24.0	0.136	0.108
1.20	80	19.0	0.137	0.108
			Mean: 0.136 ω	0.108 ω
			= 14.2%	= 11.0%

EXPLICIT SUMMARY OF EXPERIMENTAL RESULTS

No.	Method of Getting Value	Value, %
1	No load Saturation and Short-Circuit curves	$x_d = 121.6$
2	Slip Test	$x_d = 119.5$
3	Oscillograms	$x'_d = 15.8$
4	"	$x''_d = 13.5$
5	Locked Line-to-Line Test	$x''_d = 14.1$
6	Slip Test	$x_q = 79.3$
7	Equating x'_q to x_q	$x'_q = 79.3$
8	Locked Line-to-Line Test	$x''_q = 16.8$
9	Locked zero phase sequence Test	$x_o = 4.8$
10	Sustained double line-to-neutral Short Circuit	$x_o = 7.5$
11	Average of x''_d and x''_q (Nos.5 and 8)	$x_2 = 15.5$
12	Sustained line-to-line short circuit (voltmeter)	$x_2 = 14.2$
13	" " " " (wattmeter)	$x_2 = 11.0$

DISCUSSION AND FINAL VALUES

x_d - Two values are offered for this constant in the explicit summary. Fortunately there is relatively little difference between them, because it is difficult to make a choice. The possibility of an error in each method is about equal. In the first method, the air-gap line may not be in its proper position; and in the second method, the observed values may be in error due to the diffiuulty of reading the end values of a constantly swinging meter needle.

The value 120.0% is probably a good one for x_d .

x''_d - Two values are offered for this constant in the explicit summary. Although the two oscillographic methods tend to indicate the lower value, nevertheless I feel that the higher, 14.1%, is the better value for x''_d because of the ease and straightforwardness of the locked line-to-line test. It is gratifying to notice the small difference in these values obtained by such radically different methods.

x_o - Two values are offered for this constant in the explicit summary. The values differ widely. On two separate occasions these tests were repeated, but contrary to our fondest hopes the values checked consistently, proving conclusively that the values are correct for the methods employed. Both methods assume that the zero phase sequence resistance of the generator is negligible which may or may not be true. Theoretically, for method number 10 the current in the neutral should be 3 times rated current to get precise values, but we could not safely provide such a heavy current. Since this requirement does not apply to number 8, I feel the better value for x_o is 4.8%.

X_2 - Three values are offered for this constant in the explicit summary. I am confident that the value given for number 11, namely 15.5%, is that nearest the correct value, first because theory shows clearly that the method is correct, and second because I have confidence in the values of x''_d and x''_q for the reason that both are given by the accurate locked line-to-line test. Furthermore, the other two values can only be approximately correct because of assumptions made which are not strictly true.

FINAL SUMMARY OF REACTANCE VALUES FOR THE GENERATOR

Reactance	Value, %
x_d	120.0
x'_d	15.8
x''_d	14.1
x_q	79.3
x'_q	79.3
x''_q	16.8
x_2	15.5
x_0	4.8

Part 3: PROTECTIVE RELAYS FOR A. C. SYSTEMS

"They also serve who only stand and wait."

When John Milton produced that immortal line in the middle 16 hundreds to bring to a triumphant close his sonnet "On His Blindness", he was thinking of those eyes capable of transmitting to the brain a living picture of the beauties and wonders of our world. His had long ago ceased to function.

The blind are the object of the most profound pity. Theirs is an irreparable loss. The thought of imposing upon a blind person is a repulsive one. Realizing this, and with due respect, I feel the quoted line expresses wonderfully the situation of the Relay.

A popular name for the Relay is Silent Sentinel. The name is descriptive and appropriate. The total working time per annum of any relay will certainly not exceed a few minutes. It may, in fact, do no active work whatsoever in a period considerably longer than a year. On the other hand, however, it may operate several times in one hour.

Each operation is very brief, requiring but a few seconds or fraction of a second to do its duty. But so important is it that the relay be there to step in at an emergency that their long periods of idleness are regarded as more than compensated for by the few moments of activity.

Perhaps the statement about long periods of idleness should be qualified. For although they are idle from the point of view of accomplishing work, nevertheless they are constantly on the alert. They are indefatigable watchmen.

QUALITIES AND DUTIES

The protective relay has three qualities; it is accurate in operation, sensitive in adjustment, and sturdy in construction.

Its duty is to discover the existence of electrical abnormalities in its territory, and once having discovered their existence, to instigate action to relieve or protect the circuit or apparatus with which it is associated. The actual relief is afforded by the circuit-breakers, but the relays decide when the breakers are to function. There exists a cooperative union of brawn and brain.

THE GENERAL PROBLEM

A relay is an electrical instrument designed to react in a specified manner when certain predetermined conditions arise. The conditions are those which will result from a fault or other abnormality on the electrical system. If, for any reason, the relay operates when no such abnormality exists, then the relay may be regarded as having undergone an incorrect operation. Incorrect operations are not to be blamed on the relay, but upon the characteristics imposed upon the relay by the engineer - that is, the fault is the engineer's. A good relay invariably operates as directed. The task of directing the operation of each relay in a large and complicated system is one requiring a considerable store of knowledge and experience on the part of the protection engineer. He must protect any portion of the system with a concise picture in mind of the rest of the system.

As will appear later, there are a large variety of relays being manufactured. Their applications shade into one another, so that it frequently happens that a choice has to be made between two or more relays for one particular service. The final choice will often depend upon the exact nature of the type of service required, consideration being given to related services which one type of relay may effect in contrast to the others.

Not only are there a great number of relays, but there are several relay schemes. Recognized advantages and disadvantages exist for each scheme, and again a choice must be made.

It is safe to say that many systems which are considered adequately protectwd by the use of certain relays and schemes may be as adequately protected by other relays and schemes. But the latter arrangement may prove to be a whole lot more expensive than the existant one, and for that reason would not be recognized as a good engineering job.

This question of economy brings forth a further problem. Suppose the relay equipment of a system is seen to be incompletely protective: for a particular kind of fault, say, a line will be removed from service without just cause. It is also seen that to remove this trouble, an exceptionally elaborate installation will be required. Then the problem to be decided is this: is it worth the investment charges to guarantee uninterrupted service on that line for all faults not involving that line? Pertinent questions will arise: How important is the load? What are the chances that such an incorrect operation will occur, and are they likely to occur often? Will the reputation of the Company suffer? Will there be danger of a loss of good-will? Will the loss of revenue during periods of interruption be great or small? A dozen other similar questions will come to mind.

We see, then, that economy is a guiding and all-important principle by which to steer one's path. As stressed above, any job which could have been done as well for less money is not a good engineering job.

FUNDAMENTAL NOTIONS

The greatest danger on an electrical power system is the danger of faults. It is the one generally borne in mind when designing a relay scheme. However, it is not the only one. The danger caused by over-load may be great enough to warrant the employment of relays. Over-voltage may also be a source of danger. But when we come to consider these further dangers, we find that they may be regarded as events which would normally occur as the result of a fault. That is to say, if we protect against faults, we may have the comforting thought that we have thereby protected against all dangers. Whether or not this is strictly tme is a subject for debate, but operating experience seems to point to its veracity.

Assuming, then, that we are to protect against faults only, we notice that there are three, and only three, fundamental indications of fault to form the basis of relay schemes.

These manifestations are:

1. Abnormal magnitudes of electrical quantities.
2. Abnormal ratios of electrical quantities.
3. Abnormal magnitudes of circuit quantities.

One(or more) of these manifestations points to a fault.

Something should be said about the range or magnitude of abnormality. Suppose that in the case of item 1, the electrical quantity being measured is current. Modern practice calls for non-automatic protection against over-load. If over-load develops, it may be brought to the attention of the operators by meters or an alarm, who may attempt load transfers. But to have an overloaded generator trip off the bus is merely to aggravate an already serious condition, by further overloading the machines still on the bus.

If the over-load persists for a dangerous length of time, thermal relays may operate, and shut-down will follow. Before this has occurred, however, the load will likely have decreased to normal, since most overloads are nearly instantaneous in character.

As another example, suppose voltage is suddenly removed from the system. Obviously, we do not want every switch on the system opened on this account. So that a relay which operates on under-voltage alone would be unsatisfactory. Uner-voltage is generally an indication of fault, but it is not an absolute indication.

TYPES OF INSTRUMENTS

Electrical instruments may have embodied in it one or more of the following three principles:

1. Moving coil or dynamometer.
2. Induction.
3. Moving iron or solenoid.

Using these three principles, the following four fundamental instruments are made: (1) ammeter; (2) voltmeter; (3) wattmeter; (4) ohmmeter.

Since these make up the entire list of fundamental instruments, and since relays are electrical instruments, that is, instruments to measure electrical quantities or changes in these quantities, it is obvious that any relay, no matter how complicated it may be, can be analyzed and shown to be made up of one or more of the above four fundamental instruments. In order further to stress this point, I repeat the statement that a relay is simply a contact-making or contact-breaking electrical instrument. Whereas in the ordinary instrument the mechanical force developed is transferred to a pointer, in the case of a relay this force acts to make or break an electrical circuit thereby promoting the required series of events.

REQUIREMENT OF TIME DELAY

It has been found necessary to introduce time delays in relays in order to ensure proper sequence of operation in coordinated systems. This introduction of extra time, while absolutely necessary in certain schemes of relay protection, is unfortunately a step in the wrong direction. When a fault occurs, it should be cleared as soon as possible for at least two good reasons: First, the fault causes damage proportional to or some function of the time of existence of the fault. Second, during a fault very little power can be transferred past the point of fault, and the danger of loss of stability is also proportional to the time of existence of fault. Modern systems are so large, and transmit so much power, that it has become exceedingly important to clear faults in very short time, and for this reason time delay schemes are not regarded with favor.

However, in some cases time delay is essential in which case a linear relation is made to exist between time and the electrical quantity concerned.

Referring back to the three fundamental instrument principles, we see that the solenoid type is not adapted to the use of time delay relays because it is inherently instantaneous in operation. If time delay characteristics were required from this type of instrument, then mechanical braking would have to be applied. In the old days of relaying this was actually done by bellows with a small hole or orifice permitting air to escape at a definite rate.

Mechanical braking is not one to be regarded as absolutely constant in effect for subsequent operations with the same conditions imposed. In the case of bellows, the material stiffens with age. Friction brakes wear.

Electrical braking, on the other hand, is exact and permanent. The introduction of the induction type of relay paved the way for accurate time delay relays, and so popular did these become that they appear to have replaced the solenoid relays entirely, even in the field of instantaneous operations. This seems to be contrary to reason, because just as the solenoid type is inherently instantaneous, so is the induction type inherently time delaying in nature. The most probable reason for the universal use of the induction type is that the large manufacturing companies concentrated on this type to the utter exclusion of the other, so that the induction relay received great development while the others received none. With more and more urgent demands being made for fast relays, it will be interesting to follow their further development, and also to observe if any radical changes in principle are attempted.

THE DEVELOPMENT OF THE RELAY ART

Relays have a surprisingly brief history, about 35 years at this time of writing. They are the result of a gradual development of the various devices first used for the purpose of automatically tripping the circuit breaker. This development, necessitated by a demand for greater refinement of adjustment and greater reliability, has led to the invention of many forms of relays, some entirely distinctive and others related in their method of protection.

The very first device for protective service was the fuse. It has great reliability and also includes many characteristics of the present-day relay. But it has the great disadvantage of requiring replacement after each operation before service can be restored.

Because of this disadvantage automatic switches were developed; they served to disconnect a circuit upon the occurrence of any fault causing excessive overcurrent, low voltage, or other abnormal condition. These switches were, of necessity, of relatively small rupturing capacity.

Systems grew, and finally it was found impossible to embody conveniently the discriminating features right in the breaker and still maintain sturdy structures. It was decided to remove the "brain" from the switch proper, and to develop each independently. This marked the birth of the relay.

This new relay was not a new instrument in any sense of the word. The device to operate the automatic circuit-breaker was of the solenoid principle - and the new relays were exactly similar in principle.

The disadvantages of this type of relay have already been described, and the merits of the induction type of relay discussed. This latter type of relay made its appearance in 1902. Its function was to protect against overload. Eleven or twelve years later the torque compensator was incorporated, giving the relay a combination characteristic of both inverse and definite timing - a decidedly important feature.

In the meantime, a reverse current relay was introduced. A period of development resulted in the reverse power relay. It is interesting to note that although patents were granted for this latter relay as early as 1907, it was not until 1916 that the relay was put on the market.

The next major type of relay to appear on the market seems to be the impedance or distance relay. It is just 10 years old, and has found great favor. It is intended for use on large complicated systems when the application of overcurrent and directional relays is either extremely difficult or impossible, and has the further advantage of guaranteeing very fast operation, involving a minimum of time delay.

This impedance relay, although popular on this continent, appears not to have found favor with the Europeans. They have, in fact, gone a step further, and have used the reactance relay extensively. These reactance relays are now being manufactured here as well.

Balance relays, loosely named differential relays, are extensively used today, and appear to have a promising future as the fundamental principle behind more elaborate schemes, such as those using pilot wires or carrier currents.

A representative list of relays manufactured today is given as an indication of the multiplicity of uses to which they may be applied: overcurrent relays, directional relays, selective differential (better known as balance) relays, impedance relays, reactance relays, temperature relays, reverse-phase relays, voltage relays, power relays, polarity-directional relays, transfer relays, periodic reclosing relays, thermostatic relays, phase-balance relays, service-restoring relays, frequency relays and ground relays.

It is desirable to operate a power system in various combinations because of the saving of copper, better regulation, greater flexibility and most important of all, to give assurance against service interruptions. At least two lines should be run to an important load center, so that a failure of one does not interrupt any part of the load. To operate in this way without selective and directional relays is practically impossible. I mention that here as an illustration of the need for, or at least a definite use of, numerous types of relays.

DESCRIPTION OF RELAYS

This is not the place to describe the physical makeup of relays. The Relay Handbook and Supplement is as comprehensive a volume as can be found anywhere. A work of this nature need not include the mechanical details of universally known instruments.

METHOD OF TREATING PROTECTION

The Relay Handbook very appropriately points out that "there are two ways of viewing the problem of protecting a.c. systems. From one point of view, there are certain parts of the system to be protected. Each of these parts has certain requirements, and each such part can be studied in detail and the proper method of protection can be analyzed. From another point of view, there are a number of protection principles which have been developed. The advantages and disadvantages of these various principles can be studied, and their particular fields of application defined."

MAIN OBJECT OF PROTECTION

The object of protection is more or less obvious. Preceding pages carry strong suggestions. The object of this particular section is to state concisely the object and expectations of relay protection.

At the outset, we can say that the objects of protection are two in number: (1) the minimizing of service interruptions, and (2) the minimizing of damage to apparatus or equipment.

When we see a sturdy transmission line stretching out into the distance, or watch the never-ending rotation of a generator, we must ever bear in mind that some day there will be a failure - and the questions then arise: what are we going to do about it? - Are we prepared to step in and cut off the diseased part? - Or is the malady to spread and finally overwhelm and mortify the whole? The answer to the last question is obvious.

PROTECTIVE PRINCIPLES

There are, according to the Relay Handbook, 11 protection principles to be borne in mind when contemplating the design of system protection. These are:-

1. Overcurrent - This is the simplest of all the principles to be mentioned, but it has serious limitations. For example, it will never be sensitive to small overcurrents because the current setting must be high to prevent operation on transients.

2. Inverse Time - This is a refinement of number 1; a linear relation exists between current and time to trip. Settings may be made lower, and sensitivity, thereby increased. Transients will not last long enough to trip the relay, but if a slight fault overload persists long enough, operation will result.

3. Definite Time - Modern relays incorporate numbers 2 and 3 in one case to give the familiar inverse definite minimum time relay. Above a certain value of current, the relay requires a fixed length of time to close its contacts, regardless of the magnitude of the fault current. This principle is of great value in protecting radial systems.

4. Directional - In a great many cases, normal current is in one direction, while a reversal indicates a fault. A relay with directional feature may be made very sensitive to reversals while entirely inoperative for normal flow of current. The most popular (and most expensive) base of reference is potential.

5. Differential - This is an exceedingly important type of protection. Briefly, the idea is to balance two currents or two powers. Unbalance means a fault. The principle is applied to the protection of apparatus and lines, but in the latter case if applied to a single line it generally requires a large expenditure of capital, approximately proportional to the length of the section being protected. More will be said of this principle later.

6. Ground or Residual - A more modern term is zero phase sequence current. This principle protects against ground faults only on a grounded neutral system, but is very sensitive since zero phase sequence current only flows for a ground fault.

7. Impedance, or Distance, or Overcurrent with Undervoltage - This principle recognizes the fact that when a fault occurs the voltage rises with distance from the fault, being a minimum right at the fault: the current is substantially the same anywhere in the line. The net result is that a relay of this principle automatically adjusts its time to trip with distance from the fault.

8. Thermal - Principle number 7 is applied to lines only; this one is applied to apparatus only. The application of this principle has already been described. It is incorporated in a relay to protect against damage from heating, and is not concerned with the cause of the overheating.

9. Fault Detection - Due to the high reactance of many sections of systems, it is occasionally the case that fault conditions do not differ greatly from load conditions. Another factor is the wide range of connected generating capacity due to load fluctuation. The relay designed on this principle discovers the presence of a fault by its ability to detect changes in electrical quantities, and having located a fault, transmits such intelligence to the protective relays.

10. Over-and-Under-Voltage - The principle of over - or under-voltage protection could be included in 9 above. The familiar under-voltage release on motor starters is an example of the application of this principle. It may be necessary to install over-voltage relays on generators having poor speed control, for sudden large losses of load are not uncommon. (Such a loss occurs during a short-circuit). These relays might act to cut in field resistance and thus limit the magnitude of the over-voltage.

11. Symmetrical Components - In a balanced system, only positive phase sequence currents flow. Generally, the system will be slightly unbalanced, so that small negative phase sequence currents will flow. Any marked increase in this current will denote a fault, either line to line, line to ground or open phase. This increased current may be less than normal full load current, but by the proper use of filters, the relay element will have applied to it a voltage proportional or equal to the negative phase sequence component. That is, the new feature is the filter - the relay may be of the overcurrent or overvoltage principle.

Zero phase sequence components have been treated in number 6.

APPLICATION TO TWO MAIN SECTIONS

The principles outlined above can be applied to the solution of any problem of protection. Problems of this nature naturally fall into two classes: station protection and transmission line protection. The station may contain generating equipment, or may merely be a substation.

This paper will first deal briefly with the protection of station equipment, concentrating later upon the more difficult problem of avoiding system disruption due to line faults.

PROTECTION AGAINST INTERNAL FAULTS IN APPARATUS

Faults in apparatus are rare, fortunately, but nevertheless protection must be provided. Modern protective schemes remove the faulted apparatus from all possible sources of electrical energy only in case of internal fault. This removal must be accomplished rapidly if repair bills are to be kept low.

Internal faults might be classified roughly as phase-to-phase short-circuits, short-circuited turns, open circuits, and grounds. Experience has shown that most of the internal faults which occur in larger types of rotating electrical apparatus develop originally as a ground from phase to frame. Unless the neutral is grounded, it will be very difficult to detect the fault until it has grown to a phase-to-phase fault.

Neutrals, when grounded, are either dead-grounded, or grounded through an impedance. There are notable advantages and disadvantages for each method, which will appear in the following matter.

The higher the value of impedance in the neutral, the smaller the ground fault current in the apparatus, which reduces the likelihood of damage from such currents and also reduces the shock to the system, lessening the I^2R loss. However, the smaller this current, the greater the voltage stress and the more difficult the protection against ground faults.

Even if the neutral is dead-grounded, it may happen that the ground current is very small. Such a condition exists if the fault is very near the neutral, or if the fault has a high resistance.

We see, then, that adequate ground protection is of primary importance. However, it is also necessary to include protection against phase-to-phase faults where these latter may arise accidentally or develop from a ground fault. This could be provided for by overcurrent relays, but since the current setting would have to be above maximum load current and the time setting higher than others on the system, the installation would hardly be called satisfactory.

By far the best method of protection against internal faults is that provided by the differential or current-balance scheme. Figure 46 shows for one phase a simple differential scheme using an overcurrent relay. The other two phases are similarly protected. As long as the primary currents of the two current transformers are equal, no current flows through the relay. A fault on the phase will upset this balance, causing operation of the relay, and consequent removal of the machine from the bus.

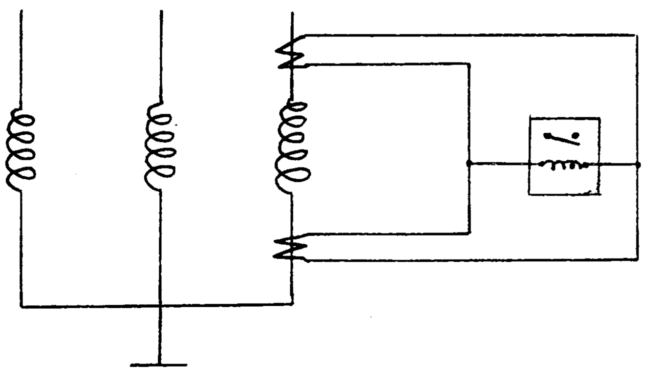

Fig 46

There are several modifications of this scheme. One of the most important is that known as the percentage differential scheme. Its claim for prominence rests on its great sensitivity.

From the brief account of the simple differential scheme, it would appear that it is extremely sensitive. Theoretically, it is; practically, it is not. The trouble lies in the characteristics of the current transformers. Minor variations in their manufacture cause the same primary current to produce slightly different secondary currents. In the case of a heavy through fault ~~the difference~~

the difference is intensified, and unless the overcurrent relay setting is such that the relay does not respond for such faults, incorrect operations will result. This means a sacrifice of sensitivity. Hence the application of the percentage differential scheme.

The new relay has the advantage that its tripping current varies directly with the load current instead of remaining constant as heretofore. This desirable characteristic is supplied by a restraining winding carrying the equivalent of the load current.

This scheme protects against all internal faults but two: open circuit and short-circuited turns. As seen from Figure 47, which shown one phase protected by the percentage differentail scheme, both ends of each phase must be brought out of the machine.

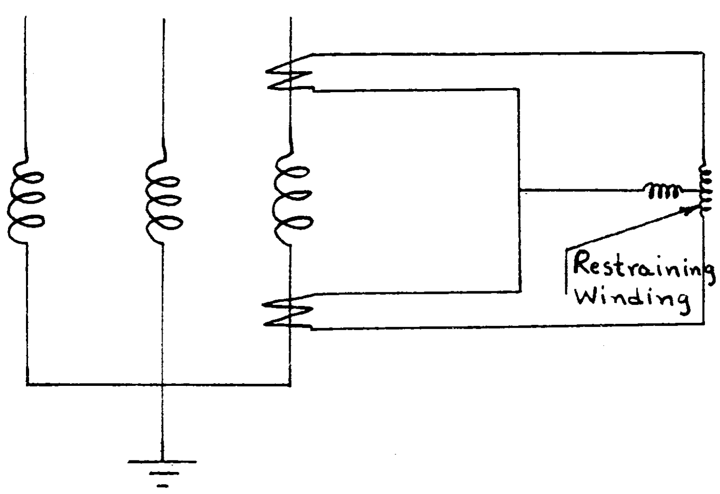

Fig 47

A machine with only one neutral brought out may be protected as well, but requires the further installation of three reverse current relays. In this scheme, the residual line current is balanced in the percentage balance relay against the neutral current. This will protect the generator against any faults involving ground on a grounded-neutral system; the reverse current relays, set to trip for power flow toward the generator, detect phase-to-phase faults, provided that there are other machines in parallel which will feed power back into the fault.

PROTECTION OF PARALLEL WINDING GENERATORS

Large generators are frequently made with the armature conductors connected in two or more parallel paths. Not only is this an improvement from the point of view of design, but such construction lends itself readily to complete internal fault protection, including open circuits and short-circuited turns.

The scheme requires all neutrals brought out, and is familiarly known as the combination of split-conductor with percentage differential scheme. With nine leads brought out, six relays and twelve current transformers are required; with twelve leads , only three relays and six current transformers are required.

In the former case, one set of relays is arranged to operate on a predetermined unbalance between the two ends of each phase winding, just as before, but in addition another set of relays is connected to operate on any unbalance between the two parallel branches. This latter set discovers open circuits and short-circuited turns.

In the latter case (12 leads brought out), because of inherent discrepancies between the electrical constants of each path, there is a decrease of sensitivity to offset in great part the decrease in complication and cost of the relay installation.

GENERAL PROBLEM OF TRANSFORMER PROTECTION.

Small distribution transformers are protected by fuses or automatic circuit breakers.

The larger power transformers in the generating- and sub-stations require relay installations. In the event of an internal fault the transformer must be completely isolated from the system, both from the L. V. and H. V. sides, unless, of course, there is no possibility of back-feed from one side.

The best schemes employ the principles of differential protection. There are, however, special problems. For example, due to the ratio of the power transformer, the primary and secondary currents, that is , the terminal currents, are dissimilar; very often it is impossible to obtain standard current transformers having ratios which will produce equal secondary currents. Also, if a transformer bank is connected delta-star, there will be a phase displacement between the currents in the two phases on the two sides of the transformer. Furthermore, special solutions are required for the protection of three-winding transformers, Scott-connected transformers, etc.

If the secondary currents on the two sides of the transformer differ in magnitude, the relay currents can be equalized by means of current-balancing autotransformers. Also, if the L. V. and H. V. line currents are not in phase, due to the star-delta connection, the secondary currents can be brought into phase by connecting the current transformers in just the opposite fashion: star on the delta side and delta on the star side.

PERCENTAGE DIFFERENTIAL SCHEME OF TRANSFORMER PROTECTION.

In this scheme, the same relays are used as for the corresponding scheme of generator protection. Fig.48 shows the connection for a single-phase transformer. It may be extended for the various three-phase connections.

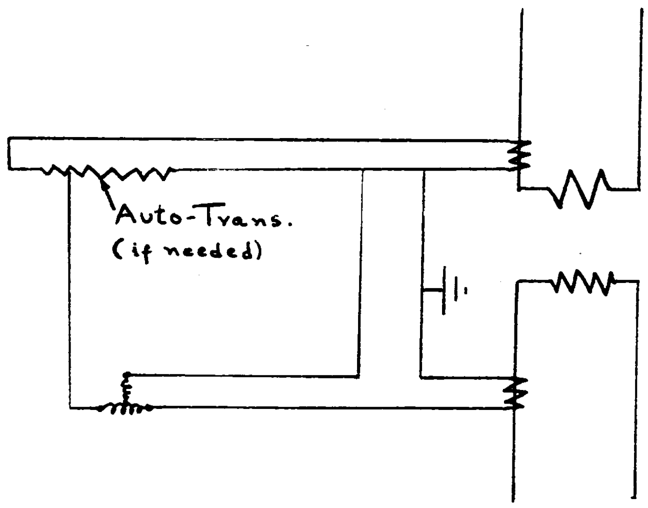

Fig 48

When a transformer is thrown onto a line, there is a rush of magnetizing current, the magnitude of which depends upon the instant that the switch is closed. Fig.49 is an oscillogram of the inrush of a small laboratory transformer. The transformer switch was closed very near the point of maximum voltage, as shown by the 60 - cycle sine wave of voltage, so that the inrush is very near minimum value. We succeeded in taking an oscillogram with the switch closed near the instant of zero voltage, but the current wave for the first half dozen cycles ran way off the film.

In order to prevent this magnetizing current from operating the relay, it has been found necessary to construct the relays so that with zero load current they will not function on an unbalance of less than 25 to 50 per cent of normal full load current. This operates to decrease the sensitivity somewhat, but not to a serious extent.

Follow p. 93

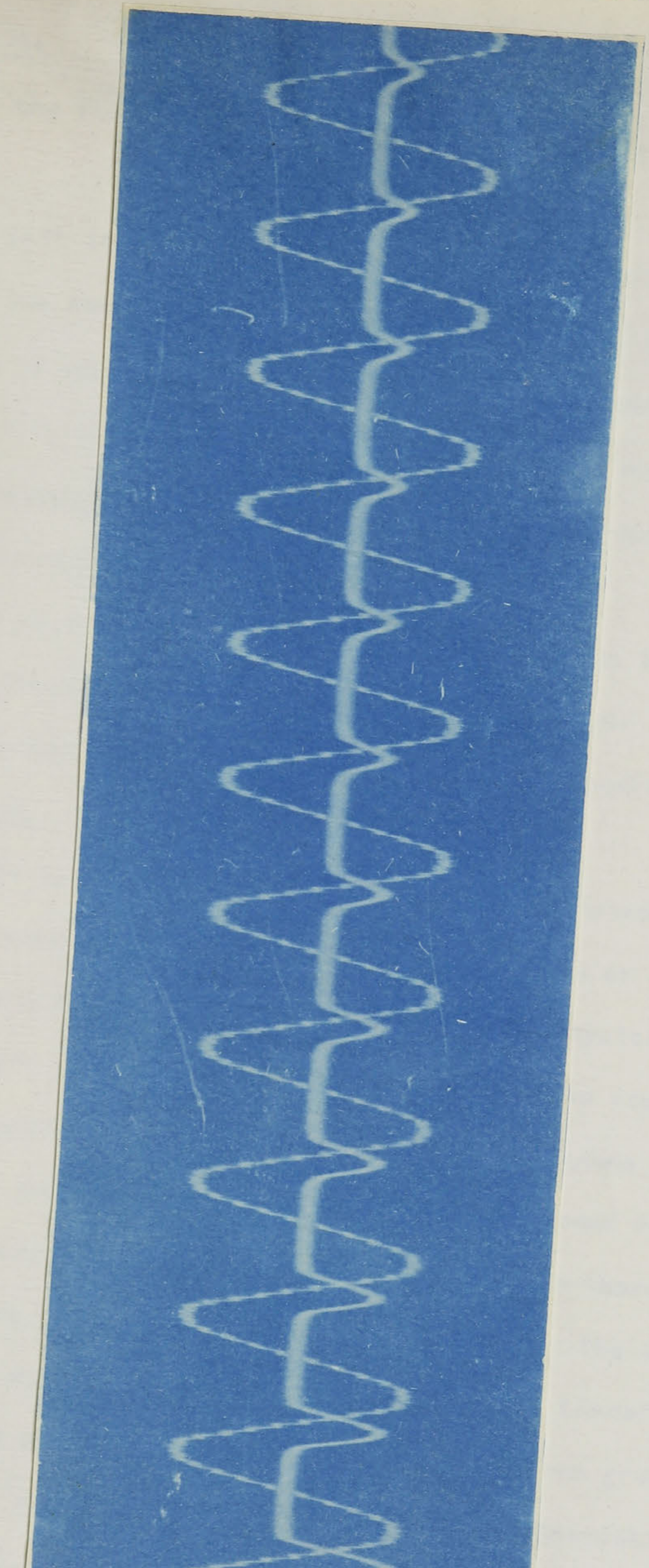

Fig. 49

BUS PROTECTION.

This is the final item in the discussion of station protection to be taken up here.

"In the past it has not been the general practice to provide relay protection for the main bus sections in a station, as bus faults are seldom experienced, due to the method of construction and design of the bus installation. In recent years, however, there is a tendency to install some type of protection due to the large amounts of connected KV-A capacity, especially since most of the protective schemes for the rest of the system exclude the bus."

Buses are physically short so that bus protection is not radically different from machine protection. There are two general schemes of bus protection: one is the fault bus scheme, the other is a version of the current balance scheme.

FAULT BUS SCHEME.

This scheme is particularly well adapted to isolated-phase stations, i.e. stations where each phase is run into a separate room or chamber, so that a phase-to-phase short-circuit without involving ground is physically impossible. Well-grounded buses are placed in the vicinity of the phase conductors, being connected to the metal supports and shielding parts of the switches and circuit-breakers. The idea is that any fault current will not go to ground directly, but will enter this parallel grounded bus - the fault bus - and from there will flow into the ground through the primary of a current transformer. The current in the secondary operates to trip an overcurrent relay. This scheme, therefore, requires that all the protected and associated circuits be insulated from ground. The major disadvantage of this scheme, then, is the high cost of insulating metal parts from the building steel.

This is often called protection by proximity. Fig.50 shows the scheme diagramatically.

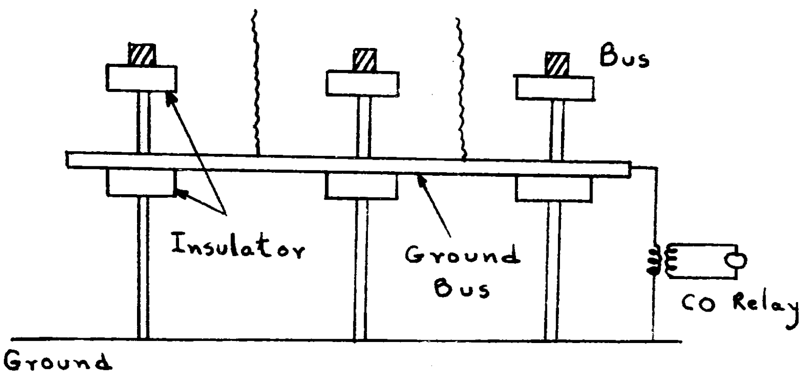

Fig 50

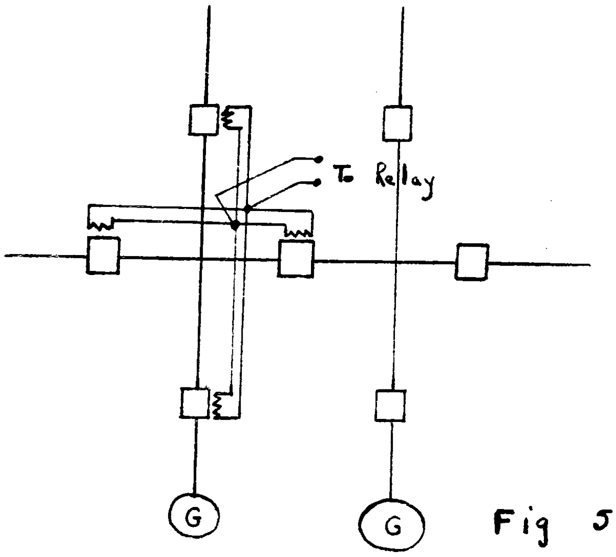

Fig 51

DIFFERENTIAL SCHEME OF BUS PROTECTION.

Although generally applicable, this scheme is particularly suited to the protection of a bus with a variable number of feeders. Each of the feeders is equipped with a current transformer, and the secondaries are paralleled. The vector sum is normally zero whether or not all of the feeders are alive, but a ground fault produces unbalance and the unbalance flows through an overcurrent relay. See Fig.51.

This scheme of protection may be used with relays of the percentage-differential type. The current transformer secondaries from the out-going feeders are connected in parallel and then through the relay to the current transformer secondaries from the incoming feeders, also in parallel with each other.

STATION PROTECTION CONCLUDED.

The above descriptions of methods of station and apparatus protection was made brief and therefore incomplete. Most of the fundamental methods were described, but the list is not complete. It is frequently found necessary, in practical installations, to modify a method, so that almost any scheme may have a variety of versions. In every case, however, the fundamentals remain the same.

THE GENERAL PROBLEM OF TRANSMISSION SYSTEM PROTECTION.

Generally speaking, it is more difficult to protect a transmission system than to protect station apparatus. In recent years the problem has been attacked vigorously, and many modern schemes display ingenuity and ability on the part of the engineers involved in the problem. It is very noticeable, from the literature on the subject, that only the largest and richest companies have made marked progress in the relay art. But this is to be expected, because only the large companies are forced to improve their protective schemes. Furthermore, new relay installations are decidedly expensive, and unless the system is expanding, the expenditure may not be justified.

Two of the most important factors influencing the general problem of protection of transmission systems are length of lines and complexity of interconnections. These two variables are virtually unknown in station protection.

UNGROUNDED AND GROUNDED NEUTRAL SYSTEMS.

Alternating-current transmission systems may be divided into two general classes:

First, those having the neutral insulated from ground.

Second, those having the neutral connected to ground metallically.

The second classification may be further subdivided into two groups known as solidly-grounded neutral systems and systems grounded through impedance. This impedance may take the form of a resistor or reactor.

SOLIDLY-GROUNDED SYSTEMS.

Such systems may have short-circuits involving ground, and short-circuits not involving ground, the majority of them falling into the class of unbalanced faults. When considering this type of system, it is generally assumed that the ground resistance between the neutral and the fault is comparitively low, so that it does not decrease the value of the short-circuit current by any great amount.

Inasmuch as the reactance component of the system impedance under fault conditions usually is considerably larger than the resistance component, it follows that the effect of the ground resistance upon the total fault current is reduced. In particular locations, it may happen that the above generatisation does not hold true, and ground resistance may be an important factor.

UNGROUNDED SYSTEMS.

Such systems have phase short-circuits as before, but a fault to ground does not produce a short-circuit. In fact, in a small system such a fault often goes unnoticed, since it produces little disturbance. This does not hold for extensive systems where large charging currents will flow into the fault.

When a phase becomes grounded, the voltage to ground of each of the other two phases automatically rises to $\sqrt{3}$ times its previous value. These phases therefore carry a higher charging current. The charging current for a fault to ground may be considered ~~as~~ due to the condensers pictured in Fig.52. It is often taken as equal to twice normal charging current.

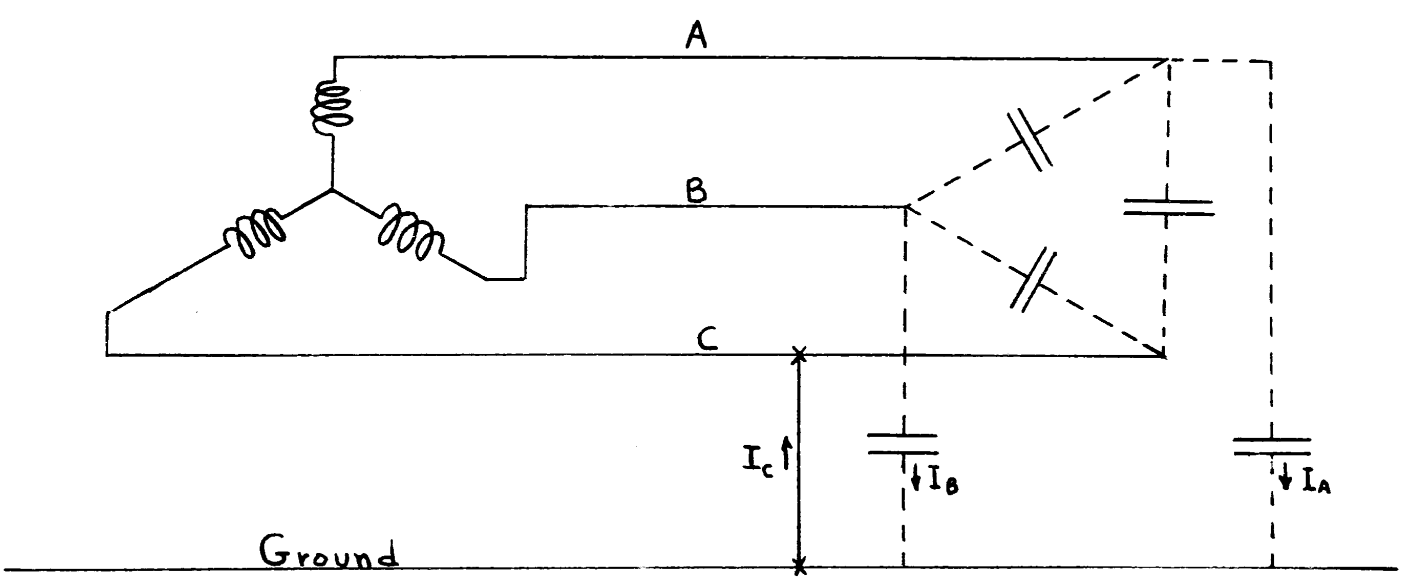

Fig 52

NEUTRAL GROUNDED THROUGH IMPEDANCE.

As already seen, a fault to ground on a small ungrounded system produces so little disturbance that successful operation may be carried on. Very often the faults are temporary, such as a flash-over on an insulator or bushing, and they clear themselves without damage.

In a large system, however, the charging current will maintain such an arc, and considerable damage will result. Therefore, on large systems protective relaying must be applied, and most often this means grounding the neutral. For this reason, and others to follow, ungrounded systems are becoming increasingly rare. Those which were built originally as ungrounded systems have been found to be very unsatisfactory from the point of view of protection as development progressed. Wholesale change-overs resulted.

Most often the power company would like to ground the neutrals solidly. This invariably brings the telephone companies' engineers down in a mob, all complaining of inductive interference, acoustic shocks, and the like. This leads to the inclusion of impedance in the neutral conductor. As far as system stability is concerned, this is an improvement to the power company as well, because smaller short-circuit currents produce less disturbance on the system. It tends, however, to make adequate protection more difficult.

One of the benefits of grounding is the decrease of strain on the line insulation due to a ground fault on another phase. The voltage no longer rises $\sqrt{3}$ times.

There are arguments both for and against the use of resistors as compared with the use of reactors in the neutral leads. The latter are cheaper, but the resistor lends itself readily to the satisfactory use of directional ground relays, which will be described.

Some day, perhaps not a long time from now, relaying and circuit-breaking apparatus will be so fast in operation that the telephone companies will withdraw their present restrictions with regard to neutral impedance. At this time, however, neighboring telephone lines must be catered to in this respect.

ARC CHARACTERISTICS.

In subsequent discussion, several characteristics of arcs will be referred to, such as for example, its impedance.

Arcs may be from phase to phase or from phase to ground. Very often they start as flash-overs due to lightning. Unless the fault is cleared practically instantaneously, there is grave danger, in a high wind, that the arc will be blown across other circuits. Exhaustive tests were made on a set of parallel circuits each of which was equipped with instantaneous relays. With the wind as low as four miles per hour, it was found that an arc was invariably blown into the other circuits. The arc has no inertia and on a system with large generating capacity it may have almost unbelievable length.

I am told that a year or two ago a substation operator opened a disconnect without first opening the oil switch. Although he was standing 15 feet away on an insulated platform, he sustained very serious burns from the arc that followed, the wind unfortunately being in his direction. This happened on the Southern Canada Power Company's 48 KV system.

Authentic cases are recorded of arcs having a length of 200 feet or more on high voltage lines. Tests made on a 154 KV line of the Southern California Edison Company gave 40 foot arcs for phase-to-phase faults.

Mr. Paul Ackerman has advanced the theory that an arc will follow the characteristic of having an approximately constant value of 400 volts per foot; tests tend to confirm this figure.

POWER FACTOR OF SHORT-CIRCUITS.

From general observations, the impression has developed that short-circuits have a power factor approaching zero. Generally speaking, that is correct. But it is not a hard and fast rule, as recent investigators have discovered. Although there is not yet universal agreement on the subject, nevertheless it appears that if a long length of line is involved, and if the fault resistance and ground resistance values are relatively high, then the power factor may be far from zero.

CLASSIFICATION OF TRANSMISSION SYSTEMS.

From the point of view of protection, it is convenient to divide transmission systems into four classes. They are, in order of complexity:

1. Radial Systems
2. Parallel Systems
3. Loop Systems
4. Networks

RADIAL SYSTEMS.

The simplest system of distribution is one having a single source of power with a number of feeders leaving the generator bus, each feeder in turn being subdivided into a number of small feeders. This constitutes a radial system.

Being the simplest system, it is also the easiest to protect. Fig.53 shows a typical radial system. It is seen that any load has only one source of supply; this constitutes a serious objection to this type of system. Hence the development of other classes of systems.

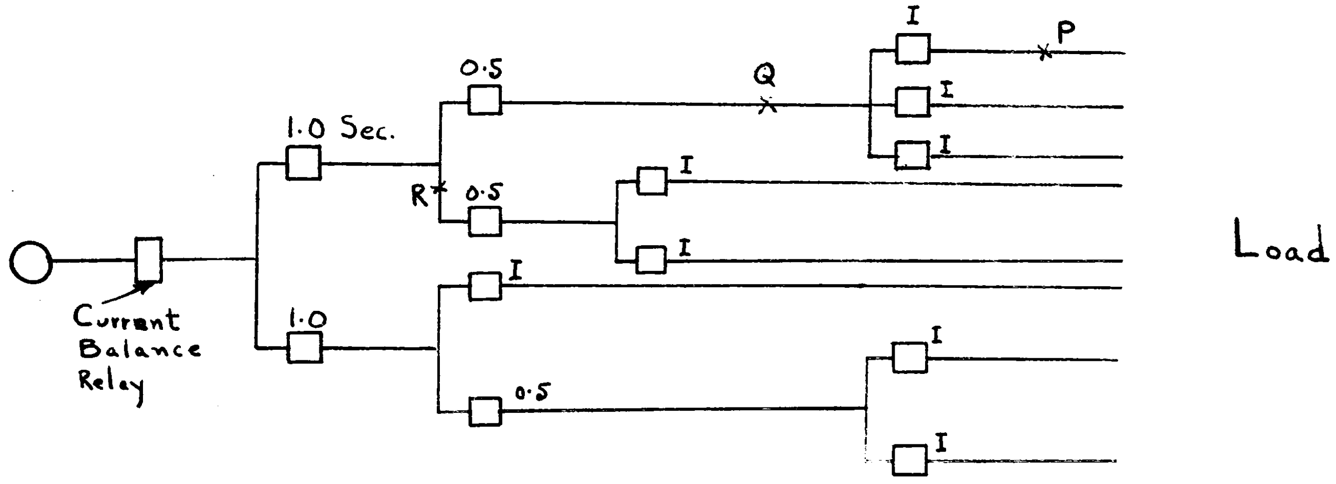

Fig 53

The system in Fig.53 is protected by overcurrent relays with adjustable values of current to trip and time to trip, time being required to provide selectivity. If a fault occurs at P, it will be cleared instantaneously. A fault at Q will be cleared in one-half second, while a fault at R will be cleared in one second. In the latter case five loads would be lost.

Selectivity is possible also by means of current settings, since a short-circuit at P will draw less current than one at Q.

No less that 0.4 second should be used between branches, and the maximum time should not be greater than 2 seconds. All current settings must be greater than full load current.

For ground faults a low energy current relay is connected in the residual circuit of the current transformers. Fig. 54 shows a typical installation.

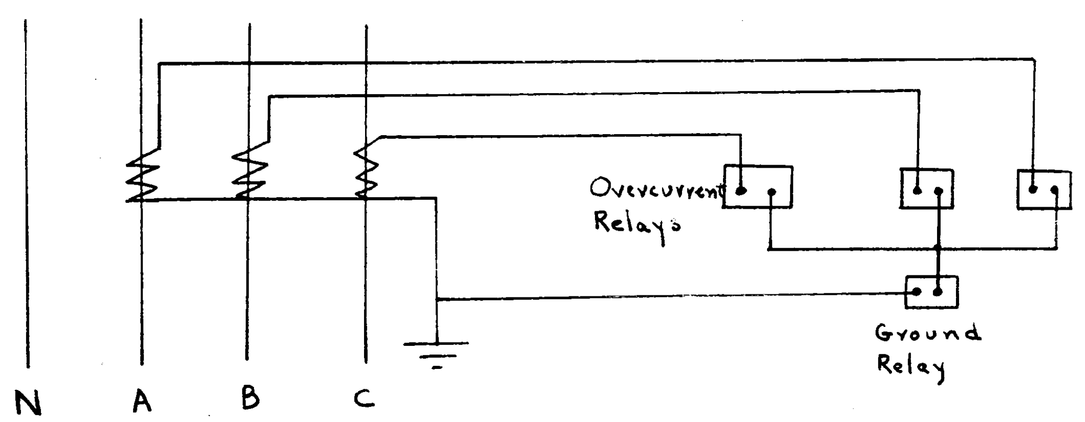

Fig 54

The question arises, what if the system becomes so extensive that the maximum time setting necessary is greater than two seconds? In such an event the system must either be interconnected, or else other types of relays must be installed, such as impedance or reactance relays. The theory behind the impedance or distance relay is very familiar to engineers; it is sufficient to say here that regardless of the position of the fault, the nearest relay will clear it in time proportional to its distance from the fault.

PARALLEL FEEDER SYSTEMS.

Parallel lines or feeders are in very common use because: (1) they are a convenient and economical means of increasing transmission capacity, (2) they form a most flexible system for the economical operation of lines, and, (3) they lend themselves very readily to relay protection. Important loads should have at least two possible sources of supply, and these may conveniently take the form of parallel feeders.

An adequate system of protection will remove a faulted line without disturbing the others, and will, furthermore, leave the other line or lines adequately protected. There are several good schemes in use. A few are described below.

OVERCURRENT AND REVERSE CURRENT RELAY SCHEME.

Fig.55 shows an application of this scheme to two parallel lines. Overcurrent relays are placed at the generating station while reverse current relays are placed at the substation bus.

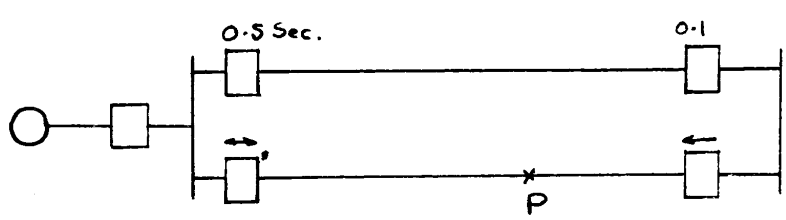

Fig 55

If a fault occurs at P the line is cleared as follows: the reverse current relay on that line operates in 0.1 second before any other relays can operate, and then after 0.5 second the overcurrent relay operates to isolate the line. The time interval is necessary to prevent incorrect operations since the currents in the two lines may not be far different on the occasion of a fault.

The chief disadvantages of this scheme number three. First, voltage for the relay is required which is expensive. Second, the scheme is not instantaneous. (Another scheme reduces the time by using impedance relays instead of overcurrent relays.) Third, high resistance grounds, or single grounds on an ungrounded system are not protected, so that other schemes must be added.

If at least two feeders are sure to be in operation all the time, then a scheme of protection may be applied not requiring the reverse current relay.

DIFFERENTIAL PROTECTION OF PARALLEL LINES.

This scheme is by far the most popular because it is very fast in operation, because it is very selective, and because of several other desirable characteristics.

Suppose two lines carry equal currents. If the currents maintain their equality in spite of their magnitude, it is a good indication that no fault exists in that particular group of feeders. On the other hand, a certain degree of unbalance could be taken as evidence of trouble on the feeder carrying the greater current.

Current balance relays, as the name indicates, balance the line currents. When both currents are equal there is no tendency forthe relay to operate, but when unbalance occurs, the relay operates, closing the contacts on the higher-current line. Relays of this principle can be installed only at generating stations in the case of two lines only, unless another source of power exists at the substation. For this reason, it is usual to install cross-connected directional overcurrent relays at the substation. This scheme may be applied to any system no matter how complex if the feeders are run parallel between the switching points. The relays may be given almost instantaneous time settings, but the current settings should not be below full load current when one line only is in operation.

Another method sometimes known as the short and long time scheme uses two sets of directional relays, but the overcurrent and directional contacts are interconnected so that each directional contact is associated with an individual line, while the overcurrent contacts are common.

One of these elements has a short time setting and the other a long time setting. The first is arranged to be cut out by auxiliary switches on the circuit breakers when either line is open, thus leaving the long time setting in service for single line operation.

PROTECTION AGAINST GROUNDS.

The methods outlined above are for phase faults, but in many cases also provide for ground faults unless the grounding resistance is very high. Most often, however, supplementary ground protection is obtained by inserting a ground relay in the residual lead of the star-connected current transformers, as previously indicated in Fig.54.

The following features are worthy of note:

1. Experience has shown that most faults start as a flash-over or fault to ground; therefore, on a grounded system, the flow of current is a positive sign of trouble. Because of this, ground fault protection is of extreme importance, and has become recognized as a "front line defense against damage caused by fault currents."

2. Zero phase sequence currents flow only during a ground fault. They may be isolated by means of a simple network; the residual currents mentioned above are zero phase sequence currents.

3. Because zero phase sequence currents are normally absent, ground relays may have very sensitive settings.

4. The sensitive settings are really quite necessary, since the ground current may be small due to large impedance in the neutral connections or in the earth return.

5. When ground relays are used, those protecting against phase-to-phase faults can be regarded as providing excellent back-up protection.

6. On many systems, inverse-time over-current residual-current ground relays may be used to provide selectivity, that being nearest the fault operating first.

7. Ground relays are independent, for all practical purposes, of surges due to switching, etc.

8. Ground relays prevent lines down on the ground from remaining energized.

9. Ground relays usually clear up flash-overs before the arc has had time to be blown into the other phases.

GROUND FAULTS ON UNGROUNDED SYSTEMS.

The few remaining ungrounded systems are not, as a rule, protected against ground faults. There is a scheme in existence, however, which acts to throw another ground through a high resistance on a healthy phase, thus creating a short-circuit through ground. This current operates protective relays. If a physical neutral exists, such as that in a star, then the scheme is varied by temporarily grounding the neutral instead of one of the phase lines.

This scheme, naturally enough I think, has not found favor with engineers. It seems to be a step in the wrong direction to throw a ground on a healthy phase, even though it is only temporary. Operating experience indicates that the probability of severe shocks to the system is high.

LOOP SYSTEMS.

The loop system is simply a continuous transmission line running through a series of substations and finally terminating at its starting point. Many high voltage transmission lines are so designed because it is often the most economical from the point of view of first cost, and because it often forms the best way of securing uninterrupted service without extra feeders.

The relay protection of complicated loop systems has been attempted in a large number of ways, but probably none are entirely satisfactory since even the best bring in some time delays.

One scheme uses overcurrent and reverse current relays, as shown in Fig. 56.

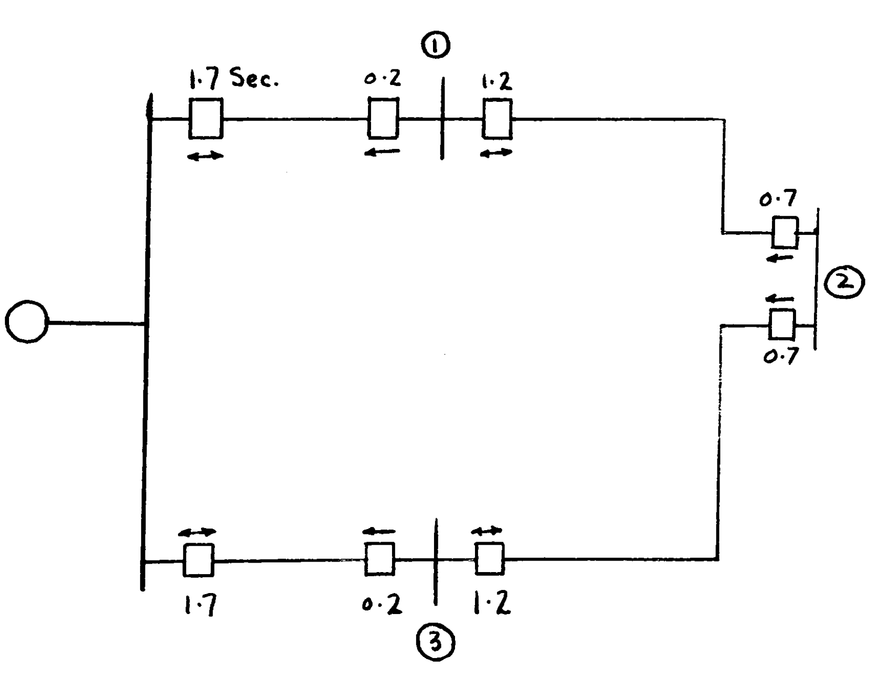

Fig 56

It is seen that even with only three substations in the loop, the time setting on the relays at the generating station must be made as high as 1.7 seconds. And this brings out the great limitation of this scheme.

Aside from that, however, the scheme is regarded favorably for a small number of stations, the more so if low resistance grounding is used, since in that case the scheme also cares for ground faults as well.

The application of distance relays largely removes the difficulty of long time in a considerable number of installations. A directional element is added to the relay main element, and applied to the system exactly as before. The choice between the two schemes is dependent mainly on the cost, the distance relays being more expensive and requiring potential connections.

There are two special limitations of the impedance relay: (1) it cannot be applied to sections of such short length that there is not at least a 4.2% voltage drop between ends of the section with minimum fault current flowing; (2) as usual, the impedance relay is not satisfactorily applicable to the protection of ground faults.

PILOT-WIRE SCHEMES.

Pilot wire schemes have a great disadvantage in that they are very expensive. But they have the advantages of giving fast operation and of being independent of the setting of selective relays protecting the same section. The scheme is ideal from the standpoint of quickly isolating the faulty section of the line. It is especially advantageous in eliminating the difficulty of relaying on complex loops, and, it may be mentioned here, on networks.

The idea of using pilot wires probably developed from a study of the applications of current balance relays. The usual scheme consists of balancing the sedondary currents of current transformers at both ends of the line, but there are several variations.

The first of these is the simple opposing-voltage scheme. The current transformers at the ends of the section of line being protected are connected together in opposition by the pilot wires. Since the transformers are connected star with neutral grounded, it is theoretically possible to operate with only three pilot wires; but because of the uncertainty of the characteristics of the ground return, four wires are generally used.

Ordinarily, no current flows through the pilot wires or current transformers, so that the latter must be specially designed. Also, since no current flows normally, a break in the pilot wire may easily go undetected.

To do away with the requirement of the costly current transformers, another scheme has the secondaries connected in series aiding rather than opposing, so that a small current circulates. A change in this current is translated as indicating a fault. Obviously, if a pilot wire breaks, the relay will open the circuit breakers, while a short-circuit in the pilot wire will prevent operation.

These two schemes both use overcurrent relays. The next step was to apply balance relays with these two schemes - the applications are ingenious and highly satisfactory, but costly.

Recently a new scheme has been put into service in Oklahoma requiring only one, or preferably two, pilot wires. It insures quick isolation on the occurrence of any type of line or ground fault where there is a source of power at both ends of the line section, such as in a loop or network. The circuit may be used simultaneously for telephone communication; the wires are, in fact, leased from the local telephone company.

MAIN METHODS OF OVERALL PROTECTION

There are two main methods of using telephone lines for overall protection, the schemes being given the titles "directional comparison" and "transferred tripping." We are familiar enough with the idea of the first. The relative directions of the fault currents in each end of the line are compared by the telephone line which is arranged to trip both ends of the line when the relation obtained indicates a fault on the protected section. This scheme has an advantage over pilot wires because a telephone line can be provided at less expense than pilot wires. Indeed, most power lines are paralleled by telephone lines either oned or leased by the company for communication purposes.

Figure 57 shows the method of obtaining overall protection by directional comparison. Each of the relays closes when the flow is from bus to line. Normally, therefore, one relay will be closed and one open. If a fault occurs, both relay contacts close, closing A and B. This completes the telephone circuit, so that C and D are closed, and this in turn closes both oilswitch trip circuits.

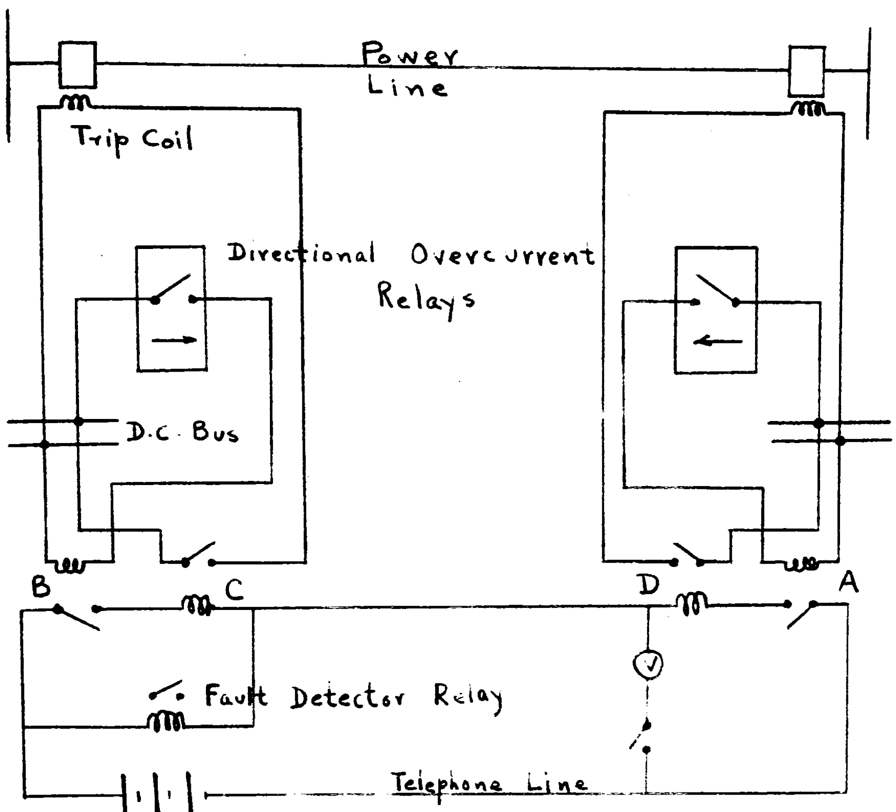

Fig 57

In the case of a source of supply at one end only, the other end is provided with instantaneous overcurrent and instantaneous under-voltage relays with their contacts in series. If the fault is a through one, the current contacts will close, but voltage being maintained on the line, the voltage contacts will remain open. Both sets of contacts close for a fault in the section. Similar arrangements protect against ground faults.

When a system is operating near the stability limit, it is extremely important to clear the fault instantaneously. The method of transferred tripping is applicable as an extension to a selective timing relay system for the purpose of having both circuit breakers open upon the operation of a relay at either end. It assumes, therefore, the presence of a relay scheme to provide instantaneous clearing at one end of the line at least.

The general arrangement for transferred tripping is shown in Figure 58. Generally speaking, the former method is considered more desirable because of cost and complication.

CARRIER-CURRENT SCHEMES

The pilot wire schemes, because of the cost of pilot wires, are applicable only to short lines. Now we know that adequate protection was becoming more and more essential, so that considerable interest was shown in the pilot wire schemes of overall protection of transmission lines - called overall protection because both line ends are tripped instantaneously for all faults on the line but having non-operative characteristics for system faults not on the line. It was evident that this consisted of very selective operation, and thus approached the ideal relay system. But, unfortunately, it was very definitely restricted to short lines. The problem was to discover a new and less expensive method of applying pilot wire principles to long lines.

Well, this was just the old story of a major problem confronting the world's experts in science and technology. The consequent attack produced results, as it was bound to do. Every sane problem is solvable, and most are in the process of being solved. Some require more time for solution than others, partly because of complexity, partly because of lack of experience. Eventually a solution is forthcoming, which in the light of developments may require modification.

The problem being discussed here perhaps cannot be considered solved completely. Nevertheless, great progress has been made in the right direction as must be evident from a study of the telephone line methods given above. The newest scheme applies carrier currents to the problem of transmission line protection.

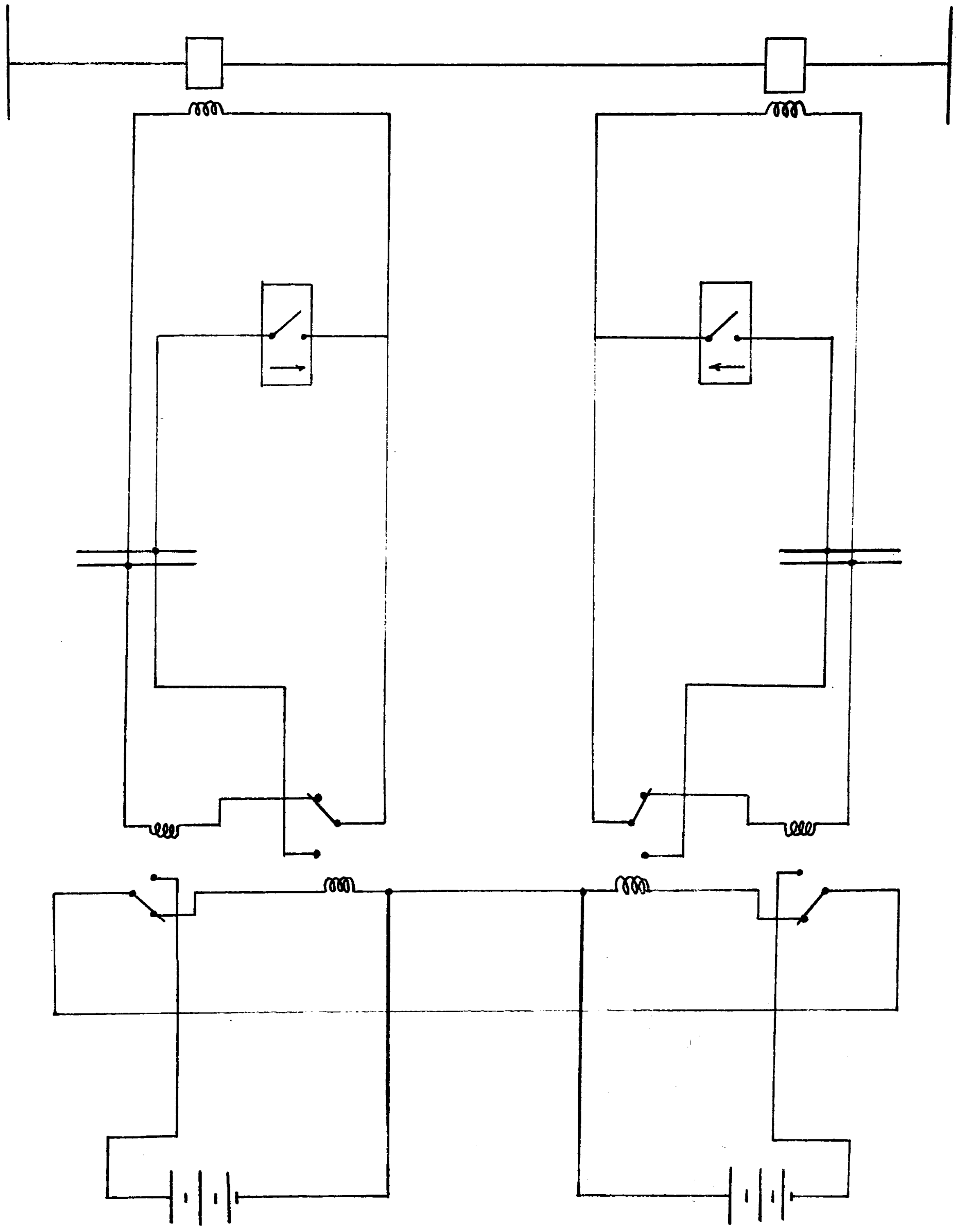

Fig 58

CARRIER CURRENTS

The term "carrier-current" is descriptive of high frequency alternating currents which lie, roughly, between 10 and 200 kilocycles. At these frequencies, the transmission of electrical energy exhibits special characteristics due to which it is possible to superpose carrier-current control circuits on power lines.

The purpose of the carrier-currents is, of course, to do away with the pilot line. The principles might be expected to be exactly the same. It is not, however, desirable to employ exactly similar principles because carrier current is transmitted by resonant circuits so that exact electrical ratios are not always possible of achievement.

In the earliest scheme, the relative instantaneous directions of the residual current at each end of the line were compared by means of the carrier-current equipment, rather than the relative directions of residual current flow. The disadvantage of this scheme was that protection could be obtained only for phase faults or ground faults, but not both simultaneously with the same equipment. It has since been modified to take care of all faults by directional comparison of fault current flow.

A very ingenious system has been devised which balances the instantaneous polarities of the current waves at the two ends of a line section, using the carrier-current.

Under normal conditions, the instantaneous direction of current flow at each end of the transmission line is the same. At the time of fault, however, one end generally becomes zero or reverses. The line current is used to supply plate and grid voltages to three-electrode oscillators. During one half cycle a signal is transmitted from A to B, say, while during the other half cycle, the signal is sent from B and received at A. This carrier-current is used to hold open the contacts of an overcurrent realy. When a fault occurs in the section being protected, the carrier-current receiver at each end is rendered automatically inoperative, permitting the overcurrent relays to function at both ends to clear that faulty section from the system.

Figure 59 shows a carrier-current sbheme. It operates on the principle

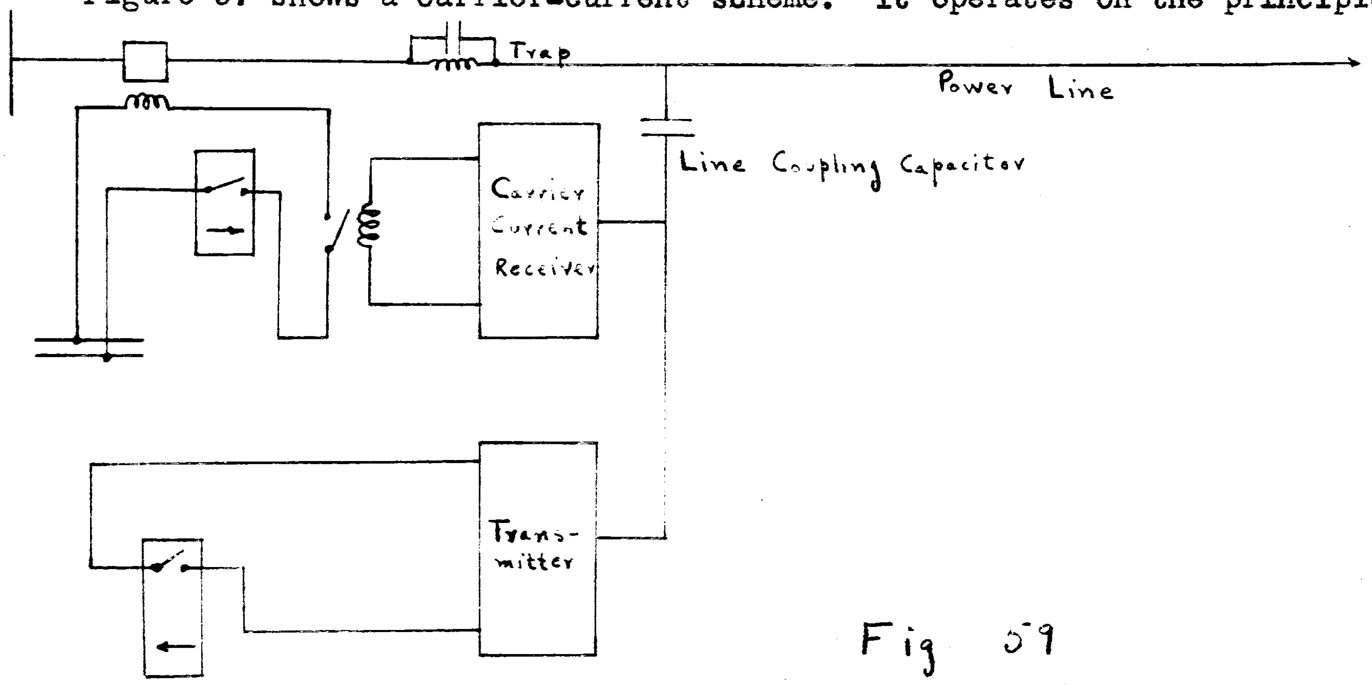

Fig 59

that an interruption of carrier-current indicates a fault. This explains the need for the carrier-current trap. External faults must not interfere with the regular communication.

This particular scheme uses a single frequency of 100,000 cycles. The filaments are kept hot continuously, so that only $3\frac{1}{2}$ cycles are necessary to complete the initial tripping operations.

NETWORKS

The preceding discussion should have demonstrated the fact that the simple radial and loop systems usually lend themselves very readily to schemes of relay protection. When we realize that a network is generally made up of a main loop, subdivided by ties between substations into two or more local loops, it becomes evident that the relay protection problem is much more complicated. Networks do, in fact, require the most involved protective schemes of all the various transmission systems.

Each network is an individual problem. The most successful method of attack is to divide the network into elements, and apply to each element the protective principles and methods appropriate to that element. For example, there may appear parallel, radial, or loop portions, and the treatment for these individual sections becomes readily apparent.

One important reason for the complexity of the problem is the necessity for flexibility and general adequacy. Operating conditions are bound to vary. During periods of light load, for example, it may be desirable to de-energize a tie line. This will cause a new distribution of load while possibly destroying one or more of the network elements.

When designing a system of protection, an eye must be kept to the future. Any scheme put in should be easily adapted to future changes or extensions.

A study of any network will usually reveal certain portions which are much more important than the others. Generating station tie feeders may fall into this class. Their importance may warrant the use of relatively expensive but very helpful pilot wire or carrier-current schemes.

MODERN DEVELOPMENTS AND TENDENCIES

The fundamentals of system protection have been presented. Retracing our steps, we find that a network is the most complicated system of power transmission. Any network usually can be analyzed into component parts, such as parallel lines, loops and the like. At the other end of the scale of complexity we find the radial system, the simplest of all systems in all respects but one: the maintenance of continuity of service after a fault.

Adequate protection of these components is secured by the application of relays designed after certain principles. In discussing protection, one of two methods could have been followed: (1) the known principles could have been described and then applied to all possible components; (2) the components could have been described and all possible methods of protection given. In the present writing the latter method was followed.

So far this thesis has had little or nothing to say about the relays themselves. I assumed that we are familiar enough with the overcurrent and the impedance relay to make a description superfluous. No doubt the literature of 1923 and 1924 on the subject of protection was plentifully scattered with long and joyful accounts of every detail of the impedance relay, but today it is an old story. The average engineer knows the details of the relay and is no longer interested in further descriptions. The relay art has progressed and is progressing. And so we find that although the impedance relay is an old story, nevertheless there are new relays on the market today about which we know very little, if anything. A brief description of something new is always interesting, so I shall mention briefly reactance relays, gasfilled relays, high speed distance relays, and phase sequence relays.

The largest, richest, and most progressive companies try out these new relay schemes and announce their results. Any scheme which definitely proves its worth sooner or later finds a place in the protective scheme of other systems. These new schemes must be regarded as steps in the march of progress so that although the very latest thing out, like our autos, they will probably be traded for something newer and better in the future.

The new relays are designed to care for the most pressing problems. And what greater problem have we than the protection of networks? So we find that relays are being designed for speedy operation to aid and further the tendency for networks - networks because they offer the best guarantee for continuity of service.

REACTANCE RELAYS

The first relays of this type to be put into service on this continent were installed early in 1930, just three years ago. The reasons advanced for the installation were:

1. A short-circuit at the end of a long section could be lower than normal load current.

2. The opening of a section under fault frequently required the adjacent sections to carry as much as twice normal load current.

3. Overcurrent relays were definitely inadequate.

4. Distance relays were found suitable, but reactance measurements were preferred to impedance to avoid the difficulties of arc resistance.

One of the chief difficulties in applying reactance relays is the wide variation in power factor during load swings.

A mathematical analysis shows that the apparent impedance to a fault equals the true impedance to the fault, plus the fault resistance plus a resistance times a vector. This latter term therefore has a reactive component, so that although not generally recognized, an arc has some reactance - and this reactance may sometimes be positive and sometimes negative. The effect, of course, is to make the fault appear further or nearer, respectively. Hence the reactance relay cannot "be applied indiscriminately as a cure-all for the effects of fault resistance."

GASFILLED RELAYS

The vacuum-tube industry has made such wonderful progress that it seems certain such tubes will soon be applied to system protection.

The gasfilled relay is essentially a three-electrode gas-discharge rectifier in which the large rectified output can be controlled by the application of a minute amount of energy to a controlling electrode. The presence of the gas gives the tube the characteristic properties which makes it of practical value.

In the August 1932 issue of the English G.E.C. Journal several applications of the gasfilled tubes are described, such as switching, measurement of transients, permanent indication of a transient regardless of cause or duration, etc. In the event of an overload, the gas-filled relay may be used in conjunction with a contactor to open the circuit.

There are several difficulties yet to be overcome but work is progressing rapidly.

HIGH SPEED DISTANCE RELAY

This new relay, named HZ by the Westinghouse Company, truly acts in a "split second". They operate in a single cycle, one-sixtieth of a second, and base their decisions upon the comparison of the instantaneous values of fault current with voltage drop from the station to the short circuit. This measures impedance and automatically provides selectivity.

Figure 60 shows the time characteristic of the HZ relay.

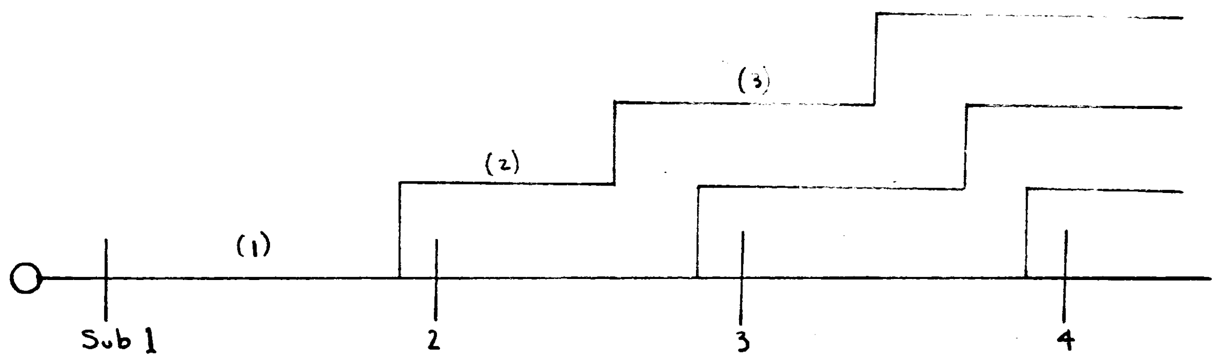

Fig 60

The time does not increase directly with distance from the fault, but instead increases by definite amounts at definite points. In zone (1) the relay operates in one cycle or less. In zone (2) the relay operates at a definite time delay depending on the relay setting. Zone (3) provides back-up protection for the next section.

PHASE SEQUENCE RELAYS

Electrical Engineering literature to date (March, 1933) makes mention of only one installation of Sequence Relays, and that was in New York on a 13.8 KV network feeder system.

There was a particularly good reason for the installation. It had to do with the network protectors. The protector is a circuit breaker with necessary relays, and is located in each of the feeds to the network. Now it is a fact that in certain localities each of these protectors operate needlessly several thousands of times each year due to current reversals caused by regeneration and the like. This huge number is due to the small reverse setting on the relays. In the majority of cases, I repeat, the operation was needless - and furthermore, it was harmful, because of wear and because of the removal of a supply source which should be available at all times.

The new relay: (1) checks phase sequence; (2) checks any interchange of phase wires on the supply feeder; (3) connects the protector to the network only when power will flow from the feeder; (4) prevents "pumping"; and (5) permits closing in on a de-energized network.

The relay consists of a single induction-disk directional element and two overcurrent elements supplied by positive phase sequence voltage and current filters. Selective and sensitive tripping is given by combined operation of these elements.

Practically all power reversals, other than those resulting from a fault, are balanced. A fault or an unbalanced load acts as a source of negative phase sequence current. Therefore, if the above combination is supplemented by an overcurrent relay supplied with negative phase sequence current, then the protector will open only on unbalanced or fault reversals on the H.V. feeder. This aid is actually employed.

The above material is a very sketchy account of the new relay. Needless to say, numerous problems were encountered which had to be overcome, and no doubt plenty more will arise. In the meantime, the installation appears to be very satisfactory - but it must be expensive!

APPENDIX A

VOLTAGE SUPPLY TO DIRECTIONAL AND DISTANCE RELAYS

The necessity of a supply of voltage was mentioned when discussing directional and distance relays, but nothing was said of the method of supplying the voltage to the relay terminals.

A vital requirement for these relays is a reliable and adequate supply of voltage to represent accurately the primary voltage, not only in magnitude but in phase as well.

The problem is not difficult when the primary voltage is low, but it is much more difficult to obtain, at a reasonable cost, the required accuracy, volt-ampere output, reliability, and immunity from insulation when the voltage is high, say 110,000 or 220,000 volts.

There are several units on the market to supply suitable voltage from such sources, and they can be divided into three types according to the manner in which they function.

1. Potential Transformers. - This unit is simply a specially designed potential transformer connected directly to the line to be protected. There are several important advantages and disadvantages for this type of supply.

An American engineer writes: "Potential transformers are the best and most economical form of potential supply, in the long run."

An English engineer writes: "It is the opinion of many engineers that the mere fact of connecting directly to a high-voltage network a primary winding of a voltage-transformer consisting of a large number of turns of comparitively fine wire forms a weak link in the insulation security of the network as a whole." He concludes his paper by choosing the third scheme, mentioned below, to the exclusion of this one.

2. Voltage Compensators. - This method utilizes a potential transformer, connected to the low-voltage side of a power transformer, the high side of which is connected to the transmission line or network. The voltage drop due to the load or fault current flowing in the power transformer is taken care of by a compensator.

This unit has not found general favor because of the following disadvantages: (1) the compensator is not accurate under short-circuit conditions; (2) for this reason it is not suitable for supplying directional and distance relays; (3) it requires complicated connections; (4) its accuracy cannot be experimentally determined until the whole equipment involved is in commission and can be subjected to short-circuit tests on site.

3. Capacitance Couplings. - This is the unit most popular in England: it is also in extensive use in America.

This unit has a coupling condenser which is connected directly to the high-voltage line to be protected. The current is used to energise an auxiliary transformer, and this in turn supplies potential to the relay.

The coupling condenser may be constructed upon the same lines as standard condenser-type bushings, hence the descriptive term "bushing potential device."

The advantages claimed for this unit are: (1) they are accurate within their ratings; (2) they are cheap; (3) the risk of insulation breakdown is negligible, since the only portion connected to the high-voltage line is the condenser bushing itself; (4) because of this there is no need for costly high voltage fuses, resistors and switches.

The disadvantages commonly put forward are: (1) high cost of adjustment and test after installation; (2) a change in secondary loading at any time requires about as much work as the initial test and adjustment; (3) the volt-ampere rating is definitely limited, being wholly inadequate for certain relays; (4) there is a fairly large phase angle error at low voltages. The very best units to date have an error not greater than 20 per cent at 10 per cent of normal operating voltage; (5) an installation of this nature must be devoted entirely to the service of the relays, so that synchroscopes, voltmeters, frequency meters, watthour meters, etc., require another source of potential, regularly supplied by potential transformers.

APPENDIX B

PHASE SEQUENCE MEASUREMENTS

When describing the application of phase sequence principles to the protection of transmission lines, I mentioned the fact that a scheme in existence uses "an overcurrent relay supplied with negative phase sequence current", but I did not indicate how this electrical quantity could be obtained. I shall give here a brief description of appropriate networks.

Several different transformer connections and networks may be used to measure some of the sequence quantities.

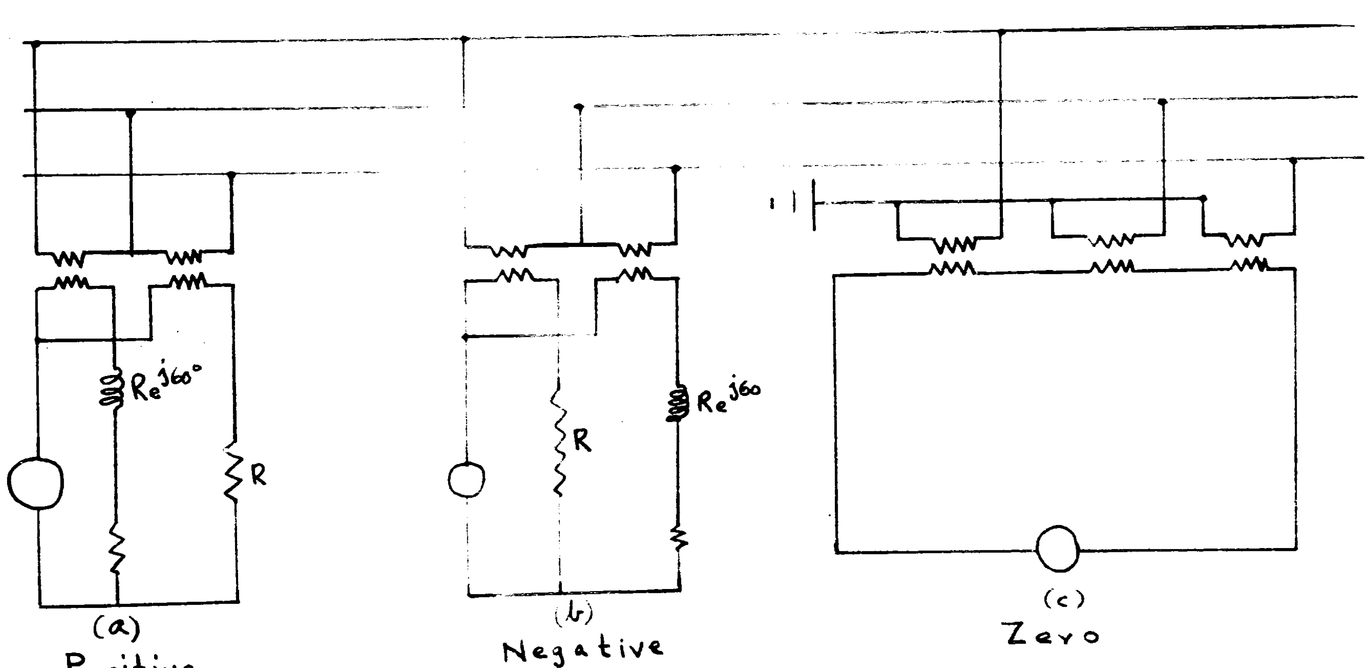

Fig 61

Figure 61 shows the various voltage sequence networks. In each case, a current flows through the measuring device which is directly proportional to the sequence voltage. In (a) both negative and zero phase voltages have been eliminated, the latter by the use of delta voltages. The fundamental condition is that the impedance in the phase which leads by 120° shall have a phase angle 60° greater than that of the other impedance.

In (b) the resistance and impedance branches have been interchanged; this is precisely what should be expected from a knowledge of the difference between positive and negative phase sequence quantities.

In (c) we see the old familiar residual voltage measurement.

Should phase sequence currents be desired, then suitable networks can be designed; they are as simple as those shown in Figure 61.

APPENDIX C : Typical Relay Application

It may be well to state at the outset that in most systems so many complications are present that it is usually impossible to secure a perfect scheme of protection. Before any one scheme can be applied, the system must be studied very carefully indeed, by making short-circuit calculations, etc.

The subject of this Appendix could easily make up the body of a complete thesis if gone into thoroughly. Without delving too deeply, I shall outline below a typical application to a network with one power-house and a number of substations. Only by means of short-circuit current studies may definite current and time settings be made, but preliminary studies are possible.

Figure 62 is a schematic diagram of the system to be protected. It is entirely imaginary.

Either one of two schemes may be applied: (1) the overcurrent reverse-current scheme, or (2) the directional impedance scheme. Very likely both could be used advantageously, but this discussion will deal with the first-mentioned.

In working out the scheme a time interval of 0.5 second will be allowed between successive settings, and care will be taken to keep the maximum time as low as possible.

At first glance the system looks complicated. But consideration shows that it is really a loop system with a tie line, No. VII, and an additional feeder, No. III.

Because there are six substations in the loop, the maximum time-setting of the relays at the generating station would be 3.1 seconds allowing 0.1 second for the instantaneous relays. This is too high: about

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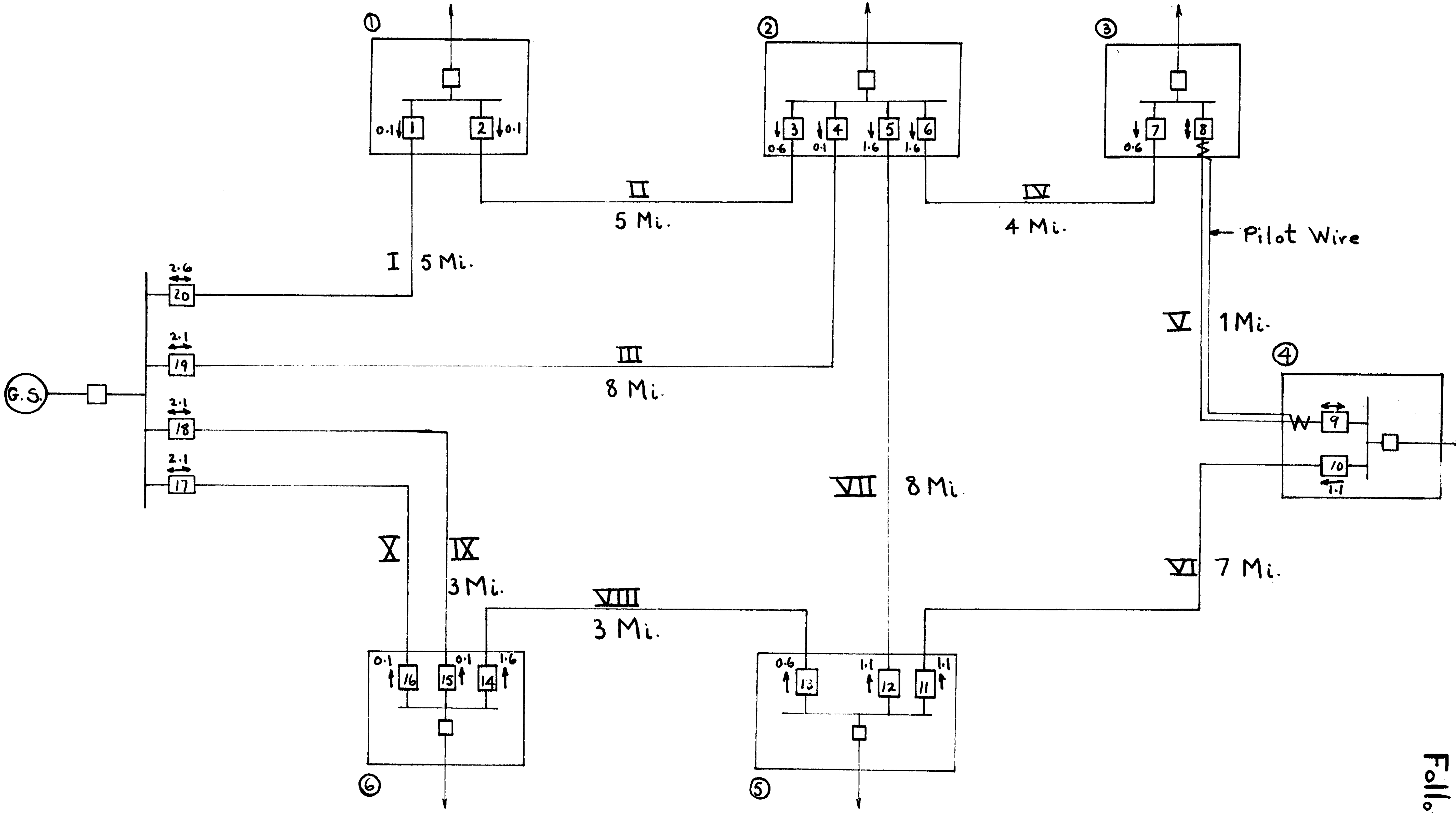

Fig. 62

2 seconds is the maximum permissable. The obvious solution is to cut the number of stations in the loop to four. This can be done in this particular system by dropping substation (1) from the loop, using No. III as the loop line, and by applying a pilot wire scheme to the very short line, No. V.

The following time settings may now be assigned with the knowledge that the reverse current relays are to be so connected that the directional element contacts will close only when excess current flows from the substation bus.

Beginning at substation (2), relay 4 is set to trip instantaneously for power flow away from the bus and is marked 0.1 second. Relay 7 is then set for 0.7 second, relay 11 for 1.1 seconds, relay 14 for 1.6 seconds and relays 17 and 18 for 2.1 seconds. The last two relays need not have directional features.

Now, going around in the opposite direction and starting at substation (6), directional relays 15 and 16 are given instantaneous settings. Relay 13 is set for 0.6 second, relay 10 for 1.1 seconds, relay 6 for 1.6 seconds and relay 19 for 2.1 seconds, the last non-directional.

Settings for relays 5 and 12 at the ends of the tie line, No. VII, must now be determined as well as those on lines I and II.

There is no definite rule to follow in order to establish the best values of time setting for relays 5 and 12. Very often the settings are made short so that on excess current the line opens up quickly, leaving thereby a simpler system to protect in the periods of stress. The following settings are satisfactory: for relay 5 a time of 1.6 seconds; for relay 12 a time of 1.1 seconds - both for excess current from the bus.

Having gone so far, substation (1) may now be taken care of by assigning to relays 1 and 2 an instantaneous setting as shown, to relay 3 a time of 0.6 second and to relay 20 a time of 2.6 seconds.

There are several variations of the above scheme. All the relays may be replaced by impedance or distance relays, nondirectional and directional features being included where necessary, just as above. The two parallel lines, Nos. IX and X, may be further protected by current-balance relays installed at each end. Then a fault on either line will be removed instantaneously and the overcurrent scheme will provide back-up protection.

In order to check the settings, faults will be assumed on each of the lines in turn.

I - Relay 1 will trip in 0.1 second and 20 in 2.6 seconds. It will be noticed that a suitable division of current is assumed from lines III, IX, X, so that none of these lines will be overloaded heavily. In the final analysis it is expected that the relays on these lines will operate selectively with relay 20 by means of their current settings.

II - Relay 2 will clear in 0.1 second and relay 3 in 0.6 second. Relay 7 also has a time setting of 0.6 second, but the current through this line to the fault would be a fraction only of the fault current, because of lines III and VII. Here again selectivity is obtained by current settings.

III - Relay 4 will clear in 0.1 second and relay 19 in 2.1 seconds, being selective with 17 and 18, etc., by means of current differences.

IV - Relay 6 will clear in 1.6 seconds and 7 in 0.6 second. If the current in VII is heavy enough to give relay 12 its definite minimum time of tripping, then 12 will open too, but although this removes VII from service it does not seriously affect operation.

V - Faults on this line will be cleared instantaneously.

VI - Both 10 and 11 will clear in 1.1 seconds.

VII - Relay 5 will operate in 1.6 seconds, being selective with 2 and 7 by means of current differences. Relay 12 will open in 1.1 seconds, being selective with 2, 7 and 10 by means of current differences.

VIII - Relay 13 will operate in 0.6 second and 14 in 1.6 seconds.

IX and X - One end of either line will clear in 0.1 second and the other in 2.1 seconds.

The preceding discussion of variously located faults demonstrates the great difficulty - if not impossibility - of planning adequate protection without a knowledge of the fault currents and their distribution. Once these currents are known, the time of operation of the relays may be found from the relay time-current curves.

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