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Polarizing Sources for Directional Ground Relays

POLARIZING SOURCES FOR DIRECTIONAL GROUND RELAYS

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INTRODUCTION

Directional ground relays require that a reference quantity be established in order for the relay to determine the direction of the current flow at the relay location. This reference quantity is referred to as the polarizing quantity and for directional ground relaying it may be either zero sequence current or voltage. It is against this reference that an operating quantity is compared. The operating quantity will in all cases be proportional to and derived from the line current at the relay location. Illustrated in Figure 1 is a typical transmission system showing the relative direction of the line currents at breaker A for various faults on the system. The line current for a fault at Fl will appear to be in the opposite direction to the line current for a fault at F2 or F3. The line currents will reverse as a function of the fault location, therefore it is imperative that the polarizing quantity remain fixed in direction if the relay is to operate correctly. If the polarizing quantity were to reverse in direction, the relay could be fooled and false operation may be the result. The major problem in applying directional ground relays therefore lies in selecting a stable polarizing quantity. It is also necessary to assure that the quantity will be of ample magnitude to assure relay operation. It is the purpose of this paper to discuss polarizing sources, the different schemes available, the problem pertinent to each and to provide a concise grouping for commonly used schemes.

Zero sequence directional ground relays were originally designed in which either current polarization alone or voltage polarization alone were used. Subsequent static as well as electromechanical directional ground relays were designed so that either current polarization or voltage polarization or a combination of both may be used. When current alone is used as the polarizing quantity the relay is said to be current polarized. When voltage alone is used as the polarizing quantity the relay is said to be voltage polarized. When both types of polarization are used the relay is said to be dual polarized. Certain advantages, to be discussed subsequently, are gained by using dual polarization.

Present multi-function static analog and digital relays offer negative sequence directional functions which are used to provide directional control of zero sequence overcurrent functions. This technique and its advantages will also be discussed later.

CURRENT POLARIZATION

Current polarization may be used at those points in the system where power transformers having suitably grounded neutrals are located. The polarizing current may be obtained in a number of different ways, among which are:

1. Current transformer in the power transformer neutral
2. Current transformer(s) in the tertiary of the power transformer
3. Various combinations of current transformers located in the high side, low side or neutral of the power transformer.

It should be noted that although there may be a neutral grounded transformer available, a suitable source of polarizing current may or may not be present depending on the transformer arrangement and/or system conditions.

Figure 2 illustrates typical two winding transformer arrangements. The neutral current in the delta-wye arrangement shown in Figure 2A proves to be suitable as a source of polarizing current. A single CT located in the transformer neutral is used to obtain the polarizing current from the residual current $3I_0$, For system ground faults on the wye side of this transformer the zero sequence current will always flow up the power transformer neutral. Faults on the system on the delta side of this transformer will produce no zero sequence current in the neutral of the wye winding.

A bank connected wye ungrounded-wye grounded is illustrated in Figure 2B and this transformer arrangement does not provide a suitable source for current polarization because it will not pass nor is it a source of zero sequence current. It has been assumed that the bank illustrated in Figure 2B does not have a tertiary. However, if core type construction is used in the bank, a phantom tertiary may exist and the presence of the phantom tertiary may make the neutral suitable for polarizing purposes. The manufacturer of the bank in question should be consulted if this type of application is being considered.

Figure 2C illustrates a wye grounded-wye grounded transformer bank without a tertiary. Here it is possible for currents to flow in both of the neutrals for ground faults on either side of the transformer bank. Such a bank is not a suitable source for polarizing zero sequence directional ground relays for the following reasons. Consider a fault on the high voltage side of the bank in which the current will flow up the neutral on the high side and down the neutral on the low side. Now consider a fault on the low voltage side of the bank. In this case, current will flow up the neutral on the low voltage side and down the neutral on the high voltage side. This is just the opposite of that which occurs for faults on the high voltage side of the bank. Thus, the neutral currents on both sides of the transformer bank will reverse for faults on one side as opposed to the other side of the bank and a relay connected to a CT located in either of the neutrals will be unable to determine correctly the direction of the fault. In some cases involving power transformers having two grounded neutrals, it is possible to obtain a suitable polarizing current by parallel connection of CT's located in each of the neutrals. The CT ratios must be inversely related to the turns ratios of the power transformer windings having the neutral CT's. However, CT ratios selected on that basis will, in the case of the two winding transformer shown in Figure 2C, result in zero current to the polarizing circuit of the relay for all system faults. Therefore, the neutral currents of the power transformer bank illustrated in Figure 2C cannot be used as a source of polarizing current. Here again, if the bank is of core type construction, a phantom tertiary may exist. The bank will then be similar to the three winding bank to be discussed subsequently and shown in Figure 4 and it may be possible to obtain a suitable polarizing current with CT's located in each of the neutrals and connected in parallel. Refer to the transformer manufacturer if this type of application is being considered.

Three winding transformer banks are frequently encountered in sub-stations and these too can often be used as sources for polarizing currents. Figure 3 shows a typical three winding transformer arrangement that is suitable for use as a current polarizing source. Illustrated is a wye undergrounded-delta-wye grounded transformer bank and the CT connections required to obtain the polarizing current. For system ground faults on the wye grounded side of the bank the neutral current will always flow up the neutral. The delta connected winding provides a path for this current to circulate. There can be no current in the neutral of the power transformer for system faults on the wye ungrounded or delta side of the bank.

Figures 4A and 4B illustrate a three winding transformer bank in which two of the windings are connected wye-grounded and the third winding is connected in delta. This transformer arrangement will prove suitable as a polarizing source even though the currents in each of the neutrals will reverse for system faults on one of the grounded sides of the bank as opposed to the other grounded side. Two CT's connected in parallel are required - one located in each of the neutrals as illustrated in Figure 4. The CT ratios selected must be inversely related to the turns ratio of the windings involved. For example, if one side is rated 230KV with a 1000/5 neutral CT and the other side is rated 115KV, then the ratio of the neutral CT located on the 115KV side must be set equal to 2000/5. CT ratios selected on any other basis will lead to reversals of the polarizing current to the relay (the resultant current of the paralleled CT's) and the relay will be unable to make a correct directional discrimination.

Another common transformer arrangement often encountered is the wye-grounded autotransformer with delta tertiary illustrated in Figure 5. At first glance, it appears that the neutral of this type of transformer would seem to be a satisfactory source for polarizing current. Actually, the neutral current may or may not be unidirectional with respect to faults located on either side of the transformer. For system faults on the low voltage side of the transformer, it can be shown that the current in the neutral will always flow up the neutral. For system faults on the high voltage side of the transformer, the current could be up the neutral, zero, or down the neutral depending on the high to low side turns ratio of the transformer, the equivalent impedances of the transformer and the low side system zero sequence impedance. If it can be determined that the neutral current will always flow up the neutral for all high side faults as it does for low side faults then a CT located in the neutral of the transformer may be used for polarizing directional ground relays.

Figure 5, illustrating the conditions for zero sequence current only, will be used to demonstrate the effects of the above mentioned parameters on the direction of the neutral current for system faults on the high voltage side of the autotransformer. For the sign conventions shown in Figure 5, it can be shown that the following applies:

$$I_N \ a \left[\frac{\overline{Z}_{TO}}{\overline{Z}_{SO} + \overline{Z}_{LO} + \overline{Z}_{TO}} - N \right] I_{HO} \qquad (1)$$

I_N = Actual neutral current

N = Transformer ratio
= V_L/V_H

$\overline{Z}_{T0}$ = Transformer tertiary equivalent impedance
$\overline{Z}_{L0}$ = Transformer low side equivalent impedance
$\overline{Z}_{S0}$ = Low side system source impedance
} Per Unit on common MVA base

$\overline{I}_{H0}$ = High side current

Examination of Figure 5 in conjunction with equation (1) will show the following to be true.

1. The neutral current will always flow down the neutral if the term in brackets is greater than zero.
2. The neutral current will always flow up the neutral if the term in brackets is less than zero.
3. The neutral current will be zero if the term in brackets equals zero.

It can be established from condition 2 and equation (1) above that the neutral current is always up the neutral for all high side system faults if the following constraints are met.

$$N > \frac{\overline{Z}_{TO}}{\overline{Z}_{SO} + \overline{Z}_{LO} + \overline{Z}_{TO}}$$

Thus, if these constraints are met for all system conditions, the neutral current for all high side faults will always flow up the neutral, and a CT located in the neutral will provide proper polarization. However, it must be remembered that the low side source impedance will vary with different system operating conditions and with system growth. For this reason, it must be emphasized that a CT located in the neutral of an autotransformer is not recommended for use as a source of polarizing current.

Up to this point, polarizing current obtained from the residual current in the neutral(s) of the power transformer only has been discussed. Various power transformer arrangements have been described and those that are suitable for polarizing from the neutral have been pointed out. Examination of Figures 3, 4 and 5 will show that zero sequence current also flows in the tertiary winding of the power transformer thus introducing the possibility of using it as a source of polarizing current. As noted above, autotransformers do not usually permit the use of neutral current for polarization and for these applications transformer tertiary current usually suffices. In other cases, such as in the wye grounded-delta-wye grounded transformer illustrated in Figure 4, it may not be possible to measure the current in both of the neutrals. Here too it may be possible to use the tertiary current for polarizing purposes. If the tertiary is to be used as a source of polarizing current, the number of CT's required to supply the current to the directional relays will depend on whether the tertiary is operated loaded or unloaded. For unloaded ternaries, only one CT is required and it may be located in any of the legs of the tertiary. If the tertiary is to be operated with some load, then three CT's, one in each leg of the tertiary and connected in parallel as illustrated in Figure 3C will be required. Three CT's are required when the tertiary is operated with some load in order to cancel out the effects of load current; i.e., the positive and negative sequence component of the current will add up to zero and only the zero sequence component will be supplied to the relay. In most cases the tertiary will be suitable as a source of polarizing current; however, there are some cases in which even the tertiary current will suffer a reversal thus making it unsuitable for polarizing purposes. The problem arises when the impedance of one of the branches of the transformer assumes a negative value. For example, consider the equivalent zero sequence circuit for the autotransformer illustrated in Figure 5 and assume that the low side transformer impedance $\overline{Z}_{LO}$ is negative. Depending on the value of the source impedance $\overline{Z}_{SO}$, the total branch impedance $\left(\overline{Z}_{SO} + \overline{Z}_{LO}\right)$ can be positive, negative or zero. If the branch impedance is positive an analysis of the circuit illustrated in Figure 5B will show that the tertiary current will flow in the direction shown. On the other hand, if the total branch impedance is negative the tertiary current will flow in the direction opposite to that shown. The tertiary current will be zero if the total branch impedance is zero. Thus, if the combination of source and transformer impedance can during some system conditions be positive and for other conditions be negative the tertiary will be unsuitable for current polarization because tertiary current reversals can occur. If the tertiary current is in the same direction for all system condition, then regardless of that direction, the tertiary will be suitable as a source for current polarization. In general, the tertiary will be suitable for current polarization purposes only in those cases where the total branch impedance is positive. An autotransformer has been used for purposes of illustration, but similar reasoning can be applied to the three winding wye grounded-delta-wye grounded transformer illustrated in Figure 4. In the case of an autotransformer with delta tertiary, the problem of current reversals in the tertiary is not as predominant as the problem of current reversals in the neutral. Therefore the tertiary is almost invariably used as a source of polarizing current in these type of transformers.

One problem that often arises is the lack of CT's or an oversight in supplying CT's in the tertiary when it is desired to use it as a source of polarizing current. In those cases where tertiary CT's are not available, special schemes have been devised in which it is possible to use the high side, low side or neutral CT’s in various combinations to derive a current proportional to the tertiary current [1]. These schemes, discussed in the reference and illustrated in Figure 6, are based on the premise that the net ampere turns among the windings of the power transformer must be zero, and the CT ratios are so selected to recognize this fact. In each case, the polarizing current will be proportional to the tertiary current as shown in the equations of Figure 6 and it will for the majority of fault cases be in the correct direction for polarization regardless of the fault location. If however, one of the branches of the equivalent circuit can assume a negative value as previously described, then the tertiary current will suffer a reversal and likewise will the polarizing current supplied by the schemes. As explained in the reference, other problems arise when using these schemes that must be considered if they are to be applied. Briefly, the schemes shown in Figure 6B and 6C suffer in performance in that the polarizing current may reverse for certain internal transformer faults; i.e., certain faults within the zone of the CT's. These problems may not be objectionable if the transformer protection is called on to trip all surrounding breakers anyway. If the channel equipment is keyed by operation of the directional relays under these conditions and if remote breakers or other functions such as automatic reclosing would be adversely affected, then these problems should be considered. The scheme of Figure 6A is most applicable of the three because the polarizing current will not reverse for faults internal to the transformer. One other problem that should be noted is the problem of CT saturation during faults not involving ground. If for example on heavy phase-to-phase faults, one of the phase CT's were to saturate more than the other, then the difference current could be fed to both the operating and polarizing circuits of the ground directional relay and false operation could occur.

Because tertiary CT's are not required in the schemes illustrated in Figure 6, they are readily adaptable to some applications involving power transformers without delta connected windings but of core type construction. In this type of construction, an equivalent or phantom tertiary may be created due to tank effects and the effect of this phantom tertiary may be sufficient to provide adequate current for polarizing purposes. Because the tertiary is not actually present, the schemes of Figure 6 may be used to obtain a polarizing current proportional to the tertiary current that arises as a result of the phantom tertiary. For example, consider a wye-grounded autotransformer without a delta tertiary but of core type construction. The neutral of this transformer may not be suitable as a source of polarizing current, but a phantom tertiary may exist and sufficient tertiary current may be available for polarizing purposes. If the tertiary current is sufficient, then one of the schemes of Figure 6 may be used to obtain a polarizing current for directional ground relays. For a specific application involving core type transformers the manufacturer of the bank in question should be referred to.

POTENTIAL POLARIZATION

Potential polarization may be used in those cases where current polarization is not available or not suitable or where dual polarization is desired. The potential used as the polarizing quantity in a directional ground relay is proportional to the zero sequence voltage existing at the relay location. The magnitude of the zero sequence voltage and therefore the polarizing voltage can vary over fairly wide ranges. The zero sequence voltage appearing throughout the system will be a function of the total system zero sequence impedance and it will be maximum at the fault location and will decrease in magnitude as the source is approached. At the relay location, the zero sequence voltage will be proportional to the system impedance behind the relay location and it will be less than or equal to the fault voltage depending on the location of the fault. The maximum polarizing voltage presented to the relay will be obtained for faults at the relay location and it will decrease in magnitude as the fault is moved away from the relay location. Figure 7 illustrates the zero sequence voltage profiles for faults at each end of the line in the simple system shown. Note that the voltage at the relay is at its maximum for faults at the relay location and decreases in magnitude as the fault is moved towards the remote end of the line. Any changes in the source impedance will lead to a respective change in the zero sequence voltage presented to the relay. Zero sequence voltage at the relay location will in general be smallest in solidly grounded stations and the problem will be further compounded when long transmission lines are also involved.

A number of methods are used to obtain the voltage polarizing quantity. One common method uses potential devices having double secondary windings in which one set of windings is used to provide the phase voltages for metering and phase relaying and the second set of windings is connected in broken delta to provide the polarizing voltage to the ground directional relay. This arrangement is shown in Figure 8. The voltage appearing across the broken delta will be equal to Ea + Eb + E_C which in terms of sequence components is equal to $3E_0$ For balanced conditions, three phase or phase-to-phase faults, the broken delta voltage and consequently the polarizing voltage will be zero. For faults involving ground, the polarizing quantity will be proportional to $3E_0$ and its magnitude will be a function of the system zero sequence impedance, system configuration, fault location, and the PT ratios used.

Another common arrangement uses auxiliary PT's in conjunction with main potential devices having a single winding secondary. In this arrangement shown in Figure 9, the auxiliary PT's are used to provide the broken delta connection and the secondary winding of the potential device is used to provide the phase voltages. This connection too will provide a polarizing voltage proportional to $3E_0$.

Consider the high voltage transmission lines connected to a delta-delta power transformer as shown in Figure 10. The delta-delta power transformer will not pass zero sequence quantities, but it may be possible for zero sequence current to flow in the lines as a result of grounds at other points in the high voltage system. If directional ground relays were to be applied on these lines to detect faults in the high voltage system, potential polarization would have to be used because the power transformer does not serve as a source of zero sequence current. Zero sequence voltage would be available as a consequence of the zero sequence current flow and three high side potential transformers with the secondaries connected in broken delta could be used to detect this voltage and so provide a suitable polarizing voltage. However, if PT's are available on the low side of the power transformer, it will be possible to obtain the polarizing quantity by using only a single high side PT in conjunction with the low side PT’s [2]. Figure 10 illustrates the necessary connections. In this arrangement, the single-phase-to-ground potential available from the high side PT establishes the neutral of the low side PT's thus establishing the phase to neutral potentials there. The zero sequence voltage is taken from the broken delta connection of the auxiliary PT's. There is an error in this voltage caused by the drop in the transformer due to load flow or by the flow of positive and negative sequence components of currents towards the fault if there is a source of generation on the low side of the transformer. This error will generally be small for large magnitudes of zero sequence voltage, but it can be appreciable when the zero sequence voltage is small and may cause directional ground relays to misoperate. it is possible that a directional ground relay might misoperate on magnetizing inrush if the relay was a high speed device. In general, this type of polarization is not considered suitable for high speed directional ground relaying but it may be used with time overcurrent directional relays. The connections in Figure 10 are illustrated for a delta-delta power transformer, but a similar arrangement may be used with wye-delta or delta-wye power transformers provided the auxiliary PT's are arranged to compensate for the angular shift in voltages that arise as a consequence of the power transformer connection.

Regardless of the potential polarizing scheme that is chosen, the polarizing voltage at the relay location should be checked to determine its maximum and minimum values for faults within the desired zone of protection. Either step-up or step-down auxiliary PT's may be required to provide a potential within reasonable limits yet still adequate for polarizing purposes.

DUAL POLARIZATION

Present static as well as electromechanical directional ground relays are designed so that either current alone or voltage alone or a combination of both may be used to polarize the relay. The ability to polarize the relay from both sources simultaneously offers distinct advantages over relays that can be polarized from a single source only. Because the relay can be applied with either source disconnected the need is eliminated for ordering and stocking two different types of relays. Certain operating conditions often require that directional ground relays operate with current polarization whereas voltage polarization would be advantageous under other conditions, thus by using relays with facilities for dual polarization the need is eliminated for providing two types of relays at the same location. The sensitivity of a directional ground relay is proportional to the polarizing quantity. With dual polarization in service, maximum sensitivity will be achieved because the zero sequence current will in general be high when the zero sequence voltage is low and vice versa.

NEGATIVE SEQUENCE APPROACH

It is well documented in the relay literature [4, 5] that negative-sequence directional approach is superior to the zero-sequence current and/or voltage polarized directional functions particularly when zero-sequence mutual coupling is present between parallel lines.

OPERATE and RESTRAINT input quantities for a simple "Amplitude Comparator" representing a negative sequence directional function are shown below:

OPERATE = $| V_2 - (1+k) * I_2 * Z_R |$
RESTRAINT = $| V_2 + (1-k) * I_2 * Z_R |$

Where: V_2 = Negative sequence current at the relay
I_2 = Negative sequence current at the relay
k = Offset compensation factor
Z_R = Relay reach impedance

For some system conditions, the negative sequence voltage at the relay may approach zero. Factor k which is fixed by design, is used to create a reliable operate signal under this condition. Z_R, also fixed by design, determines the sensitivity and maximum torque angle characteristic of the directional function.

The directional function described above can be used to torque control a variety of zero-sequence overcurrent functions to provide the directionality [6].

CONCLUSIONS

Directional ground relays require that a reference be established against which the fault current in the line can be compared. This reference quantity is referred to as the polarizing quantity and for zero sequence directional ground relays it may be zero sequence current or voltage. Current may be used as the polarizing quantity at those points in the systems where power transformers having suitably grounded neutrals are located. The polarizing current may be obtained from the neutral(s) of the power transformer or the tertiary winding of the power transformer may be used as the source of polarizing current. Special schemes have also been devised in which various combinations of low side, high side and neutral CT's can be used to obtain a suitable polarizing current. Potential polarization may be used where a suitable polarizing current is not available or where it is desired to dual polarize the relay. Regardless of the type of polarizing that is used, the polarizing quantity must be of sufficient magnitude and remain fixed in direction if the relay is to operate properly. Various polarizing sources and commonly used schemes have been discussed in this paper and those that are suitable and the problems pertinent to each have been noted.

Negative sequence approach for the directional ground relay provides superior performance and has been widely used in the multi-function relays (static analog and digital).

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[4] The Art and Science of Protective Relaying, C.R. Mason, page 330, John Wiley & Sons, Inc.

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[6] GET-8037A, Digital Line Protection, October '93, GE Power Management, Malvern, PA.

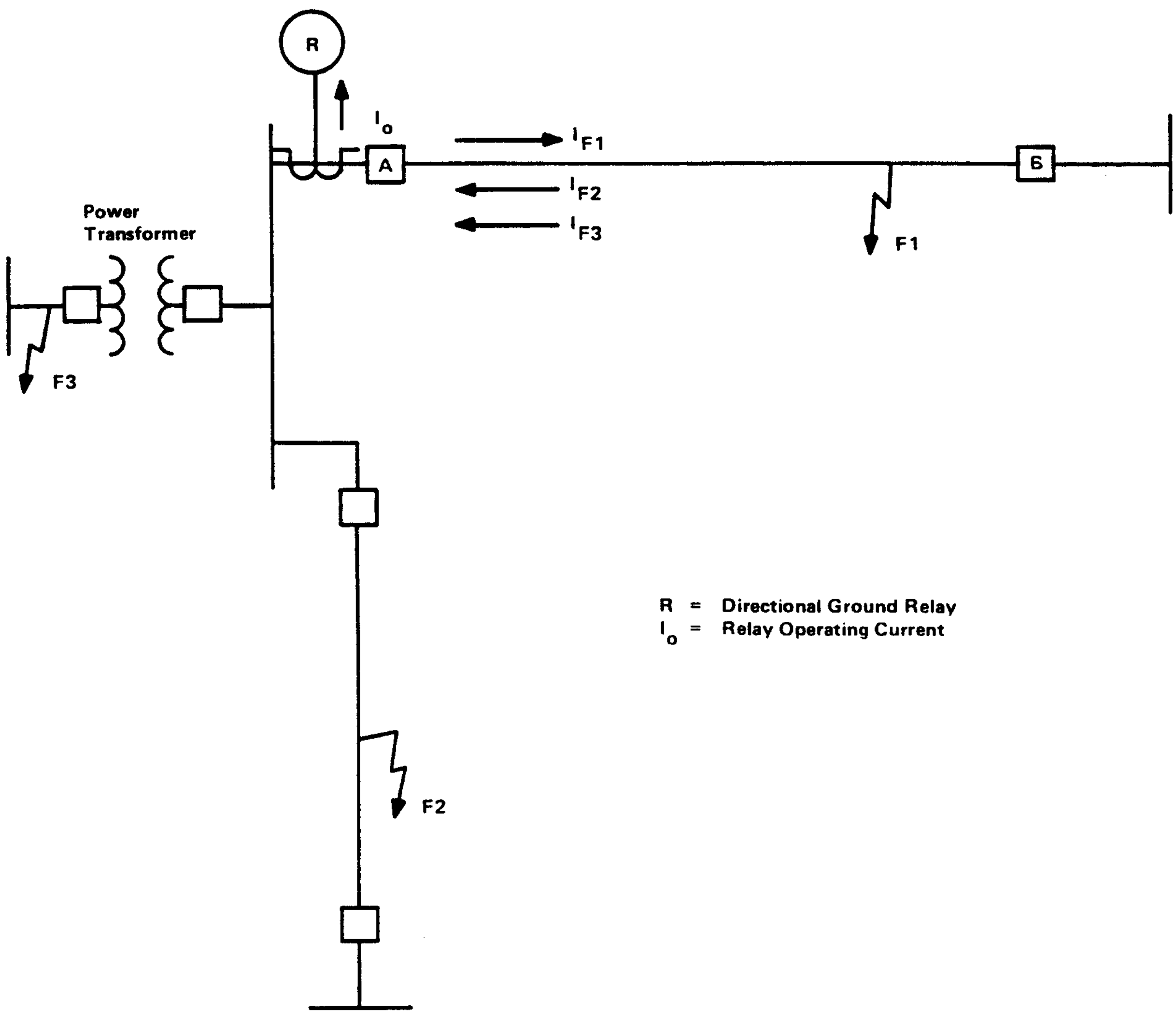
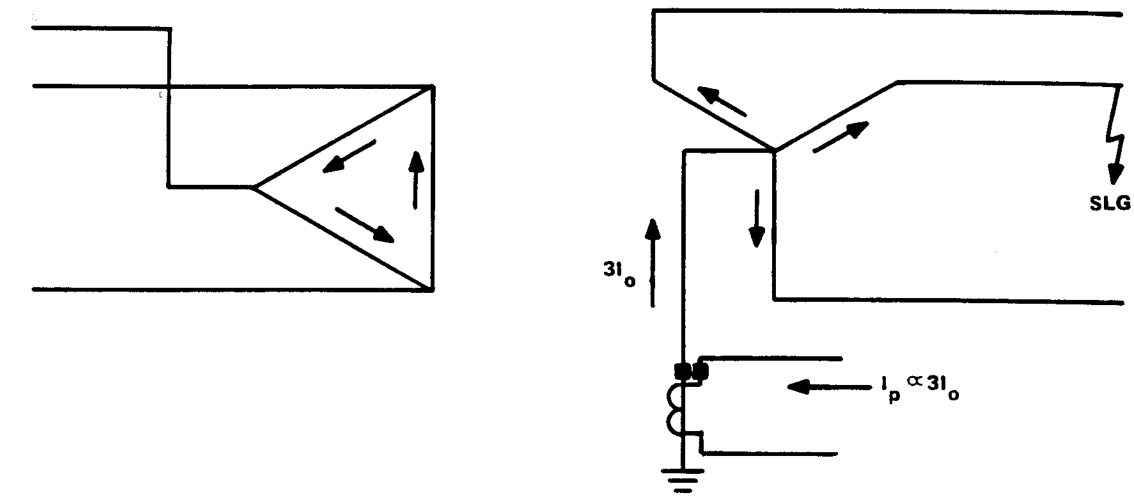
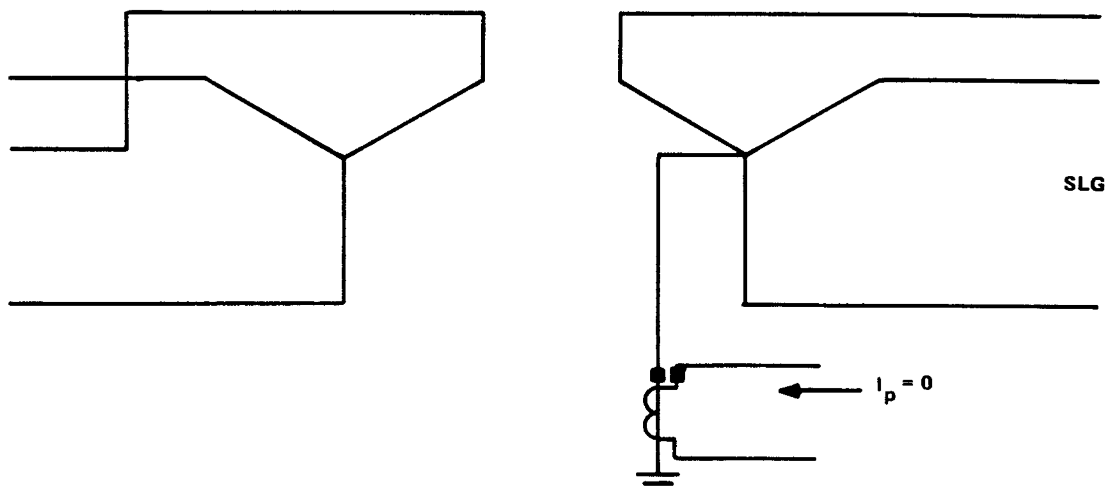


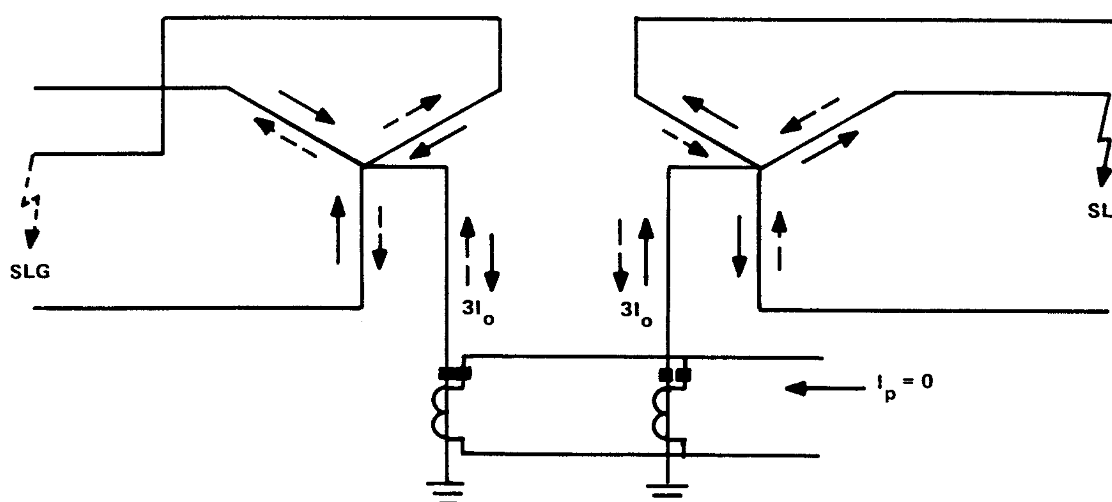
Figure 1. Typical Transmission System



A. Delta-wye grounded power transformer, suitable for current polarization.

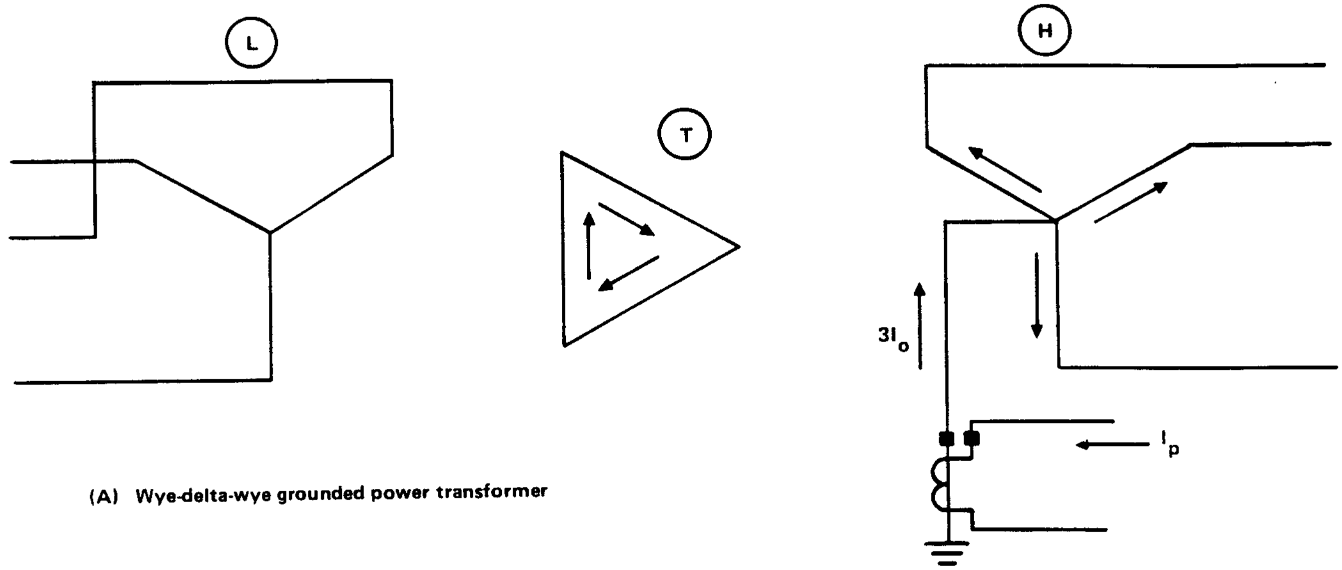


B. Wye-grounded wye power transformer, unsuitable for current polarization.

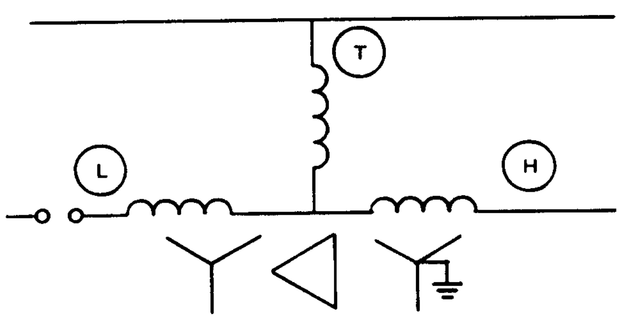


C. Wye grounded-wye grounded power transformer, unsuitable for current polarization.

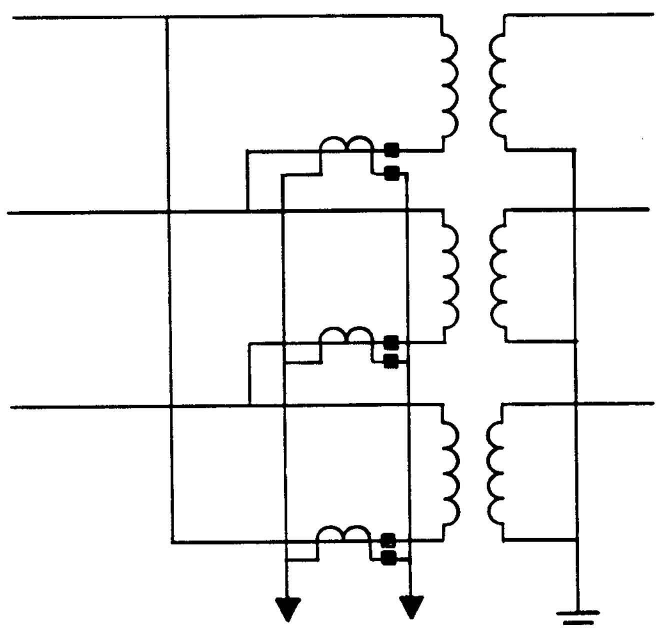
Figure 2



(A) Wye-delta-wye grounded power transformer

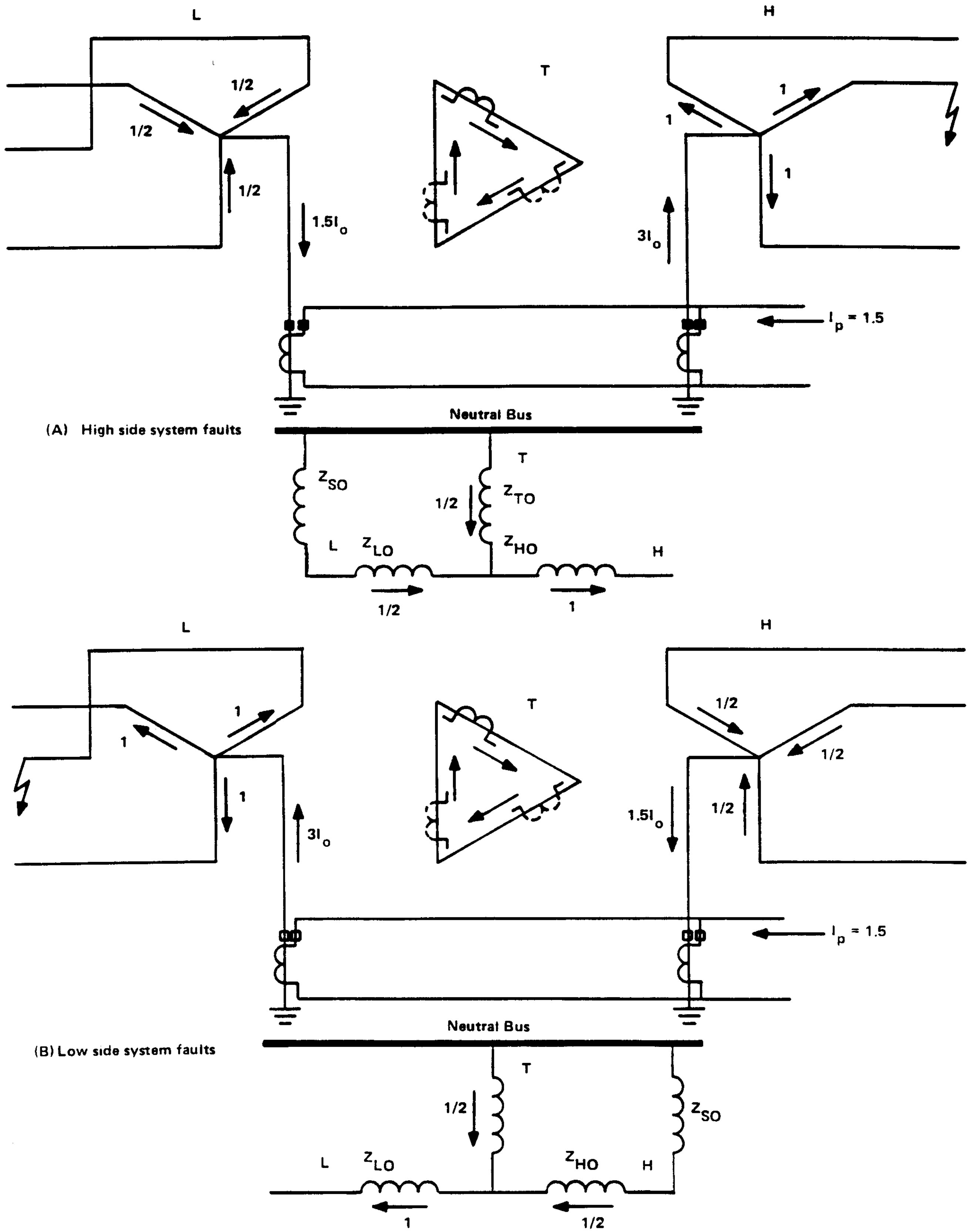


(B) Zero sequence circuit for wye-delta-wye grounded transformer



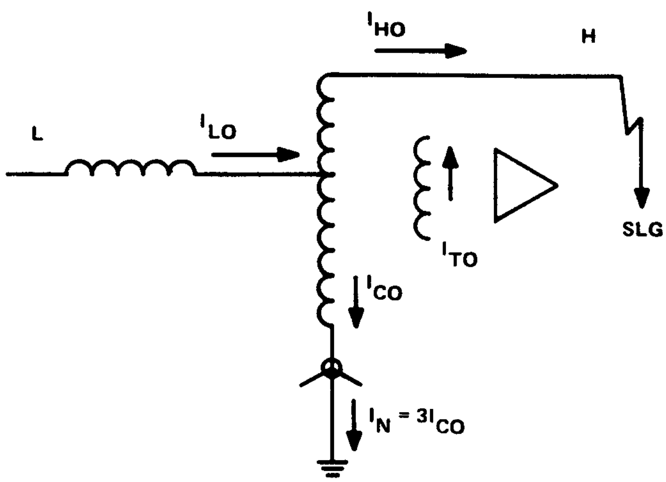
(C) Parallel connection of CT's when tertiary is loaded.

Figure 3

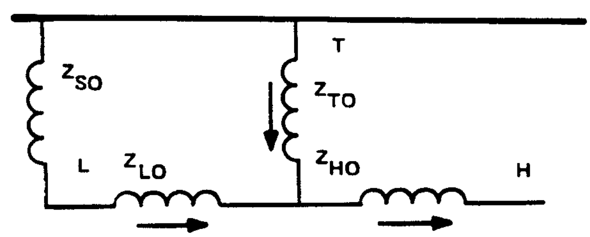


NOTE: Current distribution based on equal winding impedances, and zero source impedance. Actual distribution in general will not be equal, but polarizing current will always be in proper direction.

Figure 4. Wye-delta-wye grounded power transformer



(A) Actual representation



Z_{SO} = Low side zero sequence source impedance

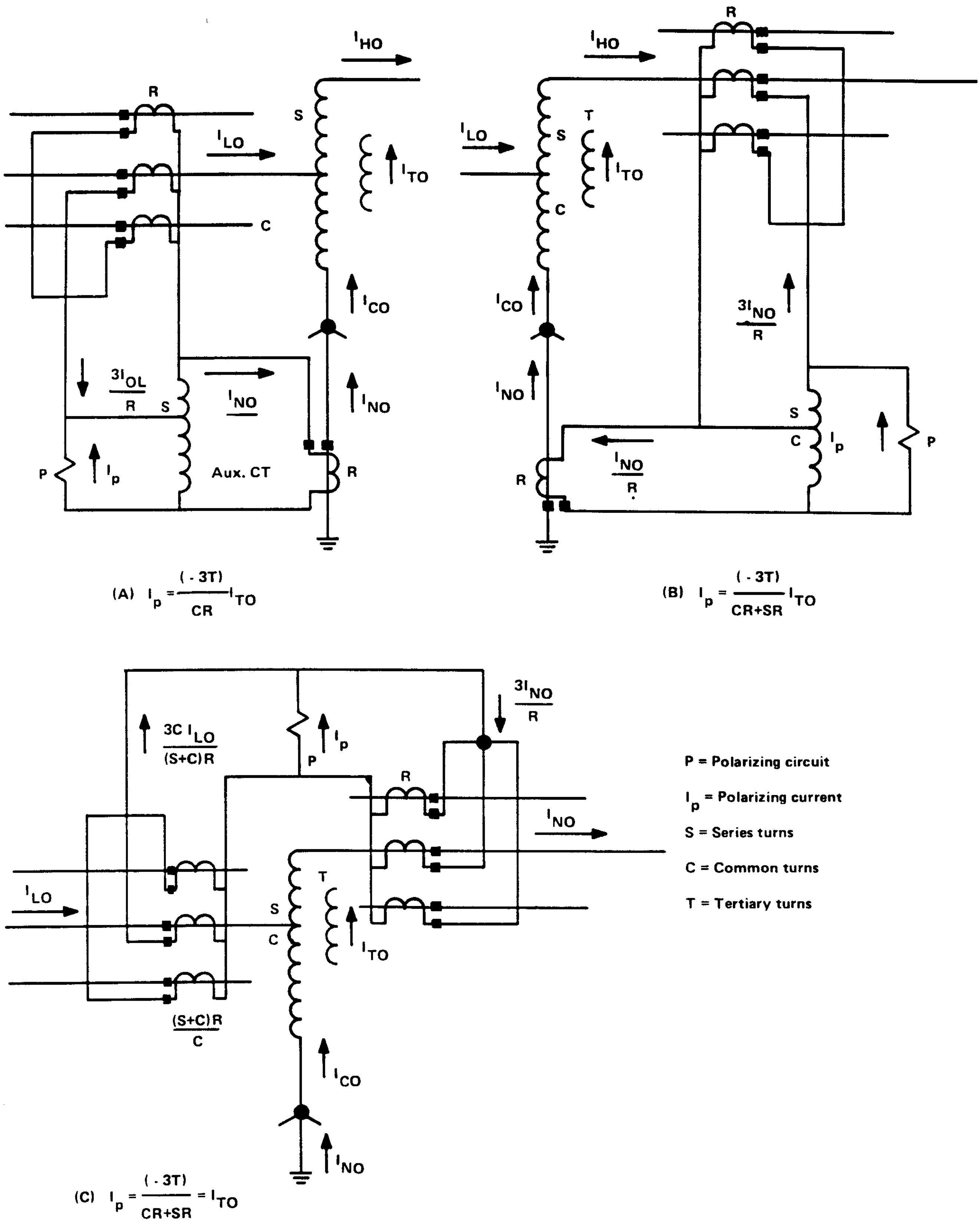
Z_{LO} = Transformer equivalent low side impedance

Z_{TO} = Transformer equivalent tertiary impedance

Z_{HO} = Transformer equivalent high side impedance

(B) Per unit representation on common MVA base

Figure 5



I_HO
I_LO
I_TO
I_CO
I_NO
R
S
C
T
3I_OL / R
I_NO / R
Aux. CT
P
I_p
(A) I_p = (-3T) / CR I_TO
3I_NO / R
(B) I_p = (-3T) / (CR+SR) I_TO
3C I_LO / (S+C)R
(S+C)R / C
(C) I_p = (-3T) / (CR+SR) = I_TO
P = Polarizing circuit
I_p = Polarizing current
S = Series turns
C = Common turns
T = Tertiary turns

Figure 6

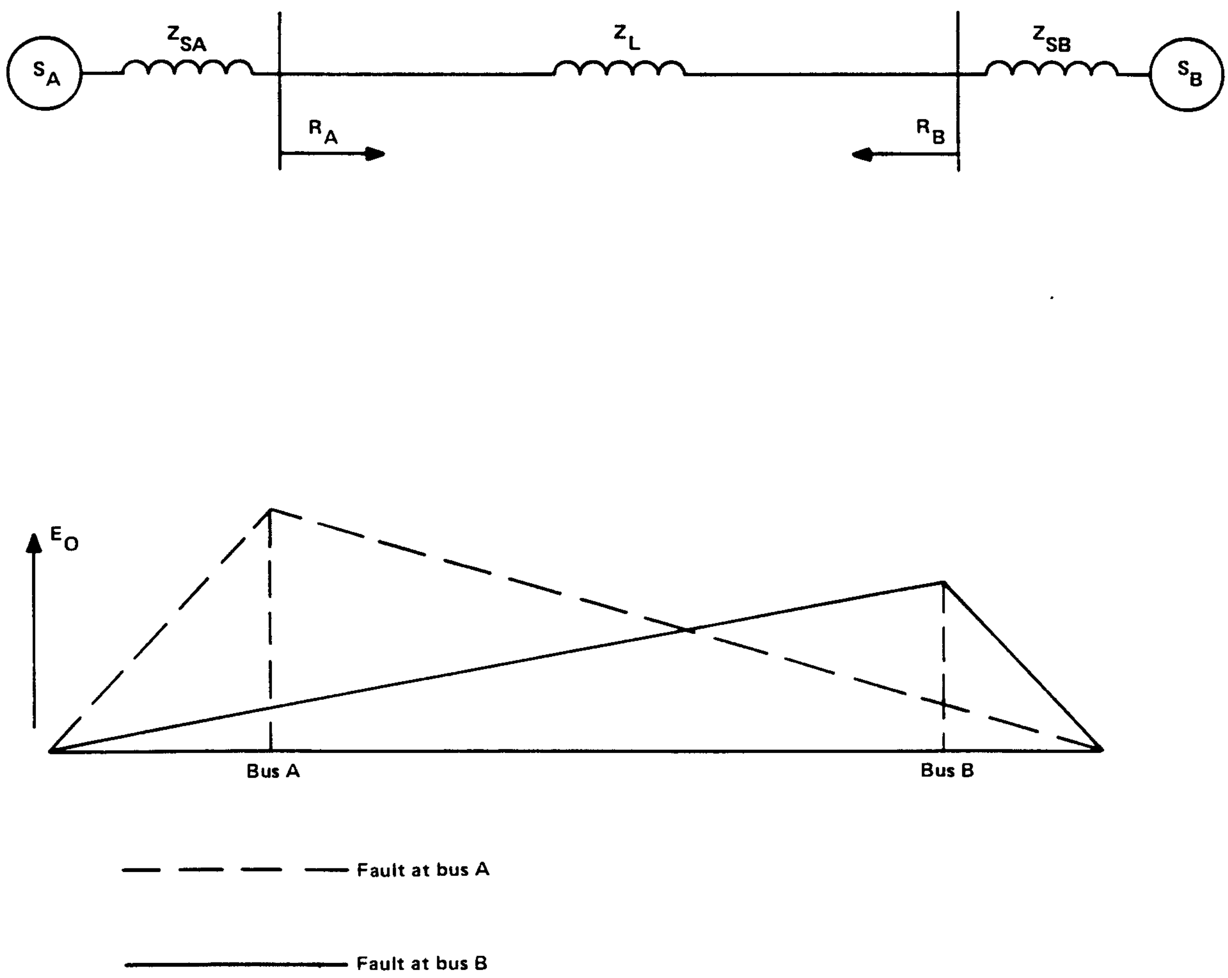


Figure 7

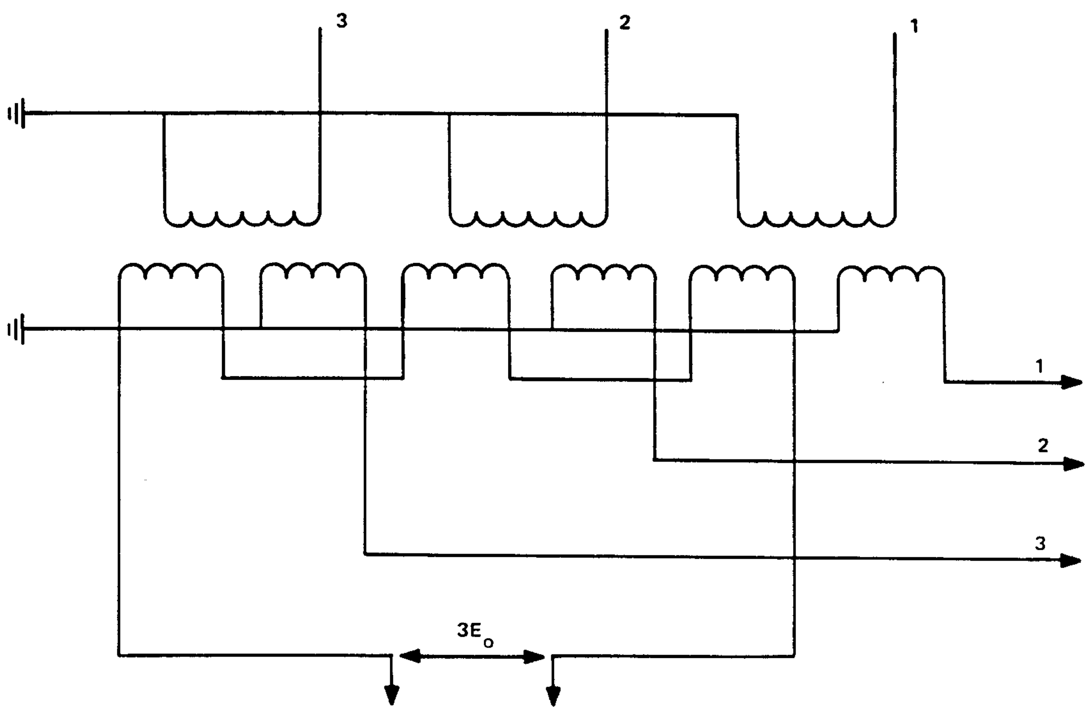


Figure 8. Potential polarization using potential coupling devices with double winding secondary

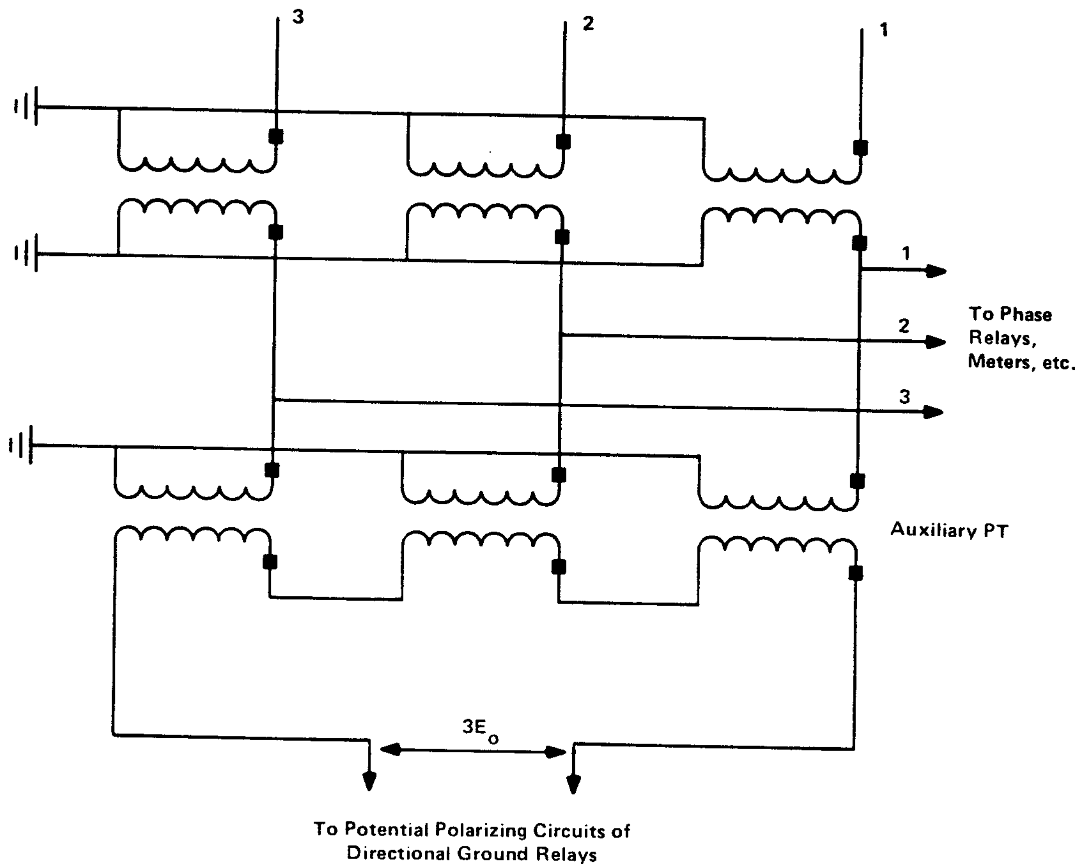


Figure 9. Potential polarization using Auxiliary PT's in Conjunction with Main Coupling Device having Single Winding Secondary

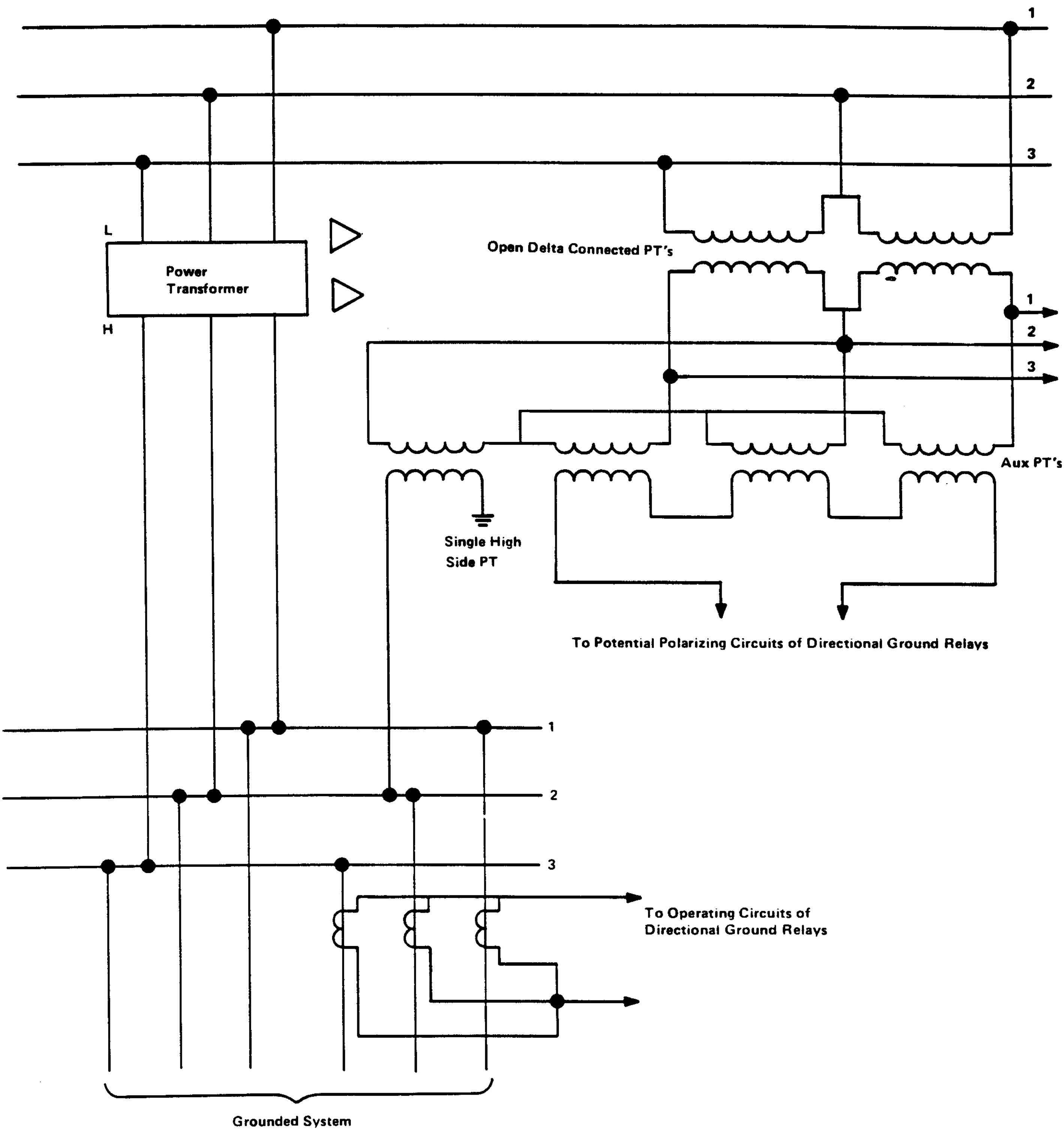


Figure 10. Potential polarization using low side PT's and a single high side PT