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LINE PROTECTION WITH DISTANCE RELAYS

Distance relaying should be considered when overcurrent relaying is too slow or is not selective. Distance relays are generally used for phase-fault primary and back-up protection on subtransmission lines, and on transmission lines where high-speed automatic reclosing is not necessary to maintain stability and where the short time delay for end-zone faults can be tolerated. Overcurrent relays have been used generally for ground-fault primary and back-up protection, but there is a growing trend toward distance relays for ground faults also.

Single-step distance relays are used for phase-fault back-up protection at the terminals of generators, as described in Chapter 10. Also, single-step distance relays might be used with advantage for back-up protection at power-transformer banks, but at the present such protection is generally provided by inverse-time overcurrent relays.

Distance relays are preferred to overcurrent relays because they are not nearly so much affected by changes in short-circuit-current magnitude as overcurrent relays are, and, hence, are much less affected by changes in generating capacity and in system configuration. This is because, as described in Chapter 9, distance relays achieve selectivity on the basis of impedance rather than current.

THE CHOICE BETWEEN IMPEDANCE, REACTANCE, OR MHO

Because ground resistance can be so variable, a ground distance relay must be practically unaffected by large variations in fault resistance. Consequently, reactance relays are generally preferred for ground relaying.

For phase-fault relaying, each type has certain advantages and disadvantages. For very short line sections, the reactance type is preferred for the reason that more of the line can be protected at high speed. This is because the reactance relay is practically unaffected by arc resistance which may be large compared with the line impedance, as described elsewhere in this chapter. On the other hand, reactance-type distance relays at certain locations in a system are the most likely to operate undesirably on severe synchronizing power surges unless additional relay equipment is provided to prevent such operation.

The mho type is best suited for phase-fault relaying for longer lines, and particularly where severe synchronizing-power surges may occur. It is the least likely to require additional equipment to prevent tripping on synchronizing-power surges.[1] When mho relaying is adjusted to protect any given line section, its operating characteristic encloses the least space on the *R-X* diagram, which means that it will be least affected by abnormal system conditions other than line faults; in other words, it is the most selective of all distance relays. Because the mho relay is affected by arc resistance more than any other type, it is applied to longer lines. The fact that it combines both the directional and the distance-measuring functions in one unit with one contact makes it very reliable.

The impedance relay is better suited for phase-fault relaying for lines of moderate length than for either very short or very long lines. Arcs affect an impedance relay more than a reactance relay but less than a mho relay. Synchronizing-power surges affect an impedance relay less than a reactance relay but more than a mho relay. If an impedance-relay characteristic is offset, so as to make it a modified relay, it can be made to resemble either a reactance relay or a mho relay but it will always require a separate directional unit.

There is no sharp dividing line between areas of application where one or another type of distance relay is best suited. Actually, there is much overlapping of these areas. Also, changes that are made in systems, such as the addition of terminals to a line, can change the type of relay best suited to a particular location. Consequently, to realize the fullest capabilities of distance relaying, one should use the type best suited for each application. In some cases much better selectivity can be obtained between relays of the same type, but, if relays are used that are best suited to each line, different types on adjacent lines have no appreciable adverse effect on selectivity.

THE ADJUSTMENT OF DISTANCE RELAYS

Chapter 9 shows that phase distance relays are adjusted on the basis of the positive-phase-sequence impedance between the relay location and the fault location beyond which operation of a given relay unit should stop. Ground distance relays are adjusted in the same way, although some types may respond to the zero-phase-sequence impedance. This impedance, or the corresponding distance, is called the "reach" of the relay or unit. For purposes of rough approximation, it is customary to assume an average positive-phase-sequence-reactance value of about 0.8 ohm per mile for open transmission-line construction, and to neglect resistance. Accurate data are available in textbooks devoted to power-system analysis.[2]

To convert primary impedance to a secondary value for use in adjusting a phase or ground distance relay, the following formula is used:

$$Z_{\text{sec}} = Z_{\text{pri}} \times \frac{\text{CT ratio}}{\text{VT ratio}}$$

where the CT ratio is the ratio of the high-voltage phase current to the relay phase current, and the VT ratio is the ratio of the high-voltage phase-to-phase voltage to the relay phase-to-phase voltage–all under balanced three-phase conditions. Thus, for a 50-mile, 138-kv line with 600/5 wye-connected CT’s, the secondary positive-phase-sequence reactance is about $50 \times 0.8 \times \frac{600}{5} \times \frac{115}{138{,}000} = 4.00$ ohms.

It is the practice to adjust the first, or high-speed, zone of distance relays to reach to 80% to 90% of the length of a two-ended line or to 80% to 90% of the distance to the nearest terminal of a multiterminal line. There is no time-delay adjustment for this unit.

The principal purpose of the second-zone unit of a distance relay is to provide protection for the rest of the line beyond the reach of the first-zone unit. It should be adjusted so that it will be able to operate even for arcing faults at the end of the line. To do this, the unit must reach beyond the end of the line. Even if arcing faults did not have to be considered, one would have to take into account an underreaching tendency because of the effect of intermediate current sources, and of errors in: (1) the data on which adjustments are based, (2) the current and voltage transformers, and (3) the relays. It is customary to try to have the second-zone unit reach to at least 20% of an adjoining line section; the farther this can be extended into the adjoining line section, the more leeway is allowed in the reach of the third-zone unit of the next line-section back that must be selective with this second-zone unit.

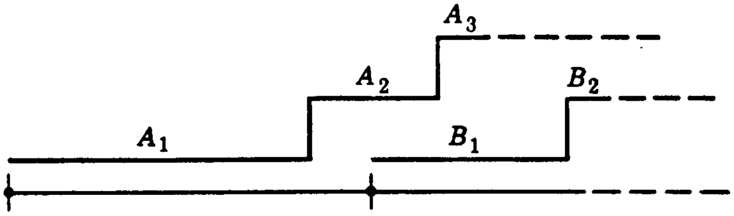

Fig. 1. Normal selectivity adjustment of second-zone unit.

The *maximum* value of the second-zone reach also has a limit. Under conditions of maximum overreach, the second-zone reach should be short enough to be selective with the second-zone units of distance relays on the shortest adjoining line sections, as illustrated in Fig. 1. Transient overreach need not be considered with relays having a high ratio of reset to pickup because the transient that causes overreach will have expired before the second-zone tripping time. However, if the ratio of reset to pickup is low, the second-zone unit must be set either (1) with a reach short enough so that its overreach will not extend beyond the reach of the first-zone unit of the adjoining line section under the same conditions, or (2) with a time delay long enough to be selective with the second-zone time of the adjoining section, as shown in Fig. 2. In this connection, any underreaching tendencies of the relays on the adjoining line sections must be taken into account. When an adjoining line is so short that it is impossible to get the required selectivity on the basis of react, it becomes necessary to increase the time delay, as illustrated in Fig. 2. Otherwise, the time delay of the second-zone unit should be long enough to provide selectivity with the slowest of (1) bus-differential relays of the bus at the other end of the line, (2) transformer-differential relays of transformers on the bus at the other end of the line,

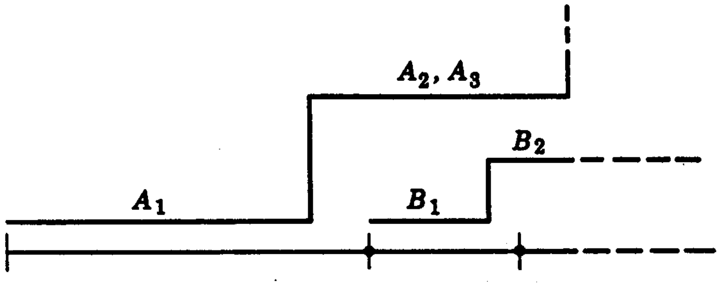

Fig. 2. Second-zone adjustment with additional time for selectivity with relay of a very short adjoining line section.

or (3) line relays of adjoining line sections. The interrupting time of the circuit breakers of these various elements will also affect the second-zone time. This second-zone time is normally about 0.2 second to 0.5 second.

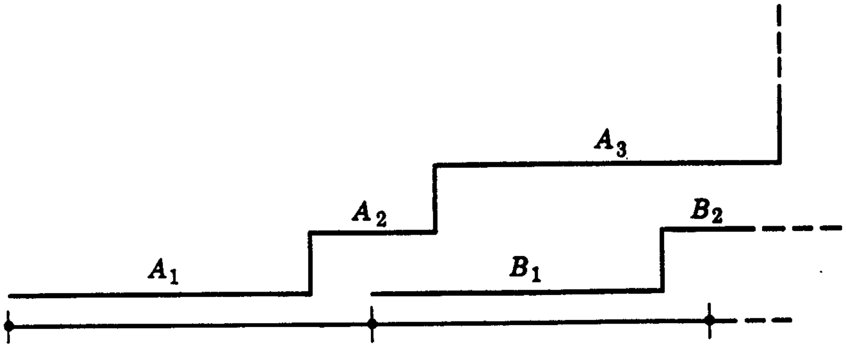

Fig. 3. Normal selective adjustment of third-zone unit.

The third-zone unit provides back-up protection for faults in adjoining line sections. So far as possible, its reach should extend beyond the end of the longest adjoining line section under the conditions that cause the maximum amount of underreach, namely, arcs and intermediate current sources. Figure 3 shows a normal back-up characteristic. The third-zone time delay is usually about 0.4 second to 1.0 second. To reach beyond the end of a long adjoining line andstill be selective with the relays of a short line, it may be necessary to get this selectivity with additional time delay, as in Fig. 4.

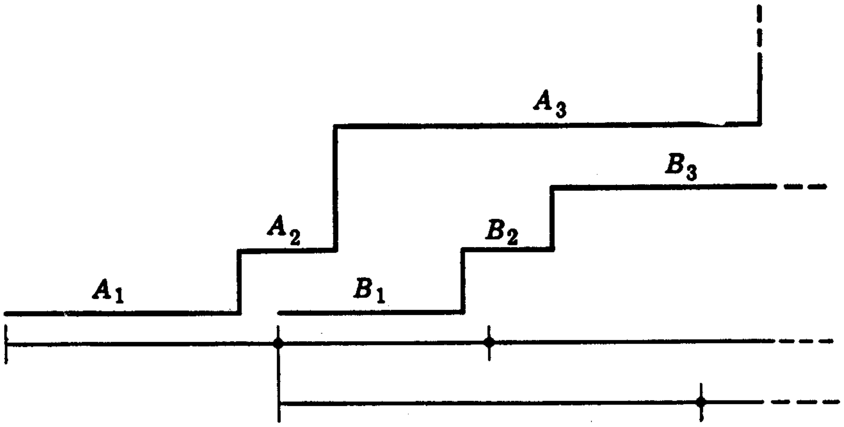

Fig. 4. Third-zone adjustment with additional time for selectivity with relay of a short adjoining line and to provide back-up protection for a long adjoining line.

When conditions of Fig. 4 exist, the best solution is to use the type of back-up relaying described later under the heading "The Effect of Intermediate Current Sources on Distance-Relay Operation." Then, one has only the problem of adjusting the first- and second-zone units. Under no circumstances should the reach of any unit be so long that the unit would operate for any load condition or would fail to reset for such a condition if it had previously operated for any reason. To determine how near a distance relay may be to operating under a maximum load condition, in lieu of more accurate information, it is the practice to superimpose the relay's reset characteristic on an *R-X* diagram with the point representing the impedance when the equivalent generators either side of the relay location are 90° out of phase. This is done by the method described in Chapter 9 for drawing the loss-of-synchronism characteristic. Stability can be maintained with somewhat more than a 90° displacement, but 90° is nearly the limit and is easy to depict, as described in Chapter 9.

THE EFFECT OF ARCS ON DISTANCE-RELAY OPERATION

Chapter 9 shows the effect of fault or arc resistance on the appearance of different kinds of short circuits when plotted on an *R-X* diagram in terms of the voltages and currents used by distance relays. Chapter 13 gives data from which arc resistance can be estimated for plotting such fault characteristics on the *R-X* diagram. It is only necessary, then, to superimpose the characteristic of any distance relay in order to see what its response will be.

The critical arc location is just short of the point on a line at which a distance relay's operation changes from high-speed to intermediate time or from intermediate time to back-up time. We are concerned with the possibility that an arc within the high-speed zone will make the relay operate in intermediate time, that an arc within the intermediate zone will make the relay operate in back-up time, or that an arc within the back-up zone will prevent relay operation completely. In other words, the effect of an arc may be to cause a distance relay to underreach.

For an arc just short of the end of the first- or high-speed zone, it is the initial characteristic of the arc that concerns us. A distance relay's first-zone unit is so fast that, if the impedance is such that the unit can operate immediately when the arc is struck, it will do so before the arc can stretch appreciably and thereby increase its resistance. Therefore, we can calculate the arc characteristic for a length equal to the distance between conductors for phase-to-phase faults, or across an insulator string for phase-to-ground faults. On the other hand, for arcs in the intermediate-time or back-up zones, the effect of wind stretching the arc should be considered, and then the operating time for which the relay is adjusted has an important bearing on the outcome.

Tending to offset the longer time an arc has to stretch in the wind when it is in the intermediate or back-up zones is the fact that, the farther an arcing fault is from a relay, the less will its effect be on the relay's operation. In other words, the more line impedance there is between the relay and the fault, the less change there will be in the total impedance when the arc resistance is added. On the other hand, the farther away an arc is, the higher its apparent resistance will be because the current contribution from the relay end of the line will be smaller, as considered later.

A small reduction in the high-speed-zone reach because of an arc is objectionable, but it can be tolerated if necessary. One can always use a reactance-type or modified-impendance-type distance relay to minimize such reduction.[3] The intermediate-zone reach must not be reduced by an arc to the point at which relays of the next line back will not be selective; of course, they too will be affected by the arc, but not so much. Reactance-type or modified-impendance-type distance relays are useful here also for assuring the minimum reduction in second-zone reach. Figure 5 shows how an impedance or mho characteristic can be offset to minimize its susceptibility to an arc. One can also help the situation by making the second-zone reach as long as possible so that a certain amount of reach reduction by an arc is permissible. Conventional relays do not use the reactance unit for the back-up zone;

instead, they use either an impedance unit, a modified-impendance unit, or a mho unit. If failure of the back-up unit to operate because of an arc extended by the wind is a problem, the modified-impendance unit can be used or the mho–or "starting"–unit characteristic can also be shifted to make its operation less affected by arc resistance. The low-reset characteristic of some types of distance relay is advantageous in preventing reset as the wind stretches out an arc.

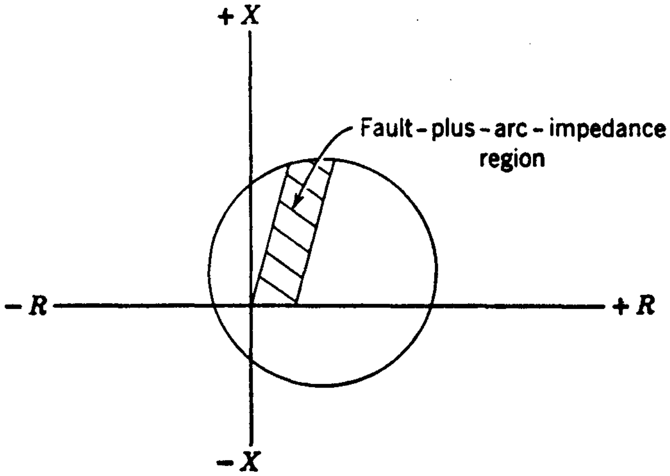

Fig. 5. Offsetting relay characteristic to minimize susceptibility to arcs.

Although an arc itself is practically all resistance, it may have a capacitive-reactance or an inductive-reactance component when viewed from the end of a line where the relays are. The impedance of an arc (Z_A) has the appearance:

$$Z_A = \frac{(I_1 + I_2)}{I_1} R_A = R_A + \frac{I_2}{I_1} R_A$$

where I_1 = the complex expression for the current flowing into the arc from the end of the line where the relays under consideration are.

I_2 = the complex expression for the current flowing into the arc from the other end of the line.

R_A = the arc resistance with current $(I_1 + I_2)$ flowing into it.

If I_1 and I_2 are out of phase, Z_A will be a complex number. Therefore, even a reactance-type distance relay may be adversely affected by an arc. This effect is small, however, and is generally neglected.

Of more practical significance is the fact that, as shown by the equation, the arc resistance will appear to be higher than it actually is, and it may be very much higher. After the other end of the line trips, the arc resistance will be higher because the arc current will be lower. However, its appearance to the relays will no longer be magnified, because I_2 will be zero. Whether its resistance will appear to the relays to be higher or lower than before will depend on the relative and actual magnitudes of the currents before and after the distant breaker opens.

THE EFFECT OF INTERMEDIATE CURRENT SOURCES ON DISTANCE-RELAY OPERATION

An "intermediate-current source" is a source of short-circuit current between a distance-relay location and a fault for which distance-relay operation is desired. Consider the example of Fig. 6. The true impedance to the fault is $Z_A + Z_B$, but, when the intermediate current I_2 flows, the impedance appears to the distance relays as $Z_A + Z_B + (I_2/I_1)\ Z_B$; in other words, the fault appears to be farther away because of the current I_2. This effect has been called the "mutual impedance" effect. It will be evident that, if I_1 and I_2 are out of phase, the impedance $(I_2/I_1)\ Z_B$ will have a different angle from Z_B.

If the distance relays are adjusted to operate for a fault at a given location when a given value of I_2 flows, they will operate for faults beyond that location for smaller values of I_2. Therefore, it is the practice to adjust distance relays to operate as desired on the basis of no intermediate current source. Then, they will not overreach and operate undesirably. Of course, when current flows from an intermediate source, the relays will "underreach," i.e., they will not operate for faults as far away as one might desire, but this is to be preferred to overreach.

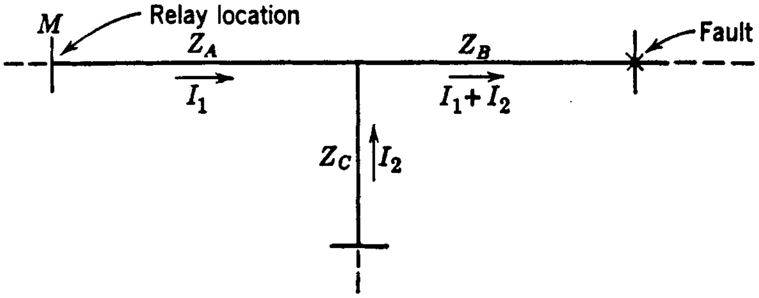

Fig. 6. Illustrating the effect of intermediate current sources on distance-relay operation.

Because of the effect of intermediate current sources, the full capabilities of distance relaying cannot be realized on multiterminal lines. It is the practice to adjust the high-speed zone of the relays at a given terminal to reach 80% to 90% of the distance to the nearest terminal, neglecting the effect of an intermediate current source. Thus, in Fig. 6, the maximum reach of the high-speed zone of the relays at *M* would be 80% to 90% of $Z_A + Z_B$ or of $Z_A + Z_C$, whichever was smaller. Neglecting the effect of an arc, if this maximum reach of the high-speed zone is less than Z_A, it will become evident that intermediate current cannot affect the high-speed-zone reach; if the maximum reach is greater than Z_A, intermediate current will cause the reach to approach Z_A, as a minimum limit. If the second-zone reach is made to include double the impedance of the common branch, tripping will always be assured although it might be sequential.[4]

Back-up protection of the conventional type described in Chapter 1 is often impossible in the presence of intermediate current sources. In Fig. 7, consider the problem of adjusting relays at *A* to provide back-up for the fault location shown, in the event that breaker *B* fails to trip for any reason. The problem is similar whether inverse-time or distance relays are involved at *A*. The magnitude of the fault current flowing at *A*, or the impedance measured by a distance relay at *A*, may vary considerably, depending on the magnitude of fault current fed into the intermediate station from other sources. The range of such variations must be taken into account in determining the back-up adjustment. In some extreme cases, the apparent impedance between *A* and the fault may be such as to put the fault beyond the reach of the relays at *A*. Obviously, this problem may apply also to the relays in the other lines except the faulted one.

A solution that has been resorted to, when a fault can be beyond the reach of conventional back-up relays, is to have the back-up unit of the relaying equipment of each line at the intermediate station operate a timer which, after a definite time, will energize a multicontact auxiliary tripping relay to trip all the breakers connected to the bus of the intermediate station.[5] Admittedly, this solution violates one of the fundamental principles of back-up protection by assuming that the failure to trip is owing only to failure in the breaker or in the tripping circuit between the relay and the breaker; it assumes that the protective-relaying equipment or the source of tripping voltage will not fail. However, it is a practical solution, and it has been considered worth the risk. A more reliable arrangement is to use separate CT's and protective relays to energize the multicontact tripping relay, employing only the battery in common. It is also possible to have the back-up relay first try to trip the breaker of the faulty line before tripping all the other breakers.[5]

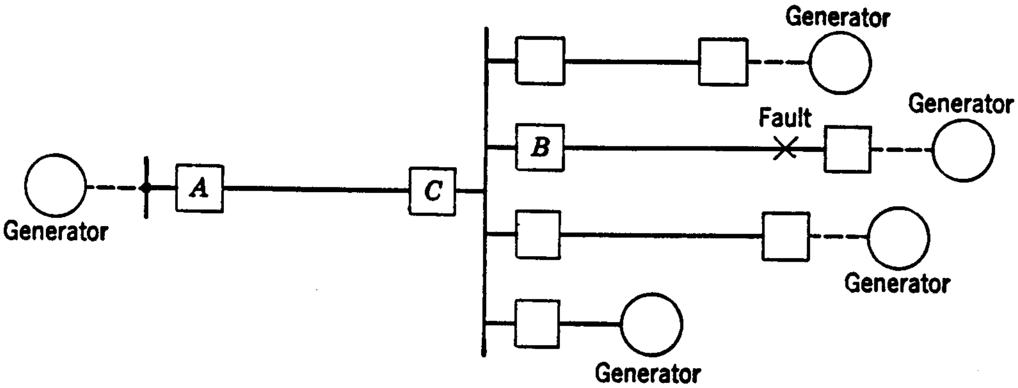

Fig. 7. A situation in which conventional back-up relaying is inadequate.

The back-up elements of mho-type distance relays can be made to operate for faults in the direction opposite to the conventional back-up direction. In fact, the reversed back-up direction, called "reversed third zone," is normally provided when mho-type distance relays are used with directional-comparison carrier-current-pilot relaying. This feature gives some relief in the problem of reaching far enough to provide back-up protection for adjoining line sections, since the backup elements, being closer to these adjoining line sections, do not have to reach so far. Referring to Fig. 7, for example, if the back-up elements located at breaker *C* are arranged to operate for current flow toward the fault, their reach can be reduced by the distance from *A* to *C* as compared with back-up elements at *A* looking toward the fault.

Various other solutions have been resorted to, depending on how many different possibilities of failure one may wish to anticipate.[6]

OVERREACH BECAUSE OF OFFSET CURRENT WAVES

Distance relays have a tendency to overreach, similar to that described in Chapter 13 for overcurrent relays, when the fault current contains a d-c offset. Other things being equal, the tendency to overreach is greatest in magnetic-attraction types of distance relays, and particularly in the impedance type where the contact-closing torque is generated by current alone. The tendency is the least with induction-type relays.

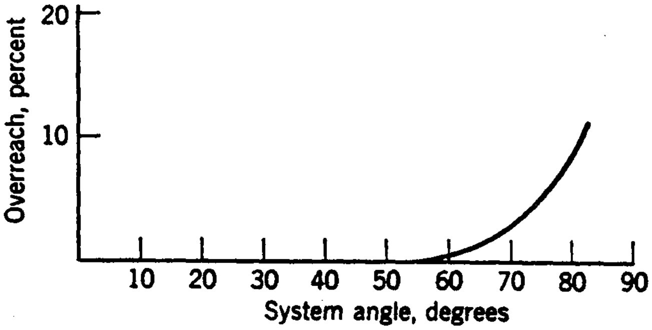

Fig. 8. Overreach characteristic of a certain distance relay.

"Percent overreach" for distance relays has been defined as follows:

$$\text{Percent overreach} = 100\left(\frac{Z_O - Z_S}{Z_S}\right)$$

where Z_O = the maximum impedance for which the relay will operate with an offset current wave, for a given adjustment.

Z_S = the maximum impedance for which the relay will operate for symmetrical currents, for the same adjustment as for Z_O.

As for overcurrent relays, the percent overreach increases as the system angle ($\tan^{-1} X/R$) increases. This angle increases with higher-voltage lines because the greater spacing between conductors makes the inductive reactance higher. Figure 8 shows a curve of percent overreach versus the system angle for one type of distance relay.

The overreach of a distance relay is of concern usually only for the first- or high-speed zone. The reaches of the intermediate and back-up zones are usually not nearly as critical as the reach of the first zone. Also, the intermediate and back-up-zone time delays are long enough for the offset to die out and to permit a distance unit to reset if it has overreached and if it is a type of unit whose reset is practically equal to its pickup.

The greater the first-zone overreach, the less of the line may the first zone be adjusted to protect. If the current wave were always fully offset, one could adjust

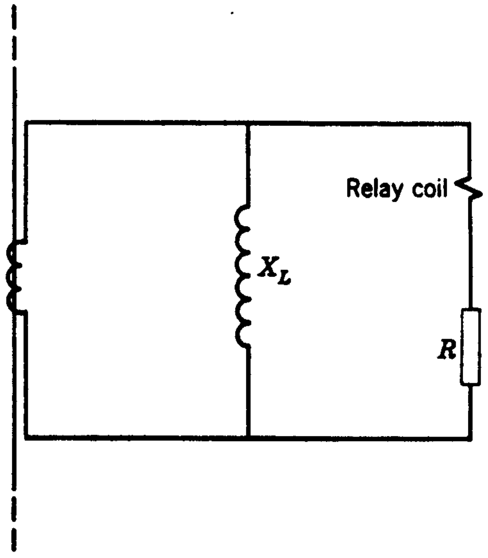

Fig. 9. A transient shunt to minimize overreach.

the relay, relying on overreach, so as to protect the desired portion of the line at high speed. But the current wave will rarely be fully offset; it will usually have little offset. Therefore, one cannot depend on *I* overreach, and less than the desired portion of the line will usually be protected at high speed. If the relays at both ends of the line are considered, and if each protects *P* percent of the line from its end at high speed, only the middle (2*P* – 100) percent of the line is protected at high speed at both ends simultaneously.

A device called a "transient shunt," shown in Fig. 9, has been used to minimize overreach with relays whose overreach might otherwise be objectionable.[7] The inductive reactor (X_L) is designed to have a very low resistance component so as to provide a low-impedance by-pass for the d-c component; the reactance is made high to block out most of the symmetrical a-c component. The resistor (R) in series with the relay coil may or may not be needed, depending on the impedance characteristic of the relay coil; the resistor is used, when necessary, to avoid a transient in the relay circuit that would occur if X/R of the relay circuit approached X/R of X_L.

OVERREACH OF GROUND DISTANCE RELAYS FOR PHASE FAULTS

Reference 8 shows that if phase-to-neutral voltage and compensated phase current are used, one of the three ground distance relays may overreach for phase-to-phase or two-phase-to-ground faults. This is not a transient effect like overreach because of offset waves; it is a consequence of the fact that such ground relays do not measure distance correctly for interphase faults. (Phase distance relays do not measure distance correctly for single-phase-to-ground faults, but, fortunately, they tend to underreach.) For this reason, it is necessary to use supplementary relaying equipment that will either permit tripping only when a single-phase-to-ground fault occurs or block tripping by the relay that tends to overreach.

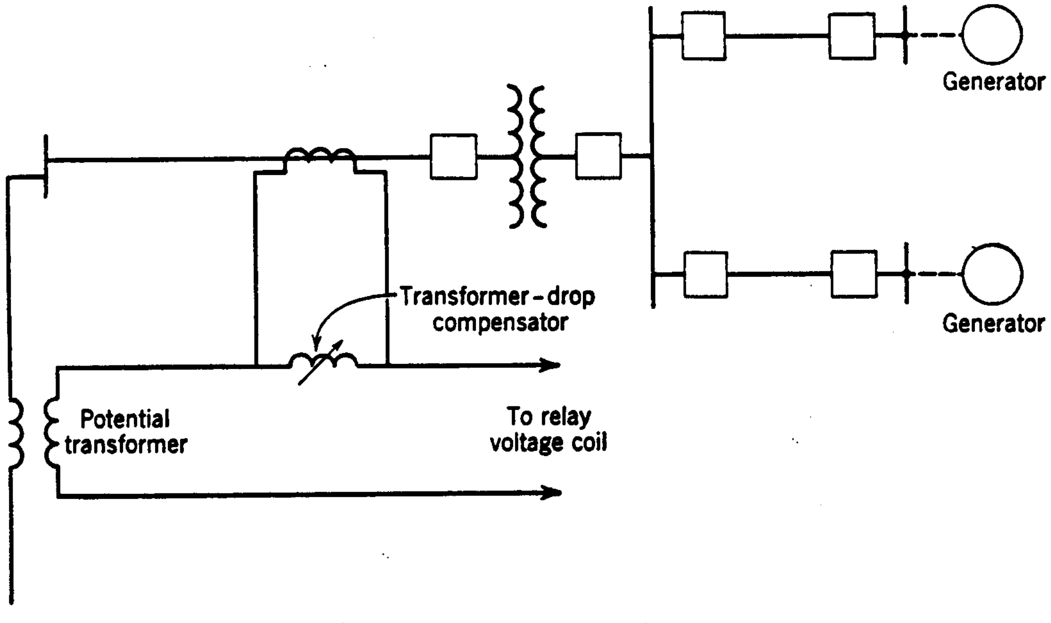

Fig. 10. Transformer-drop compensator for distance relays.

Chapter 8 shows the connections of potential transformers for obtaining the proper voltages. It is emphasized that a low-tension source is not reliable unless there are two or more paralleled power-transformer banks with separate breakers; with only one bank, the source will be lost if this bank is taken out of service.

Whenever two or more high-voltage lines are connected to generating sources, as in Fig. 10, "transformer-drop compensation" should be used. For reasons to be given later, it is not sufficient merely to provide the relays with voltages that correspond in phase to the high-tension voltages that would be used if they were available; it is further necessary to correct for the voltage rise or drop in the transformer bank. In other words, by means of transformer-drop compensation, we take into account the fact that, in terms of per unit quantities:

$$V_H = V_L - I_T Z_T$$

where V_H = the high-tension voltage.

V_L = the low-tension voltage.

I_T = the current flowing from the low-tension side toward the high-tension side.

Z_T = the transformer impedance.

Figure 10 shows schematically how the low-tension current is used to produce a voltage that is added to the low-tension voltage in order to provide the relays with a voltage corresponding in phase and magnitude to that on the high-voltage side. Reference 9 gives detailed descriptions of actual connections.

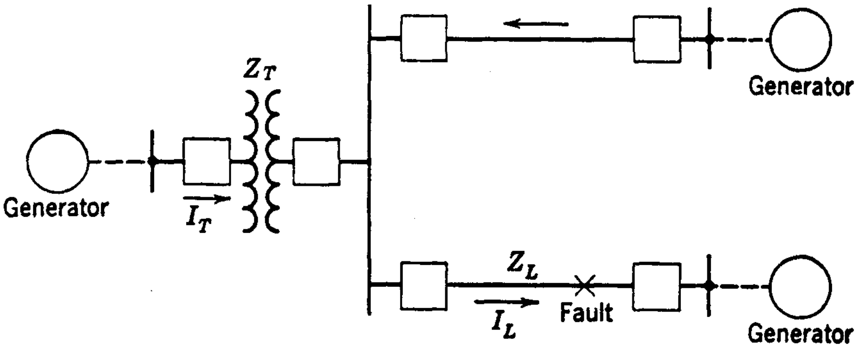

Fig. 11. Illustrating the need for transformer-drop compensation.

Transformer-drop compensation is required for Fig. 10 whether or not a generating source may be connected to the low-voltage side of the transformer bank. Synchronous motors may be considered such a source. Consider Fig. 11 in which a source is assumed to exist. Without transformer-drop compensation, and for a fault at the end of the line, the relays would see an impedance:

$$Z = \frac{I_T Z_T + I_L Z_L}{I_L} = \frac{I_T}{I_L} Z_T + Z_L$$

where Z_L is the per unit line impedance. It will be realized that I_T/I_L can be any value from zero to unity, depending on how the system is being operated; consequently, without transformer-drop compensation, the distance relays must be adjusted for $I_T/I_L = 0$ so as not to overreach. Then, for other values of I_T/I_L, the relays will underreach, and underreaching is objectionable because less of the line is protected at high speed. With transformer-drop compensation, most of the first term is eliminated and the relays see practically the correct impedance Z_L, regardless of I_T/I_L, thus minimizing underreaching.

Even if there is never to be a source of generation on the low-voltage side, transformer-drop compensation is still necessary if there are two high-voltage lines either of which may be connected to a generating source. Consider the case of Fig. 12 in which a fault has occurred on the low-voltage side, and some load current continues to flow in line *A* on the high-voltage side. Without transformer-drop compensation, one or more of the relays of *A* would be likely to operate because there might be little or no voltage restraint but sufficient voltage for polarization to cause undesired tripping. Compensation would eliminate such a possibility. This possibility exists only when there are two or more high-voltage lines either of which may be connected to a generating source at its far end; otherwise, load current could not flow as in Fig. 12.

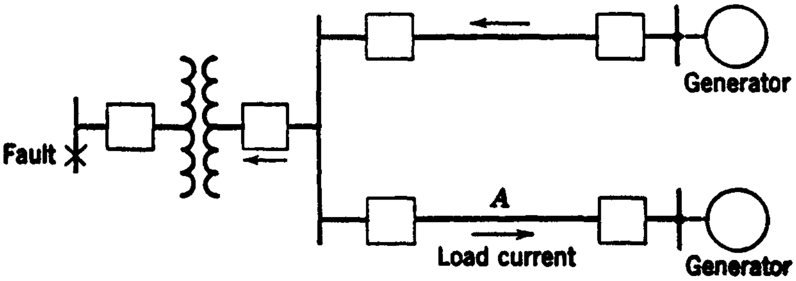

Fig. 12. Another instance in which transformer-drop compensation is needed.

Great care must be taken to avoid overcompensation. If the transformer drop is overcompensated, and if a short circuit that reduced the high-tension voltage to zero should occur on the protected line at the end where transformer-drop compensation is used, the relay voltage would be reversed in phase. This would prevent operation of the relays of the faulted line and would cause undesired operation of the relays of other lines supplying current to the fault. In order to avoid the possibility of overcompensation, the transformer drop should be undercompensated by an amount sufficiently large to take into account the effect of errors in the equipment and in the data on which the calculations are based.

Errors in compensation also affect the reach of the distance relays, and must be carefully considered so as to avoid overreach. In practice the high-speed reach of distance relays is adjusted to about 80% to 90% of the sum of the uncompensated part of the transformer impedance plus the line impedance for a fault at the far end of the line. In other words, if we use 90%

$$R = 0.9\left[\frac{(1-C)I_T Z_T + I_L Z_L}{I_L}\right]$$

where R = the high-speed reach of the distance relays.

C = the fraction of the total transformer drop that is intended to be compensated, neglecting any errors in the compensation.

I_T, Z_T, I_L, and Z_L are as previously defined. The *actual* uncompensated part of the effective transformer impedance, taking into account the effect of error, is:

$$Z_{TU} = [(1 - C) - EC]\,\frac{I_T Z_T}{I_L}$$

where E = the fractional error in C, being positive when the actual compensation is greater than C.

Therefore, the amount of the line (R_L) that is actually protected when the relay is adjusted for reach R is:

$$\begin{aligned} R_L &= R - Z_{TU} \\ &= [-0.1\,(1 - C) + EC]\,\frac{I_T Z_T}{I_L} + 0.9 Z_L \end{aligned}$$

Now, it would be undesirable for R_L to exceed $0.9Z_L$ because we need $0.1Z_L$ as a factor of safety against overreaching because of other reasons that are always applicable whether we have transformer-drop compensation or not. Therefore, the first term of the equation for R_L, must be practically zero or be negative. If we let the first term be zero, we lose the significance of $I_T Z_T / I_L$; so let us assume that the first term is 10% of our factor of safety, or $0.01Z_L$. In other words:

$$0.01 Z_L = [-0.1\,(1 - C) + EC]\,\frac{I_T Z_T}{I_L}$$

Solving for E we get:

$$E = \frac{Z_L I_L}{100C(Z_T I_T)} + 0.1\;\frac{(1 - C)}{C}$$

Let $Z_L I_L / Z_T I_T = N$. Then:

$$E = \frac{0.01N + 0.1\,(1 - C)}{C}$$

For any value of compensation, this equation gives the maximum positive error in the compensation that we can tolerate without having the relay's reach exceed 91% of the line length. An error of about ±3% is reasonable to expect, which permits about 80% to 90% compensation.

Negative compensation error will cause underreaching. This is objectionable also because less of the line will be protected at high speed, but it can be tolerated if necessary.

When a single line terminates in a power transformer with a low-voltage generating source, transformer-drop compensation offers no benefit unless it is so accurate that more than 90% of the transformer drop can be safely compensated, which is not apt to be the case. In practice compensation is not used, but the reach of the distance relays is adjusted for 80% to 90% of the sum of the transformer impedance plus the line impedance. Thus, if we adjust for 90%,

$$R = 0.9\;(Z_T + Z_L)$$

The amount of the line (R_L) that is protected with this reach is:

$$R_L = 0.9\ (Z_T + Z_L) - Z_T$$

$$= 0.9Z_L - 0.1Z_T$$

If low-tension voltage is to be obtained from one low-tension side of a three-winding power-transformer bank having generating sources on both low-tension sides, it becomes necessary to use two sets of transformer-drop compensators. The details of this application are presented in Reference 9.

It will probably be evident from the foregoing that low-tension voltage for distance relays is an inferior alternative to high-tension voltage.[10] It will not permit the full capabilities of the relays to be realized, and, unless great care is taken in the adjustment of the equipment, it may even cause faulty operation.

USE OF LOW-TENSION CURRENT

Where a suitable current-transformer source of current for distance relays is not available in the high-voltage circuit to be protected, a source on the low-voltage side of an intervening power-transformer bank may be used. This practice is usually followed for external-fault back-up relays of unit generator-transformer arrangements. Low-tension current may infrequently be used where a line terminates in a power-transformer bank with no high-voltage breaker. In either of such circumstances, the possibility of losing the current source is not a consideration, as with a low-tension-voltage source, because the current source is not needed when the transformer bank is out of service.

When low-tension current is used where a line terminates in a transformer bank without a high-voltage breaker, it is theoretically possible that occasionally the distance relays might operate undesirably on magnetizing-current inrush. If such operation is possible, it can be avoided, if desired, by the addition of supplementary equipment that will open the trip circuit during the inrush period; such equipment uses the harmonic components of the inrush current in a manner similar to that of the harmonic-current-restraint relay described in Chapter 11 for power-transformer protection. However, there is really no need for concern. The probability of getting enough inrush current to operate a distance relay is quite low. In those infrequent cases in which a distance relay does operate to trip the transformer breaker, one may merely reclose the breaker and it probably will not trip again; this is permissible so long as the transformer-differential relay has not operated. As mentioned in Chapter 11, tripping on magnetizing-current inrush is objectionable only because one cannot be sure if it was actually an inrush or a fault that caused tripping; but, if the transformer-differential relay has not operated, one can be sure that it was not a transformer fault.

To use low-tension current, it is necessary to supply the relays with the same current components as when high-tension current is used. It will be seen from Chapter 9 that phase distance relays use the difference between the currents of the phases from which their voltage is obtained. (When high-tension current is used, this phase-difference–or so-called "delta" current is obtained either by connecting the high-voltage CT's in delta or by providing two current coils on the magnetic circuits of each relay and passing the two phase currents through these coils in opposite directions. The two-coil type of relay has the advantage of permitting the CT's to be connected in wye; this is preferred because it avoids auxiliary CT's when the wye connection is needed for ground relaying.)

Figure 13 shows the current connections for one of the three distance relays used for interphase-fault protection; these connections are for a two-coil type of relay that uses the high-tension voltage V_{ab}. The connections *A* are the connections if high-tension CT's are available, and *B* and *C* are alternative low-tension connections. The power transformer is assumed to have the standard connections described in Chapter 8 for the voltage phase sequence *a-b-c*. The terminals of the two coils are labeled for each connection so that the three connections can be related. If we assume that each relay coil has *N* turns, the ampere-turns for each connection are as in the accompanying table. The significant thing about the three ampere-turns expressions is that all of them contain $(I_a - I_b)$ as required for proper distance measurement. That the ampere-turns of *B* and *C* are, respectively, 3 times and 2 times those of *A* is merely a consequence of the unity transformation ratios assumed for the power transformer and the CT's. However, connection *C* is different from the other two in that, if balanced three-phase currents of the same magnitude are supplied to the terminals of relays connected as in *A* (or *B*) and *C*, the ampere-turns of the relays of *C* will be $2/\sqrt{3}$ times the ampere-turns of the relays of *A* (or *B*). Since the adjustment procedure

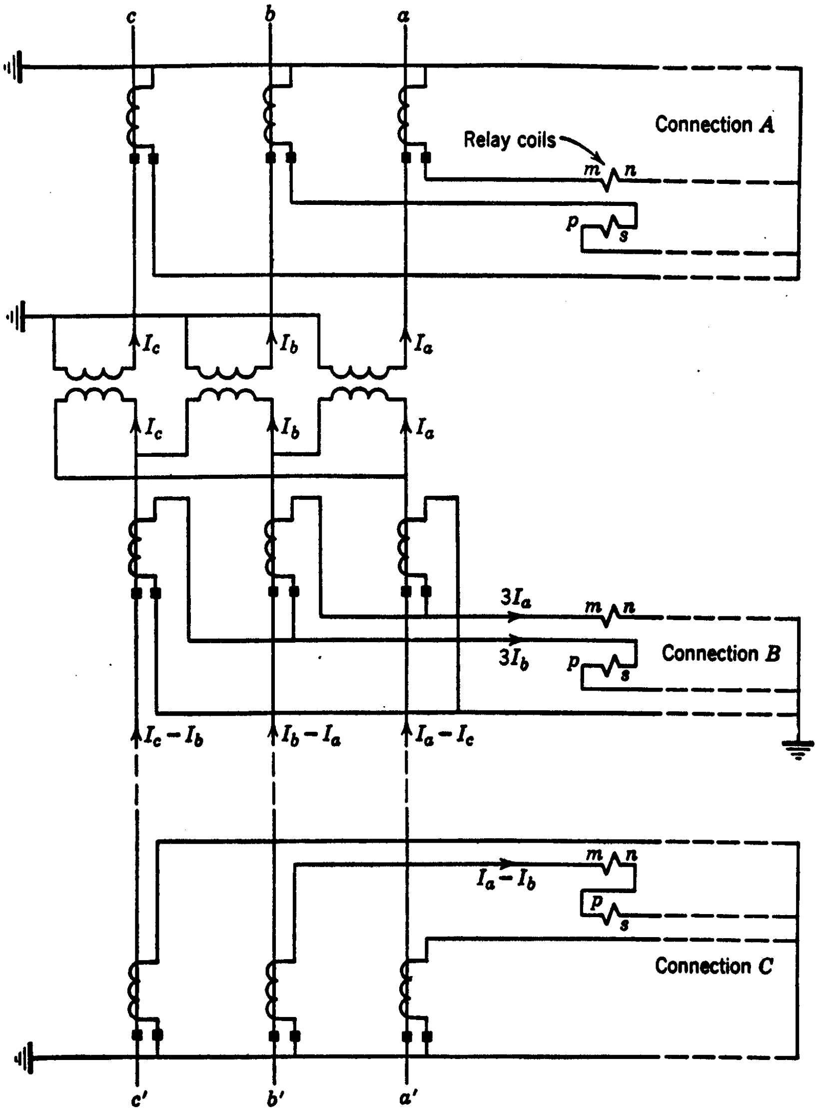

Fig. 13. Low-tension-current connections for a two-coil distance relay.

for such relays is usually given for the connections of *A*, the difference in ampere-turns can be taken care of by assuming that the magnitude of the current supplied to C is $2/\sqrt{3}$ times that supplied to *A*, or, in other words, that the CT ratio for *C* is $\sqrt{3}/2$–or 87%– of its actual value. The actual CT ratio for any connection is the ratio of the high-voltage-circuit phase-current magnitude to the relay phase-current magnitude under normal balanced three-phase conditions.

Connection	Ampere-Turns
A	$(I_a - I_b)N$
B	$3(I_a - I_b)N$
C	$2(I_a - I_b)N$

Figure 14 shows the high-tension and low-tension current connections for a single-coil type of distance relay. The CT ratio is the same as that defined in the preceding paragraph.

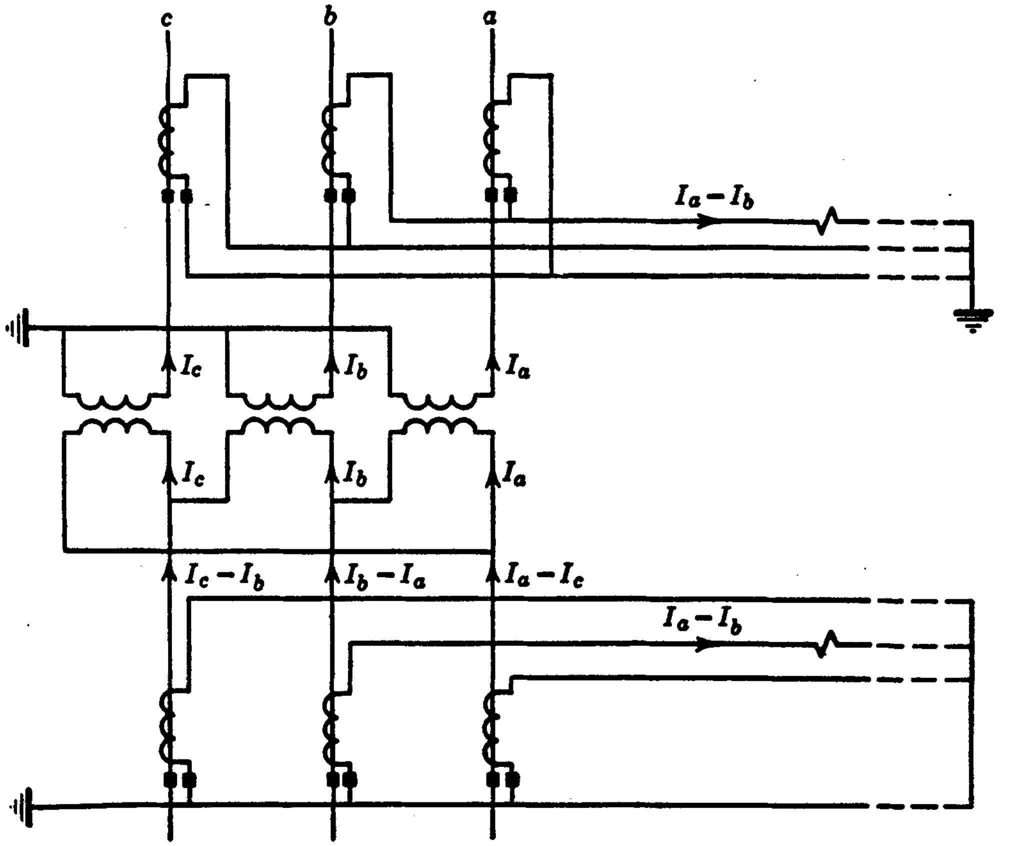

Fig. 14. Low-tension-current connections for a single-coil distance relay.

EFFECT OF POWER-TRANSFORMER MAGNETIZING-CURRENT INRUSH ON DISTANCE-RELAY OPERATION

The effect of power-transformer magnetizing-current inrush on distance-relay operation is also discussed under the heading "Use of Low-Tension Current." It is the purpose here to consider the case of inrush to the HV windings of the transformers at the far end or ends of a line.

The writer does not know of any cases of tests, theoretical studies, or actual trouble in this respect. Therefore, it is concluded that, if the possibility of distance-relay misoperation exists, it must be extremely remote. The most severe inrush that can occur in existing conventional power transformers would be less likely to operate a distance relay than would a three-phase fault on the other side of the transformer bank. This is because the rms magnitude of the initial inrush current is generally less than that of the fault current. Furthermore, the inrush contains harmonic currents to which certain relays do not respond as well as to the fundamental components. The high-speed zone of a distance relay is not permitted to reach through transformers at the far ends of a line, and, therefore, if any relay unit is to operate it would have to be either the second- or third-zone unit. These units generally have enough time delay so that the inrush will have subsided considerably before a unit could operate, which further lessens the likelihood of their operation. And, finally, the distance relays in question will usually get only a part of the inrush current in those cases in which misoperation would be most objectionable, such as when energizing a transformer bank tapped to an important line. Therefore, there is little wonder that this subject is not cause for concern.

THE CONNECTIONS OF GROUND DISTANCE RELAYS

Reference 11 shows that for accurate distance measurement, a ground relay may be supplied with a phase-to-neutral voltage and the sum of the corresponding phase current and an amount proportional to the zero-phase-sequence current. If there is another line nearby that can induce voltage in the line under consideration when a ground fault occurs anywhere, there must also be added to the phase current an amount proportional to the zero-phase-sequence current of the other line. The addition of these zero-phase-sequence quantities is called "current compensation." Reference 11 also describes an alternative to current compensation called "voltage compensation," whereby the voltage is compensated by zero-phase quantities. Compensation is necessary because variations in the distribution of zero-phase-sequence current relative to the distribution of positive- and negative-phase-sequence current would otherwise cause objectionable errors in distance measurement.

Ground distance relays can also be energized by zero-phase-sequence-voltage drop and zero-phase-sequence current to measure distance by measuring the zero-phase-sequence impedance.[12]

OPERATION WHEN PT FUSES BLOW

Distance relays that are capable of operating on less than normal load current may operate to trip their breaker when a potential-transformer fuse blows. In one system, blown fuses caused more undesired tripping than any other thing until suitable fusing was provided.[13]

Since potential-transformers are generally energized from a bus and supply voltage to the relays of several lines, it is advisable to provide separate voltage circuits for the relays of each line and to fuse them separately if fusing is to be used at all. With separate fusing, trouble in the circuit of one set of relays will not blow the fuses of another circuit. The principal objection to bus PT's is that "all the eggs are in one basket"; but, with separately fused circuits, this objection is largely eliminated.

Neon lamps should be used for pilot indication of the voltage supply to each set of distance relays.

When the relays do not have to operate on less than load current, instantaneous overcurrent units can be used to prevent tripping for a blown fuse during normal load conditions. The overcurrent-relay contacts are in series with the trip circuit. Undesired tripping is still possible should a fault occur before the blown fuse has been replaced; it is to minimize this possibility that the indicating lamps are recommended. If the ground-fault current is high enough, a single set of three instantaneous overcurrent relays can be used separately from the distance relays to prevent undesired tripping by either the phase or ground relays; otherwise, a single ground overcurrent relay would be used for the ground relays.

PURPOSEFUL TRIPPING ON LOSS OF SYNCHRONISM

When generators have gone out of synchronism, all ties between them should be opened to maintain service and to permit the generators to be resynchronized. The separation should be made only at such locations that the generating capacity and the loads on either side of the point of separation will be evenly matched so that there will be no interruption to the service.[14] Distance relays at those locations are sometimes suitable for tripping their breakers on loss of synchronism, and in some aystems they are used for this purpose in addition to their usual protective functions. However, as mentioned in Chapter 9, additions or removals of generators or lines during normal operation will often change the response of certain distance relays to loss of synchronism. Therefore, each application should be examined to see if certain distance relays can always be relied on to trip.

A completely reliable method of tripping at preselected locations is available.[15] This relaying equipment contains two angle-impedance units as described in Chapter 4, an overcurrent unit, and several auxiliary relays. It is a single-phase equipment, which is all that is necessary because loss of synchronism is a balanced three-phase phenomenon. The two angle-impedance units use the same one of the three combinations of current and voltage used by phase distance relays for short-circuit protection. Figure 15 shows the operating characteristics of the two angle-impedance units on an *R-X* diagram, together with a loss-of-synchronism characteristic for the relay's location on a tie line connecting the

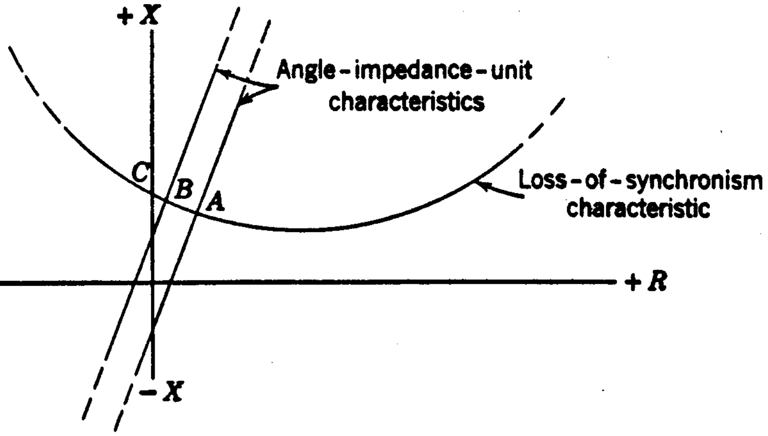

Fig. 15. Relay for tripping on loss of synchronism.

generators that have lost synchronism. The significant feature of the equipment is that the two angle-impedance units divide the diagram into the three regions *A, B,* and *C*. As the impedance changes during loss of synchronism, the point representing this impedance moves along the loss-of-synchronism characteristic from region *A* into *B* and then into *C*, or from *C* into *B* and then into *A*, depending on which generators are running the faster. As the point crosses the operating characteristic of an angle-impendance unit, the unit reverses its direction of torque and closes a contact to pick up an auxiliary relay. As the impedance point moves into one region after another, a chain of auxiliary relays picks up, one after the other. When the third region is entered, the last auxiliary relay of the chain picks up and trips its breaker. There are two such chains–one for each direction of movement–and the contacts of the two last auxiliary relays of the chains are connected in parallel so that either one can trip the breaker.

The purpose of the overcurrent unit is to prevent tripping during hunting between the generators at light load. This condition is represented by movement along a portion of the loss-of-synchronism characteristic diametrically opposite to the portion shown in Fig. 15. Such movement would also fulfill the requirements for tripping that have been described. Relatively very little current flows during hunting at light load compared with the high current flowing when generators pass through the 180° out-of-phase position which is in the *B* region on the portion of the loss-of-synchronism characteristic shown in Fig. 15. Therefore, the overcurrent unit's pickup can be adjusted so that the equipment will select between hunting and loss of synchronism.

No other condition can cause the impedance point to move successively through the three regions, and therefore the equipment is completely selective.

Changes in a system cannot cause the equipment to fail so long as there is enough current to operate the overcurrent unit when synchronism is lost. The loss-of-synchronism characteristic may shift up or down on the *R-X* diagram, or the characteristic may change from one of overexcitation to one of underexcitation, without adversely affecting the operation of the equipment.

When tripping is desired at a location where the current is too low to actuate a loss-of-synchronism relay, remote tripping is necessary over a suitable pilot channel from a location where a loss-of-synchronism relay can be actuated.[16]

When two or more loss-of-synchronism relays are used at different locations, one or more of these relays may need a supplementary single-step distance unit because the overcurrent units may not provide the desired additional selectivity.

The locations where tripping is desired on loss of synchronism may change from time to time as the relations between load and generation change. Under such circumstances, it is desirable to have installations of loss-of-synchronism-relay equipments at several locations so that the load dispatcher can select the equipments to be made operative during any period.

In lieu of complete freedom to choose the best locations to separate parts of a system when synchronism is lost, it may be necessary to resort to some automatic "load shedding." By such means, nonessential load can be dropped automatically either directly when the tie breakers are tripped or indirectly through the operation of relays such as the underfrequency type. This subject is treated in detail in Reference 24 of Chapter 13.

Tripping at certain locations is required when generators lose synchronism, but it should be limited to those locations only. If distance relays at any other locations have a tendency to trip, supplementary relaying equipment should be used to block tripping there. Also, wherever tripping can occur during severe power swings when a system is recovering from the effects of a shock, such as that caused by a short circuit, equipment to block tripping is most desirable; tripping a sound line that is carrying synchronizing power would very likely cause instability.

The method by which tripping on loss of synchronism can be blocked is very ingenious.[17] Consider the *R-X* diagram of Fig. 16. The point *P* represents the impedance for a three-phase fault well within the operating characteristic of an impedance-type distance relay. Assuming that the loss-of-synchronism characteristic passes through *P*, the problem, then, is to devise a selective relaying equipment that will permit tripping when the fault represented by *P* occurs, but not when loss of synchronism reaches a stage that is also represented by *P*. The way in which this selection is made is based on the fact that the change in impedance from the operating conditions just before the fault is instantaneous, whereas the change in impedance during loss of synchronism is relatively slow. The method used for recognizing this difference is to encircle the distance-relay characteristic with a blocking-relay characteristic such as that shown on Fig. 16. (For balanced three-phase conditions, such as those during loss of synchronism, all three phase distance relays see the same impedance; therefore, the one characteristic represents all three relays.) Then, a control circuit is provided so that, if the blocking relay operates sufficiently ahead of a distance relay, as when the impedance is changing from *S* to *T*, the distance-relay trip circuit will be opened. But, if the impedance changes instantly to any value such as *P* inside the distance-relay characteristic, the trip circuit will not be opened.

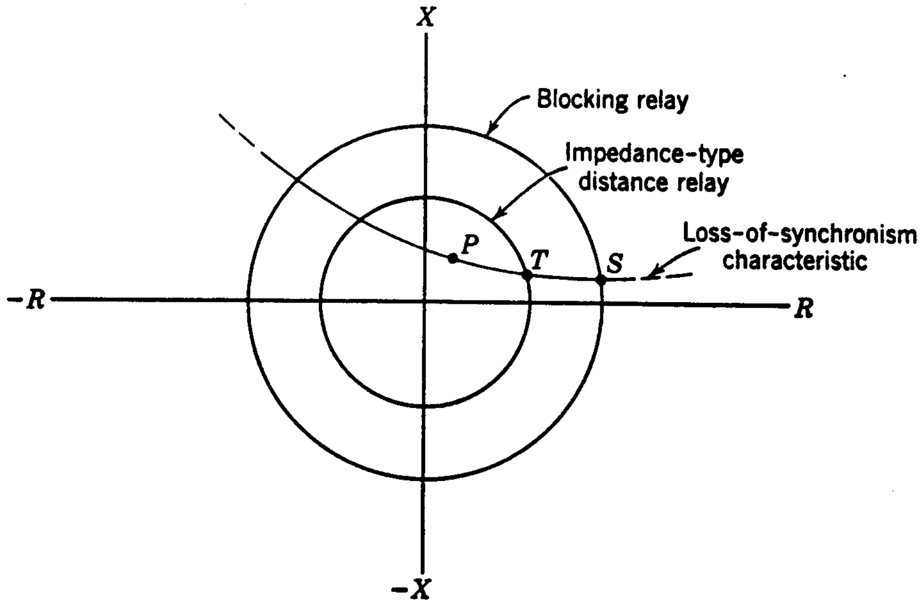

Fig. 16. Relay characteristics of equipment of Fig. 17.

The circuit for blocking tripping is shown in Fig. 17. If the blocking relay closes its contact to energize the coil of the auxiliary relay before any distance relay closes its contact to short out the auxiliary-relay coil, the auxiliary relay will pick up and open its contact in the trip circuit. The subsequent closing of a distance-relay contact in the circuit around the auxiliary-relay coil will be ineffective because the auxiliary relay will have opened its contact in this circuit. The auxiliary relay is given a little time delay to pick up so as to be sure that it will not pick up when a fault occurs requiring tripping, and the distance and blocking relays close contacts practically together.

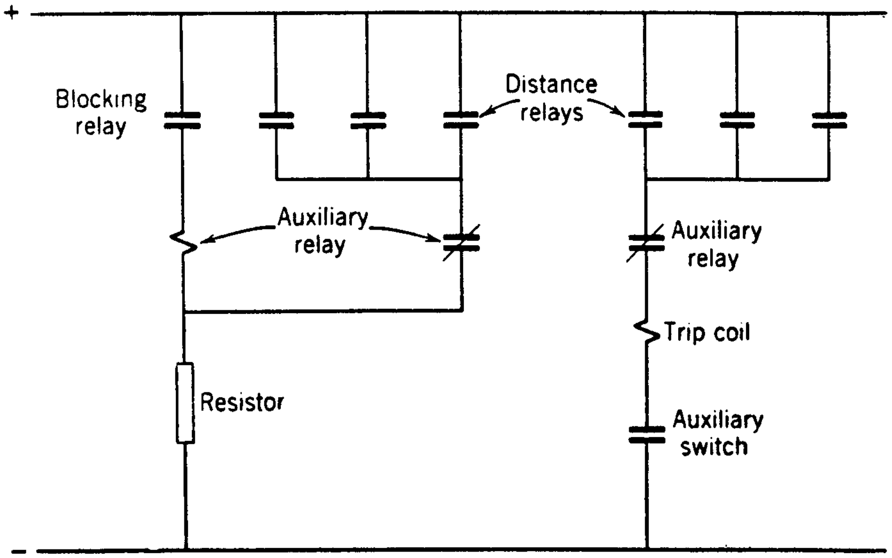

Fig. 17. Equipment for blocking tripping on loss of synchronism.

The blocking relay may be an impedance type or a mho type so long as its characteristic encircles the characteristic of the distance relays whose tripping is to be blocked. In practice the blocking relay is single phase. At one time, some considered three blocking relays necessary because a fault might still be on the system when blocking was required. Today, this is thought to be an unnecessary complication because of the general use of relatively high-speed relays. A single-phase blocking relay is permissible because loss of synchronism is a balanced three-phase phenomenon. The blocking relay uses the same voltage-and-current combination as one of the phase distance relays. Ground distance relays using phase-to-neutral voltage and compensated phase current could also tend to trip, and, therefore their tripping should also be blocked.

AUTOMATIC RECLOSING

Chapter 13 introduces the subject of automatic reclosing and describes the practices with overcurrent relaying. Here, we are concerned with the practices with distance relaying. Lines protected by distance relays usually interconnect generating sources. Consequently, the problem arises of being sure that both ends are in synchronism before reclosing. "High-speed reclosing," defined here as reclosing the breaker contacts in about 20 cycles after the trip coil was energized to trip the breaker, cannot be used because of the inherent time delay of distance relaying for faults near the ends of a line. In order to be sure that an arc will not restrike when reclosing the line breakers, the line has to be disconnected at both ends for a time long enough for the ionized gas in the arc path to be dispersed. This takes from about 6 to 16 cycles, depending on the magnitude of the arc current and the system voltage, the average being about 8 to 10 cycles.[18] To provide this time with high-speed reclosing, both ends of a line must be tripped practically simultaneously. Since, with distance relays, one end may trip 6 to 12 cycles or more ahead of the other, depending on the intermediate-time adjustment, this additional time must be added to the reclosing cycle. In other words, about the fastest permissible reclosing time with distance relays is 26 to 32 cycles or longer. The only exceptions are lines with wye-delta power transformers at both ends; there simultaneous high-speed tripping is possible.

Because of the foregoing reclosing times and also the fact that inverse-time-overcurrent relays are generally used for ground-fault protection, such lines require synchronism check, as described in Chapter 13. Of course, one end of a line can be reclosed without synchronism check. Synchronism check is unnecessary if there are enough other interconnections between the generating sources that the line interconnects so that one can be sure that both sides will always be in synchronism. Automatic reclosing can be very harmful if it causes the connection of parts of a system that are out of synchronism; this is known to have been the "last straw" that caused a major system shutdown.

It is usually the practice to provide one immediate (which is slower than high-speed) reclosure followed by 2 or 3 time-delay reclosures and then lockout if the fault persists.

When a line ends in a power-transformer bank with no high-voltage breaker, but with a grounding switch for remote tripping in the event of a transformer-bank fault, automatic reclosing of the remote breaker is affected. Some users adjust ground-distance relays' first-zone reach to 80% to 90% of the line (i.e., not to reach to the transformer) in order that the first-zone unit will not operate when the grounding switch is closed. Then, automatic reclosing is permitted only if a first-zone unit operates, thereby avoiding reclosing on the grounding switch and a transformer fault. If a three-phase grounding switch is used, the high-speed zone of the remote distance relays may be permitted to reach into the transformer bank; this will permit automatic reclosure on the grounding switch without harming the transformer, which may be permissible if the shock to the system is not too great.

EFFECT OF PRESENCE OF EXPULSION PROTECTIVE GAPS

It is generally necessary to delay tripping by the high-speed zone of distance relaying if a line is equipped with expulsion protective gaps. A minimum relay-operating time of 2 or 3 cycles is usually sufficient to prevent high-speed-relay tripping while an expulsion protective gap is functioning. This additional delay in the tripping time is provided by the addition of an auxiliary relay. The tripping circuit should be carried through the protective-relay contacts to avoid undesired tripping because of overtravel of the auxiliary relay.

EFFECT OF A SERIES CAPACITOR

A series capacitor can upset the basic premises on which the principles of distance and directional relaying are founded. These premises are (1) that the ratio of voltage to current at a relay location is a measure of the distance to a fault, and (2) that fault currents are approximately reversed in phase only for faults on opposite sides of a relay location. A series capacitor introduces a discontinuity in the ratio of voltage to current, and particularly in the reactance component of that ratio, as a fault is moved from the relay location toward and beyond a series capacitor. One can easily visualize the effect by plotting the impedance points on an *R-X* diagram. As a fault is moved from the relay side of the capacitor to the other side, the capacity reactance subtracts from the accumulated line reactance between the relay and the fault. As a consequence, the fault may appear to be much closer to the relay location or it may even have the appearance to some relays of being back of the relay location.

One way that series capacitors are used[19] minimizes their adverse effect on distance relays. A single capacitor bank is chosen to compensate no more than about half of the reactance of a given line section; if a higher degree of compensation is used, the capacitors are divided into two or more banks located at different places along a line. Also, a protective gap is provided across each capacitor bank, and this gap flashes over immediately when a fault occurs and effectively shorts out the capacitor bank while fault current flows. In other words, the capacitor banks are in service normally, are shorted out while a fault exists, and are returned to service immediately when the faulty line section is tripped.

Where capacitors are located otherwise, it will probably be necessary to add slight time delay to the distance-relay trip circuit. For fault currents that are too low to dash over the capacitor gap, it may be necessary to use phase-comparison relaying, probably with greater-than-normal sensitivity.

COST-REDUCTION SCHEMES FOR DISTANCE RELAYING

Many ways have been suggested for reducing the cost of highspeed distance relaying so that its use on lower-voltage circuits could be justified. What has been sought is a “class of protection somewhere in the middle ground between the cost, performance, and complexity of overcurrent and conventional 3-zone distance relays.”[20] These schemes may be classified as follows:

(*a*) Abbreviated relays.[20]

(*b*) Three conventional relays for phase faults and three conventional relays for ground faults, except that certain units are used in common.[21]

(*c*) Three conventional relays for both phase and ground faults by means of “current and voltage switching.”[22]

(*d*) One conventional relay for phase faults and/or one conventional relay for ground faults by means of current and voltage switching.[12,23]

(*e*) One conventional relay for both phase and ground faults by means of current and voltage switching.[22]

Current and voltage switching is a means for automatically connecting the relay to the proper current and voltage sources so that it will measure distance correctly for any fault that occurs.

With the possible exception of (*e*), all these schemes are in use in this country, although none of them very extensively. The greater the departure from the conventional arrangement of three phase and three ground relays, the poorer is the quality of relaying. They either have more time delay, are harder to apply, are less accurate, or require more frequent maintenance. Voltage switching may not be permitted with capacitance potential devices because of the errors that result from changing the burden. It is probably economically feasible to standardize on one intermediate arrangement, but there is little justification for much more.

To complete the list, other combinations of units should be included, most of which may be classified as "abbreviated" relays. They consist of various combinations of units like those used in conventional high relays.[7] Such relays supplement existing relays for speeding up the protection. For example, three single-step directional-distance relays might supplement directional-overcurrent inverse-time relays; this would provide high-speed relaying for 80% to 90% of a line plus inverse-time-overcurrent relaying for the remainder of the line and for back-up protection.

ELECTRONIC DISTANCE RELAYS

Electronic distance relays have been extensively tested[24] that are functionally equivalent to conventional electromechanical distance relays, but that are faster and impose considerably lower burden on a-c sources of current and voltage. At the same time, they are more shock resistant. Their greater speed is most effective when they are used in conjunction with a carrier-current or microwave pilot. When they are used alone, it is still necessary to have some time delay for faults near the ends of a line, which tends to reduce the advantage of a higher-speed first-zone unit.

The lower-burden characteristic of electronic relays may contribute to less expensive current and voltage transformers, and therefore may increase the use of such relays even though the greater speed may not be required.

Apart from differences in physical characteristics, the basic principles of electromechanical distance relays and their application apply equally well to electronic distance relays.

PROBLEMS

1. Referring to Fig. 18, it has been determined that load transfer from *A* to *B* or from *B* to *A* prevents setting a distance relay at either *A* or *B* with a greater ohmic reach than just sufficient to protect a 100-ohm, 2-terminal line with a 25% margin (i.e., third-zone reach = 125 ohms).

a. What is the apparent impedance of the fault at X_1 to the relay at *A*? Can the relay at *A* see the fault before the breaker at *B* has tripped?

b. Can the relay at *B* see the fault at X_1 before the breaker at *A* has tripped? Why?

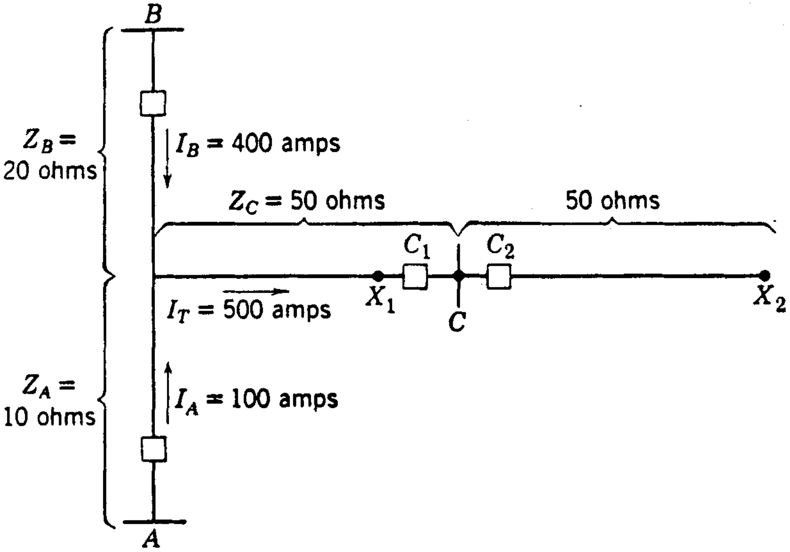

Fig. 18. Illustration for Problem 1.

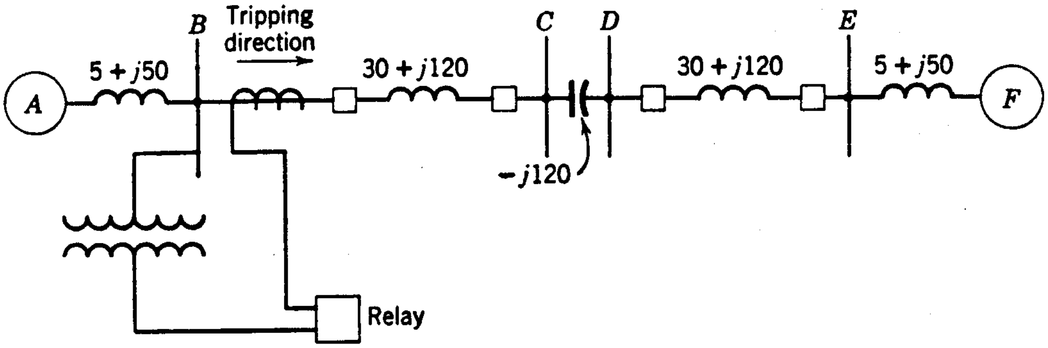

Fig. 19. Illustration for Problem 2.

c. If, for a fault at X_2, breaker C_2 fails to open, will the fault be cleared by relays at *A* and *B*? Assume the same relative fault-current magnitudes as for *a* and *b*.

d. By what means can the fault at X_2 be cleared?

2. Show the positive-phase-sequence impedances of the line sections and series capacitor of Fig. 19 on an *R-X* diagram as seen by phase distance relays at *B*, neglecting the effect of a protective gap across the capacitor. Comment on the use of distance and directional relays at *B*.

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