8 VOLTAGE TRANSFORMERS

Two types of voltage transformer are used for protective-relaying purposes, as follows: (1) the "instrument potential transformer," hereafter to be called simply "potential transformer," and (2) the "capacitance potential device." A potential transformer is a conventional transformer having primary and secondary windings. The primary winding is connected directly to the power circuit either between two phases or between one phase and ground, depending on the rating of the transformer and on the requirements of the application. A capacitance potential device is a voltage-transforming equipment using a capacitance voltage divider connected between phase and ground of a power circuit.

ACCURACY OF POTENTIAL TRANSFORMERS

The ratio and phase-angle inaccuracies of any standard ASA accuracy class[1] of potential transformer are so small that they may be neglected for protective-relaying purposes if the burden is within the "thermal" volt-ampere rating of the transformer. This thermal volt-ampere rating corresponds to the full-load rating of a power transformer. It is higher than the volt-ampere rating used to classify potential transformers as to accuracy for metering purposes. Based on the thermal volt-ampere rating, the equivalent-circuit impedances of potential transformers are comparable to those of distribution transformers.

The "burden" is the total external volt-ampere load on the secondary at rated secondary voltage. Where several loads are connected in parallel, it is usually sufficiently accurate to add their individual volt-amperes arithmetically to determine the total volt-ampere burden.

If a potential transformer has acceptable accuracy at its rated voltage, it is suitable over the range from zero to 110% of rated less voltage. Operation in excess of 10% overvoltage may cause increased errors and excessive heating.

Where precise accuracy data are required, they can be obtained from ratio-correction-factor curves and phase-angle-correction curves supplied by the manufacturer.

CAPACITANCE POTENTIAL DEVICES

Two types of capacitance potential device are used for protective relaying: (1) the "coupling-capacitor potential device," and (2) the "bushing potential device." The two devices are basically alike, the principal difference being in the type of capacitance voltage

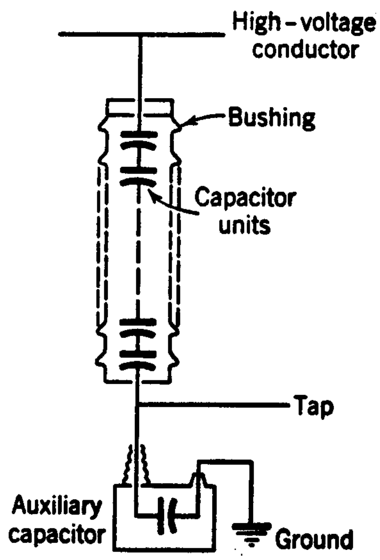

Fig. 1 Coupling-capacitor voltage divider

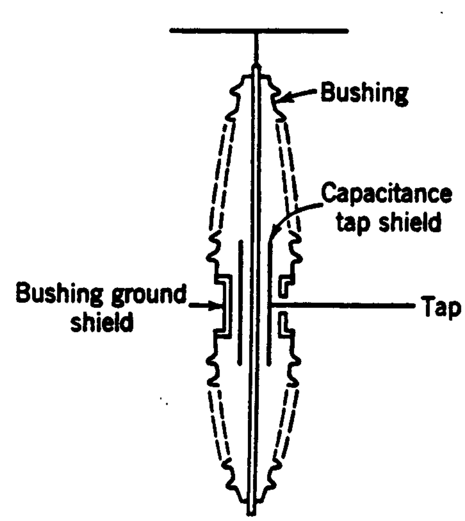

Fig. 2 Capacitance-bushing voltage divider.

divider used, which in turn affects their rated burden. The coupling-capacitor device uses as a voltage divider a "coupling capacitor" consisting of a stack of series-connected capacitor units, and an "auxiliary capacitor," as shown schematically in Fig. 1. The bushing device uses the capacitance coupling of a specially constructed bushing of a circuit breaker or power transformer, as shown schematically in Fig. 2.

Both of these relaying potential devices are called "Class A" devices.[2] They are also sometimes called "In-phase" or "Resonant" devices[3] for reasons that will be evident later. Other types of potential devices, called "Class C" or "Out-of-phase" or "Non-resonant," are also described in References 2 and 3, but they are not generally suitable for protective relaying, and therefore they will not be considered further here.

A schematic diagram of a Class A potential device including the capacitance voltage divider is shown in Fig. 3. Not shown are the means for adjusting the magnitude and phase angle of the secondary voltage; the means for making these adjustments vary with different

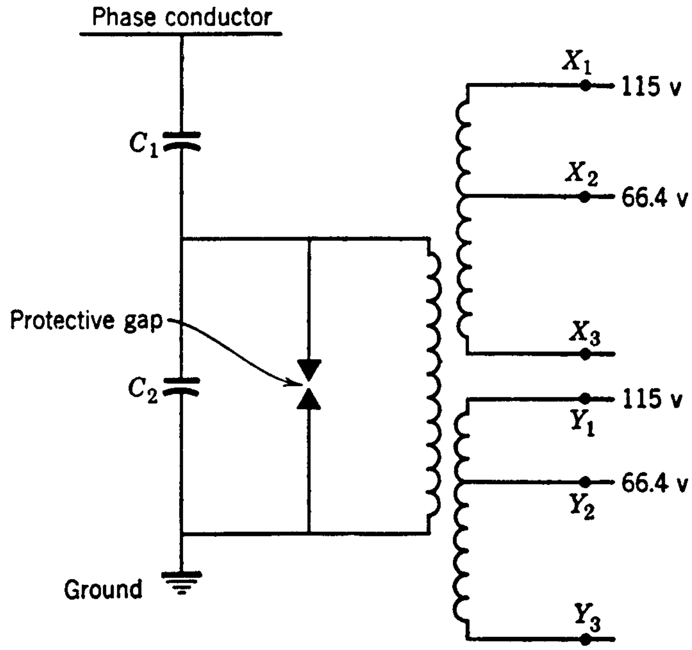

Fig. 3. Schematic diagram of a Class A potential device.

manufacturers, and a knowledge of them is not essential to our present purposes. The Class A device has two secondary windings as shown. Both windings are rated 115 volts, and one must have a 66.4-volt tap. These windings are connected in combination with the windings of the devices of the other two phases of a three-phase power circuit. The connection is "wye" for phase relays and "broken delta" for ground relays. These connections will be illustrated later. The equivalent circuit of a Class A device is shown in Fig. 4. The equivalent reactance X_L, is adjustable to make the burden voltage V_B be in phase with the phase-to-ground voltage of the system V_S. The burden is shown as a resistor because, so far as it is possible, it is the practice to correct the power factor of the burden approximately to unity by the use of auxiliary capacitance burden. When the device is properly adjusted,

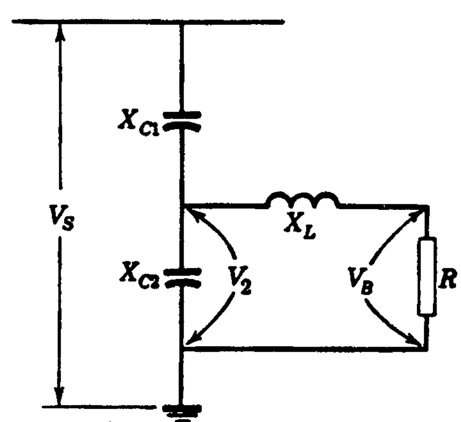

Fig. 4 Equivalent circuit of a Class A potential device.

$$X_L = \frac{X_{C1}X_{C2}}{X_{C1}+X_{C2}} \qquad (1)$$

which explains why the term "Resonant" is applied to this device. Actually, X_{C2} is so small compared with X_{C1} that X_L is practically equal to X_{C2}. Therefore, X_L and X_{C2} would be practically in parallel resonance were it not for the presence of the burden impedance.

The gross input in watts from a power circuit to a capacitance potential-device network is:[3]

$$W = 2\pi f C_1 V_S V_2 \sin\alpha \quad \text{watts} \tag{2}$$

where f = power-system frequency.

α = phase angle between V_S and V_2

C_1 = capacitance of main capacitor (see Fig. 3) in farads.

V_S and V_2 are volts defined as in Fig. 4. If the losses in the network are neglected, equation 2 will give the output of the device. For special applications, this relation is useful for estimating the rated burden from the known rated burden under standard conditions; it is only necessary to compare the proportions in the two cases, remembering that, for a given rating of equipment, the tap voltage V_2 varies directly as the applied voltage V_S.

For a given group of coupling-capacitor potential devices, the product of the capacitance of the main capacitor C_1 and the rated circuit-voltage value of V_S is practically constant; in other words, the number of series capacitor units that comprise C_1 is approximately directly proportional to the rated circuit voltage. The capacitance of the auxiliary capacitor C_2 is the same for all rated circuit voltages, so as to maintain an approximately constant value of the tap voltage V_2 for all values of rated circuit voltage.

For bushing potential devices, the value of C_1 is approximately constant over a range of rated voltages, and the value of C_2 is varied by the use of auxiliary capacitance to maintain an approximately constant value of the tap voltage V_2 for all values of rated circuit voltage.

STANDARD RATED BURDENS OF CLASS A POTENTIAL DEVICES

The rated burden of a secondary winding of a capacitance potential device is specified in watts at rated secondary voltage when rated phase-to-ground voltage is impressed across the capacitance voltage divider. The rated burden of the device is the sum of the watt burdens that may be impressed on both secondary windings simultaneously.

Adjustment capacitors are provided in the device for connecting in parallel with the burden on one secondary winding to correct the total-burden power factor to unity or slightly leading.

The standard[2] rated burdens of bushing potential devices are given in Table 1.

Table 1. Rated Burdens of Bushing Potential Devices

Rated Circuit Voltage, kv		Rated Burden, watts
Phase-to-Phase	Phase-to-Ground	
115	66.4	25
138	79.7	35
161	93.0	45
230	133.0	80
287	166.0	100

The rated burden of coupling-capacitor potential devices is 150 watts for any of the rated circuit voltages, including those of Table 1.

STANDARD ACCURACY OF CLASS A POTENTIAL DEVICES

Table 2 gives the standard maximum deviation in voltage ratio and phase angle for rated burden and for various values of primary voltage, with the device adjusted for the specified accuracy at rated primary voltage.

Table 2. Ratio and Phase-Angle Error versus Voltage

Primary Voltage, percent of rated	Maximum Deviation	
	Ratio, percent	Phase Angle, degrees
100	± 1.0	± 1.0
25	± 3.0	± 3.0
5	± 5.0	± 5.0

Table 3 gives the standard maximum deviation in voltage ratio and phase angle for rated voltage and for various values of burden with the device adjusted for the specified accuracy at rated burden.

Table 3. Ratio and Phase-Angle Error versus Burden

Burden, percent of rated	Maximum Deviation	
	Ratio, percent	Phase Angle, degrees
100	± 1.0	± 1
50	± 6.0	± 4
0	± 12.0	± 8

Table 3 shows that for greatest accuracy, the burden should not be changed without readjusting the device.

EFFECT OF OVERLOADING

As the burden is increased beyond the rated value, the errors will increase at about the rate shown by extrapolating the data of Table 3, which is not very serious for protective relaying. Apart from the possibility of overheating, the serious effect is the accompanying increase of the tap voltage (V_2 of Fig. 4). An examination of the equivalent circuit, Fig. 4, will show why the tap voltage increases with increasing burden. It has been said that X_L is nearly equal to X_{C2}, and therefore these two branches of the circuit will approach parallel resonance as R is decreased (or, in other words, as the burden is increased). Hence, the tap voltage will tend to approach V_S. As the burden is increased above the rated value, the tap voltage will increase approximately proportionally.

The objection to increasing the tap voltage is that the protective gap must then be adjusted for higher-than-normal arc-over voltage. This lessens the protection afforded the equipment. The circuit elements protected by the gap are specified[2] to withstand 4 times the normal tap voltage for 1 minute. Ordinarily, the gap is adjusted to arc over at about twice normal voltage. This is about as low an arc-over as the gap may be adjusted to have in view of the fact that for some ground faults the applied voltage (and hence the tap voltage) may rise to $\sqrt{3}$ times normal. Obviously, the gap must not be permitted to arc over for any voltage for which the protective-relaying equipment must function. Since the ground-relay burden loads the devices only when a ground fault occurs, gap flashover may be a problem when thermal overloading is not a problem. Before purposely overloading a capacitance potential device, one should consult the manufacturer.

As might be suspected, short-circuiting the secondary terminals of the device (which is extreme overloading) will arc over the gap continuously while the short circuit exists. This may not cause any damage to the device, and hence it may not call for fusing, but the gap will eventually be damaged to such an extent that it may no longer protect the equipment.

Even when properly adjusted, the protective gap might arc over during transient overvoltages caused by switching or by lightning. The duration of such arc-over is so short that it will not interfere with the proper operation of protective relays. The moment the overvoltage ceases, the gap will stop arcing over because the impedance of the main capacitor C_1 is so high that normal system voltage cannot maintain the arc.

It is emphasized that the standard rated burdens are specified as though a device were connected and loaded as a single-phase device. In practice, however, the secondary windings of three devices are interconnected and loaded jointly. Therefore, to determine the actual loading on a particular device under unbalanced voltage conditions, as when short circuits occur, certain conversions must be made. This is described later in more detail for the broken-delta burden. Also, the effective burden on each device resulting from the phase-to-phase and phase-to-neutral burdens should be determined if the loading is critical; this is merely a circuit problem that is applicable to any kind of voltage transformer.

NON-LINEAR BURDENS

A "non-linear" burden is a burden whose impedance decreases because of magnetic saturation when the impressed voltage is increased. Too much non-linearity in its burden will let a capacitance potential device get into a state of ferroresonance,[4] during which steady overvoltages of highly distorted wave form will exist across the burden. Since these voltages bear no resemblance to the primary voltages, such a condition must be avoided.

If one must know the maximum tolerable degree of non-linearity, he should consult the manufacturer. Otherwise, the ferroresonance condition can be avoided if all magnetic circuits constituting the burden operate at rated voltage at such low flux density that any possible momentary overvoltage will not cause the flux density of any magnetic circuit to go beyond the knee of its magnetization curve (or, in other words, will not cause the flux density to exceed about 100,000 lines per square inch). Since the potential-device secondary-winding voltage may rise to $\sqrt{3}$ times rated, and the broken-delta voltage may rise to $\sqrt{3}$ times rated, the corresponding phase-to-neutral and broken-delta burdens may be required to have no more than $1/\sqrt{3}$ and ⅓, respectively, of the maximum allowable flux density at rated voltage.

If burdens with closed magnetic circuits, such as auxiliary potential transformers, are not used, there is no likelihood of ferroresonance. Class A potential devices are provided with two secondary-windings purposely to avoid the need of an auxiliary potential transformer. The relays, meters, and instruments generally used have air gaps in their magnetic circuits, or operate at low enough flux density to make their burdens sufficiently linear.

THE BROKEN-DELTA BURDEN AND THE WINDING BURDEN

The broken-delta burden is usually composed of the voltage-polarizing coils of ground directional relays. Each relay's voltage-coil circuit contains a series capacitor to make the relay have a lagging angle of maximum torque. Consequently, the voltage-coil circuit has a leading power factor. The volt-ampere burden of each relay is expressed by the manufacturer in terms of the rated voltage of the relay. The broken-delta burden must be expressed in terms of the rated voltage of the potential-device winding or the tapped portion of the winding–whichever is used for making up the broken-delta connection. If the relay- and winding-voltage ratings are the same, the broken-delta burden is the sum of the relay burdens. If the voltage ratings are different, we must re-express the relay burdens in terms of the voltage rating of the broken-delta winding before adding them, remembering that the volt-ampere burden will vary as the square of the voltage, assuming no saturation.

The actual volt-ampere burdens imposed on the individual windings comprising the broken-delta connection are highly variable and are only indirectly related to the broken-delta burden. Normally, the three winding voltages add vectorially to zero. Therefore, no current flows in the circuit, and the burden on any of the windings is zero. When ground faults occur, the voltage that appears across the broken-delta burden corresponds to 3 times the zero-phase-sequence component of any one of the three phase-to-ground voltages at the potential-device location. We shall call this voltage "$3V_0$". What the actual magnitude of this voltage is depends on how solidly the system neutrals are grounded, on the location of the fault with respect to the potential device in question, and on the configuration of the transmission circuits so far as it affects the magnitude of the zero-phase-sequence reactance. For faults at the potential-device location, for which the voltage is highest, $3V_0$ can vary approximately from 1 to 3 times the rated voltage of each of the broken-delta windings. (This voltage can go even higher in an ungrounded-neutral system should a state of ferroresonance exist, but this possibility is not considered here because it must not be permitted to exist.) If we assume no magnetic saturation in the burden, its maximum current magnitude will vary with the voltage over a 1 to 3 range.

The burden current flows through the three broken-delta windings in series. As shown in Fig. 5, the current is at a different phase angle with respect to each of the winding voltages. Since a ground fault can occur on any phase, the positions of any of the voltages of Fig. 5 relative to the burden current can be interchanged. Consequently, the burden on each winding may have a wide variety of characteristics under different circumstances.

Another peculiarity of the broken-delta burden is that the load is really carried by the windings of the unfaulted phases, and that the voltages of these windings do not vary in direct proportion to the voltage across the broken-delta burden. The voltages of the unfaulted-phase windings are not nearly as variable as the broken-delta-burden voltage.

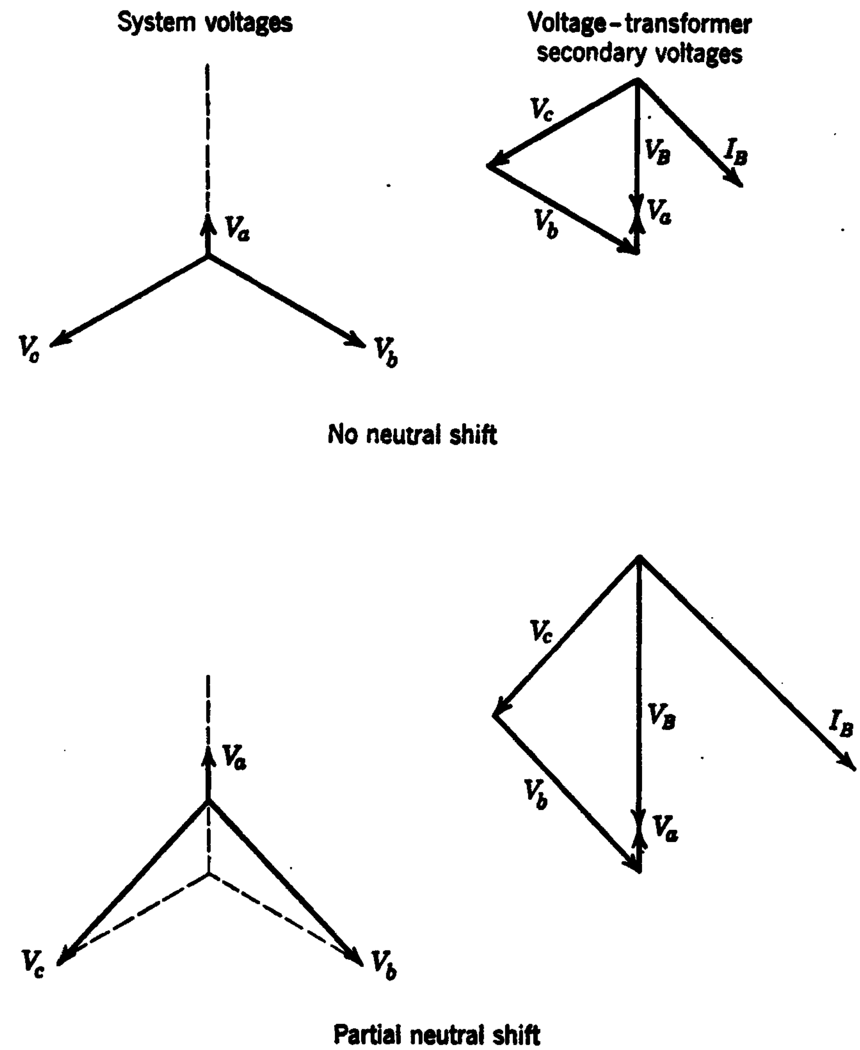

Fig. 5. Broken-delta voltages and current for a single-phase-to-ground fault on phase *a* some distance from the voltage transformer.

The winding voltages of the unfaulted phases vary from approximately rated voltage to $\sqrt{3}$ times rated, while the broken-delta-burden voltage, and hence the current, is varying from less than rated to approximately 3 times rated.

As a consequence of the foregoing, on the basis of rated voltage, the burden on any winding can vary from less than the broken-delta burden to $\sqrt{3}$ times it. For estimating purposes, the, $\sqrt{3}$ multiplier would be used, but, if the total burden appeared to be excessive, one would want to calculate the actual burden. To do this, the following steps are involved:

1. Calculate $3V_0$ for a single-phase-to-ground fault at the potential-device location, and express this in secondary-voltage terms, using as a potential-device ratio the ratio of normal phase-to-ground voltage to the rated voltage of the broken-delta windings.

2. Divide $3V_0$ by the impedance of the broken-delta burden to get the magnitude of current that will circulate in each of the broken-delta windings.

3. Calculate the phase-to-ground voltage ($V_{b1} + V_{b2} + V_{b0}$ etc.) of each of the two unfaulted phases at the voltage-transformer location, and express it in secondary-voltage terms as for $3V_0$.

4. Multiply the current of (2) by each voltage of (3).

5. Express the volt-amperes of (4) in terms of the rated voltage of the broken-delta windings by multiplying the volt-amperes of (4) by the ratio:

$$\left[\frac{V_{\text{rated}}}{\text{Voltage of 3}}\right]^2$$

It is the practice to treat the volt-ampere burden as though it were a watt burden on each of the three windings. It will be evident from Fig. 5 that, depending on which phase is grounded, the volt-ampere burden on any winding could be practically all watts.

It is not the usual practice to correct the power factor of the broken-delta burden to unity as is done for the phase burden. Because this burden usually has a leading power factor, to correct the power factor to unity would require an adjustable auxiliary burden that had inductive reactance. Such a burden would have to have very low resistance and yet it would have to be linear. In the face of these severe requirements, and in view of the fact that the broken-delta burden is usually a small part of the total potential-device burden, such corrective burden is not provided in standard potential devices.

COUPLING-CAPACITOR INSULATION COORDINATION AND ITS EFFECT ON THE RATED BURDEN

The voltage rating of a coupling capacitor that is used with protective relaying should be such that its insulation will withstand the flashover voltage of the circuit at the point where the capacitor is connected. Table 4 lists the standard[2] capacitor withstand test voltages for some circuit-voltage ratings for altitudes below 3300 feet. The flashover voltage of the circuit at the capacitor location will depend not only on the line insulation but also on the insulation of other terminal equipment such as circuit breakers, transformers, and lightning arresters. However, there may be occasions when these other terminal equipments may be disconnected from the line, and the capacitor will then be left alone at the end of the line without benefit of the protection that any other equipment might provide. For example, a disconnect may be opened between a breaker and the capacitor, or a breaker may be opened between a transformer or an arrester and the capacitor. If such can happen, the capacitor must be able to withstand the voltage that will dash over the line at the point where the capacitor is connected.

Table 4. Standard Withstand Test Voltages for Coupling Capacitors

Rated Circuit Voltage, kv		Withstand Test Voltages		
			Low Frequency	
Phase-to-Phase	Phase-to-Ground	impulse, kv	Dry 1-Min, kv	Wet 10-Sec, kv
115	66.4	550	265	230
138	79.7	650	320	275
161	93.0	750	370	315
230	133.0	1050	525	445
287	166.0	1300	655	555

Some lines are overinsulated, either because they are subjected to unusual insulator contamination or because they are insulated for a future higher voltage than the present operating value. In any event, the capacitor should withstand the actual line flashover voltage unless there is other equipment permanently connected to the line that will hold the voltage down to a lower value.

At altitudes above 3300 feet, the flashover value of air-insulated equipment has decreased appreciably. To compensate for this decrease, additional insulation may be provided for the line and for the other terminal equipment. This may require the next higher standard voltage rating for the coupling capacitor, and it is the practice to specify the next higher rating if the altitude is known to be over 3300 feet.

When a coupling-capacitator potential device is to be purchased for operation at the next standard rated circuit voltage below the coupling-capacitator rating, the manufacturer should be so informed. In such a case, a special auxiliary capacitor will be furnished that will provide normal tap voltage even though the applied voltage is one step less than rated. This will give the device a rated burden of 120 watts. If a special auxiliary capacitor were not furnished, the rated burden would be about 64% of 150 watts instead of 80%. The foregoing will become evident on examination of equation 2 and on consideration of the fact that each rated insulation class is roughly 80% of the next higher rating.

The foregoing applies also to bushing potential devices, except that sometimes a non-standard transformer unit may be required to get 80% of rated output when the device is operating at the next standard rated circuit voltage below the bushing rating.

COMPARISON OF INSTRUMENT POTENTIAL TRANSFORMERS AND CAPACITANCE POTENTIAL DEVICES

Capacitance potential devices are used for protective relaying only when they are sufficiently less expensive than potential transformers. Potential devices are not as accurate as potential transformers, and also they may have undesirable transient inaccuracies unless they are properly loaded.[5] When a voltage source for the protective relays of a single circuit is required, and when the circuit voltage is approximately 69 kv and higher, coupling-capacitor potential devices are less costly than potential transformers. Savings may be realized somewhat below 69 kv if carrier current is involved, because a potential-device coupling capacitor can be used also, with small additional expense, for coupling the carrier-current equipment to the circuit. Bushing potential devices, being still less costly, may be even more economical, provided that the devices have sufficiently high rated-burden capacity. However, the main capacitor of a bushing potential device cannot be used to couple carrier-current equipment to a power circuit. When compared on a dollars-per-volt-ampere basis; potential transformers are much cheaper than capacitance potential devices.

When two or more transmission-line sections are connected to a common bus, a single set of potential transformers connected to the bus will generally have sufficient capacity to supply the protective-relaying equipments of all the lines, whereas one set of capacitance potential devices may not. The provision of additional potential devices will quickly nullify the difference in cost. In view of the foregoing, one should at least consider bus potential transformers, even for a single circuit, if there is a likelihood that future requirements might involve additional circuits.

Potential transformers energized from a bus provide a further slight advantage where protective-relaying equipment is involved in which dependence is placed on "memory action" for reliable operation. When a line section protected by such relaying equipment is closed in on a nearby fault, and if potential transformers connected to the bus are involved, the relays will have had voltage on them before the line breaker was closed, and hence the memory action can be effective. If the voltage source is on the line side of the breaker, as is usually true with capacitance potential devices, there will have been no voltage on the relays initially, and memory action will be ineffective. Consequently, the relays may not operate if the voltage is too low owing to the presence of a metallic fault with no arcing, thereby requiring back-up relaying at other locations to clear the fault from the system. However, the likelihood of the voltage being low enough to prevent relay operation is quite remote, but the relays may be slow.

Some people object to bus potential transformers on the basis that trouble in a potential transformer will affect the relaying of all the lines connected to the bus. This is not too serious an objection, particularly if the line relays are not allowed to trip on loss of voltage during normal load, and if a voltage-failure alarm is provided.

Where ring buses are involved, there is no satisfactory location for a single set of bus potential transformers to serve the relays of all circuits. In such cases, capacitance potential devices on the line side of the breakers of each circuit are the best solution when they are cheaper.

THE USE OF LOW-TENSION VOLTAGE

When there are step-down power transformers at a location where voltage is required for protective-relaying equipment, the question naturally arises whether the relay voltage can be obtained from the low-voltage side of the power transformers, and thereby avoid the expense of a high-voltage source. Such a low-voltage source can be used under certain circumstances.

The first consideration is the reliability of the source. If there is only one power transformer, the source will be lost if this power transformer is removed from service for any reason. If there are two or more power transformers in parallel, the source is probably sufficiently reliable if the power transformers are provided with separate breakers.

The second consideration is whether there will be a suitable source for polarizing directional-ground relays if such relays are required. If the power transformers are wye-delta, with the high-voltage side connected in wye and the neutral grounded, the neutral current can be used for polarizing. Of course, the question of whether a single power transformer can be relied on must be considered as in the preceding paragraph. If the high-voltage side is not a grounded wye, then a high-voltage source must be provided for directional-ground relays, and it may as well be used also by the phase relays.

Finally, if distance relays are involved, the desirability of "transformer-drop compensation" must be investigated. This subject will be treated in more detail when we consider the subject of transmission-line protection.

The necessary connections of potential transformers for obtaining the proper voltages for distance relays will be discussed later in this chapter. Directional-overcurrent relays can use any conventional potential-transformer connection.

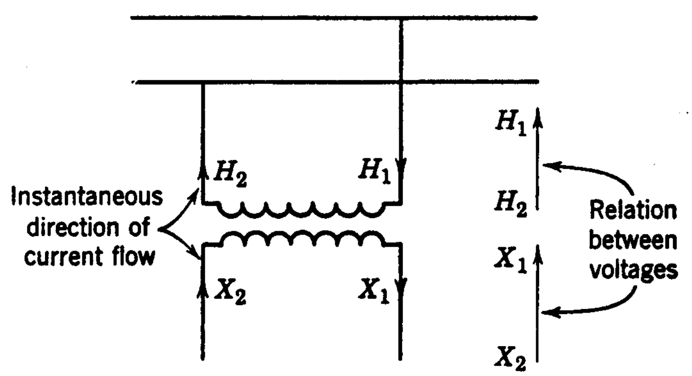

Fig. 6. Significance of potential-transformer polarity marks.

POLARITY AND CONNECTIONS

The terminals of potential transformers are marked to indicate the relative polarities of the primary and secondary windings. Usually, the corresponding high-voltage and low-voltage terminals are marked "H_1" and "X_1," respectively (and "Y_1" for a tertiary). In capacitance potential devices, only the X_1 and Y_1 terminals are marked, the H_1 terminal being obvious from the configuration of the equipment.

The polarity marks have the same significance as for current transformers, namely, that, when current enters the H_1 terminal, it leaves the X_1 (or Y_1) terminal. The relation between the high and low voltages is such that X_1 (or Y_1) has the same instantaneous polarity as H_1, as shown in Fig. 6. Whether a transformer has additive or subtractive polarity may be ignored because it has absolutely no effect on the connections.

Distance relays for interphase faults must be supplied with voltage corresponding to primary phase-to-phase voltage, and any one of the three connections shown in Fig. 7 may be used. Connection *A* is chosen when polarizing voltage is required also for directional-ground relays; this will be discussed later in this chapter. The equivalent of connection *A* is the only one used if capacitance potential devices are involved. Connections *B* and *C* do not provide means for polarizing directional-ground relays; of these two, connection *C* is the one generally used because it is less expensive since it employs only two potential transformers. The burden on each potential transformer is less in connection *B*, which is the only reason it would ever be chosen.

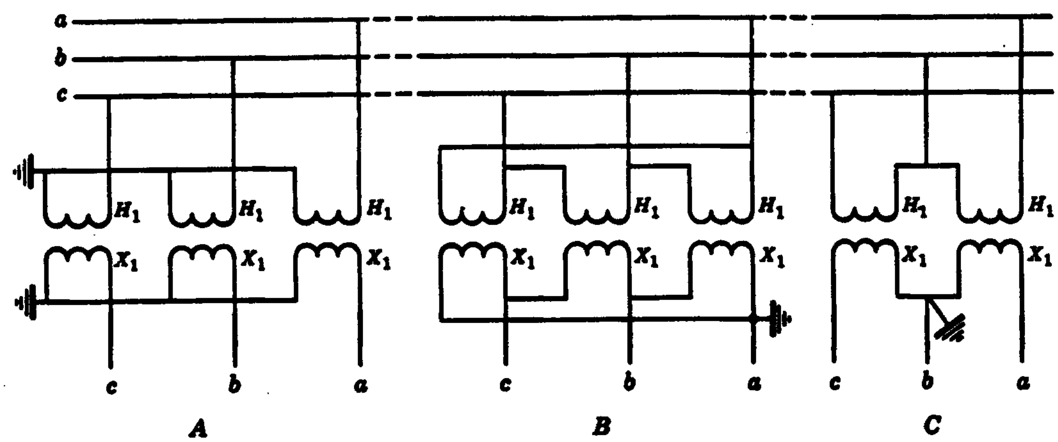

Fig. 7. Connections of potential transformers for distance relays.

The voltages between the secondary leads for all three connections of Fig. 7 are the same, and in terms of symmetrical components are:

$$
\begin{aligned}
V_{ab} &= V_a - V_b \\
&= V_{a1} + V_{a2} + V_{a0} - V_{b1} - V_{b2} - V_{b0} \\
&= (1 - a^2)\, V_{a1} + (1 - a)\, V_{a2} \\
&= \left(\tfrac{3}{2} + j\sqrt{3}/2\right) V_{a1} + \left(\tfrac{3}{2} - j\sqrt{3}/2\right) V_{a2}
\end{aligned}
$$

Similarly,

$$
\begin{aligned}
V_{bc} &= (1-a^2)\ V_{b1} + (1-a)\ V_{b2} \\
&= a^2(1-a^2)\ V_{a1} + a(1-a)\ V_{a2} \\
&= (a^2-a)\ V_{a1} + (a-a^2)\ V_{a2} \\
&= -j\sqrt{3}\ V_{a1} + j\sqrt{3}\ V_{a2} \\
V_{ca} &= (1-a^2)\ V_{c1} + (1-a)\ V_{c2} \\
&= a(1-a^2)\ V_{a1} + a^2(1-a)\ V_{a2} \\
&= (a-1)\ V_{a1} + (a^2-1)\ V_{a2} \\
&= (-\tfrac{3}{2} + j\sqrt{3}/2)\ V_{a1} + (-\tfrac{3}{2} - j\sqrt{3}/2)\ V_{a2}
\end{aligned}
$$

It will be observed that these relations are similar to those obtained for the output currents of the delta-connected CT's of Chapter 7, Fig. 7.

LOW-TENSION VOLTAGE FOR DISTANCE RELAYS

The potential transformers must be connected to the low-voltage source in such a way that the phase-to-phase voltages on the high-voltage side will be reproduced. The connection that must be used will depend on the power-transformer connections. If, as is not usually the case, the power-transformer bank is connected wye-wye or delta-delta, the potential-transformer connections would be the same as though the potential transformers were on the high-voltage side. Usually, however, the power transformers are connected wye-delta or delta-wye.

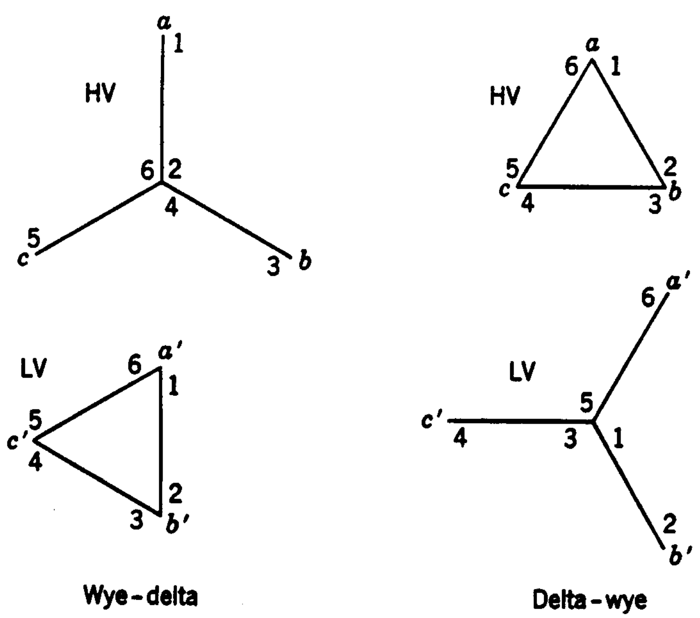

Fig. 8. Three-phase voltages for standard connection of power transformers.

First, let us become acquainted with the standard method of connecting wye-delta or delta-wye power transformers. Incidentally, in stating the connections of a power-transformer bank, the high-voltage connection is stated first; thus a wye-delta transformer bank has its high-voltage side connected in wye, etc. The standard method of connecting power transformers does not apply to potential transformers (which are connected as required), but the technique involved in making the desired connections will apply also to potential transformers. The standard connection for power transformers is that, with balanced three-phase load on the transformer bank, the current in each phase on the high-voltage side will lead by 30° the current in each corresponding phase on the low-voltage side. Also, the no-load phase-to-phase voltages on the high-voltage side will lead the corresponding low-voltage phase-to-phase voltages by 30°. For this to be true, the three-phase voltages must be as in Fig. 8, where *a´* corresponds to *a*, *b´* to *b*, and *c´* to c. The numbers on the voltage vectors of Fig. 8 designate the corresponding ends of the transformer windings, 1-2 designating the primary and secondary windings of one transformer, etc. Now, consider three single-phase transformers as in Fig. 9 with their primary and secondary windings designated 1-2, etc. If we assume that the transformers are rated for either phase-to-phase or phase-to ground connection, it is only necessary to connect together the numbered ends that are shown connected in Fig. 8, and the connections of Fig. 10 will result.

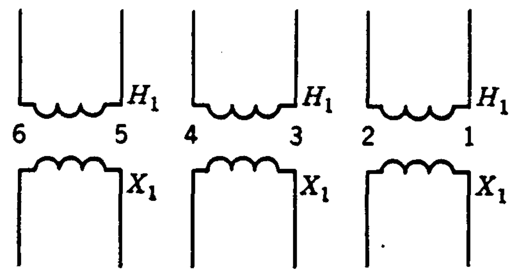

Fig. 9. Numbering the ends of the transformer windings preparatory to making three-phase connections.

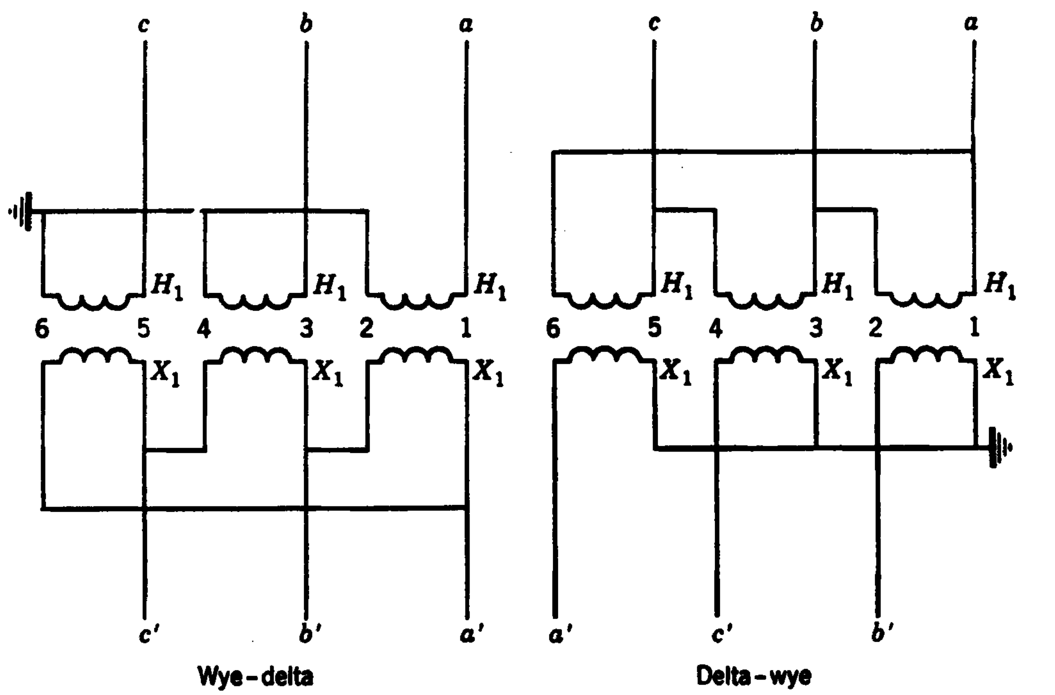

Fig. 10. Interconnecting the transformers of Fig. 9 according to Fig. 8 to get standard connections.

We can now proceed to examine the connections of potential transformers on the low-voltage side that are used for the purpose of supplying voltage to distance relays. Figure 11 shows the connections if the power transformers are connected wye-delta. Figure 12 shows the connections if the power transformers are connected delta-wye.

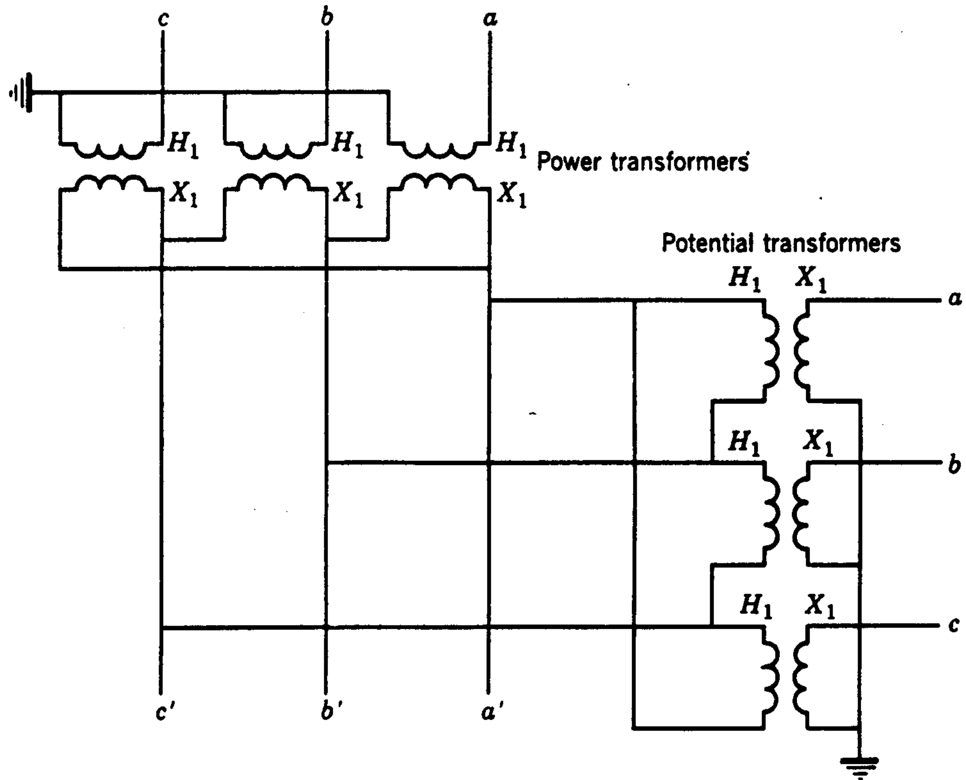

Fig. 11. Connections of potential transformers on low-voltage side of wye-delta power transformer for use with distance relays.

For either power-transformer connection, the phase-to-phase voltages on the secondary side of the potential transformers will contain the same phase-sequence components as those derived for the connections of Fig. 7, if we neglect the voltage drop or rise owing to load or fault currents that may flow through the power transformer. If, for one reason or another, the potential transformers must be connected delta-delta or wye-wye, or if the voltage magnitude is incorrect, auxiliary potential transformers must be used to obtain the required voltages for the distance relays.

The information given for making the required connections for distance relays should be sufficient instruction for making any other desired connections for phase relays. Other application considerations involved in the use of low-voltage sources for distance and other relays will be discussed later.

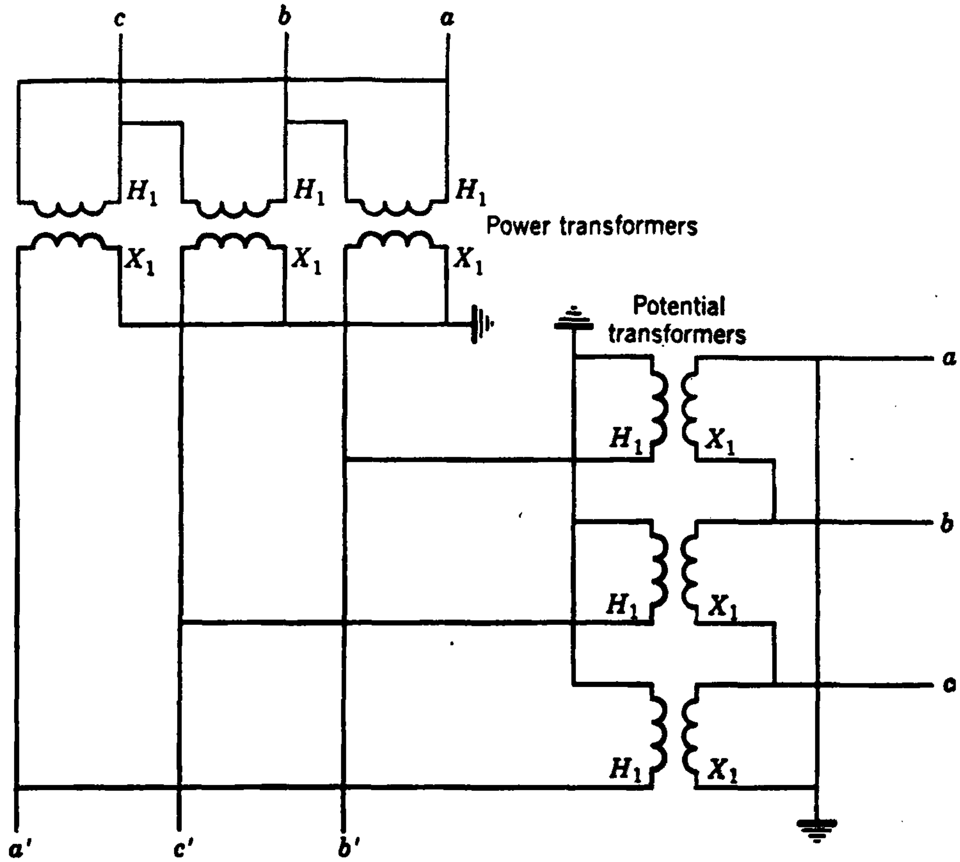

Fig. 12. Connections of potential transformers on low-voltage side of delta-wye power transformer for use with distance relays.

CONNECTIONS FOR OBTAINING POLARIZING VOLTAGE FOR DIRECTIONAL-GROUND RELAYS

The connections for obtaining the required polarizing voltage are shown in Fig. 13. This is called the "broken-delta" connection. The voltage that will appear across the terminals *nm* is as follows:

$$V_{nm} = V_a + V_b + V_c$$

$$= (V_{a1} + V_{a2} + V_{a0}) + (V_{b1} + V_{b2} + V_{b0}) + (V_{c1} + V_{c2} + V_{c0})$$

$$= V_{a0} + V_{b0} + V_{c0} = 3V_{a0} = 3V_{b0} = 3V_{c0}$$

In other words, the polarizing voltage is 3 times the zero-phase-sequence component of the voltage of any phase.

The actual connections in a specific case will depend on the type of voltage transformer involved and on the secondary voltage required for other than ground relays. If voltage for distance relays must also be supplied, the connections of Fig. 14 would be used.

If voltage is required only for polarizing directional-ground relays, three coupling capacitors and one potential device, connected as in Fig. 15 would suffice. The voltage obtained from this connection is 3 times the zero-phase-sequence component.

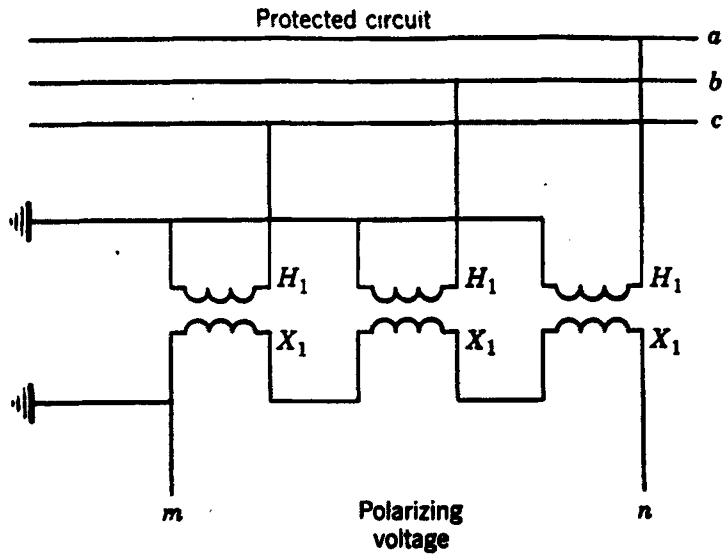

Fig. 13 The broken-delta connection.

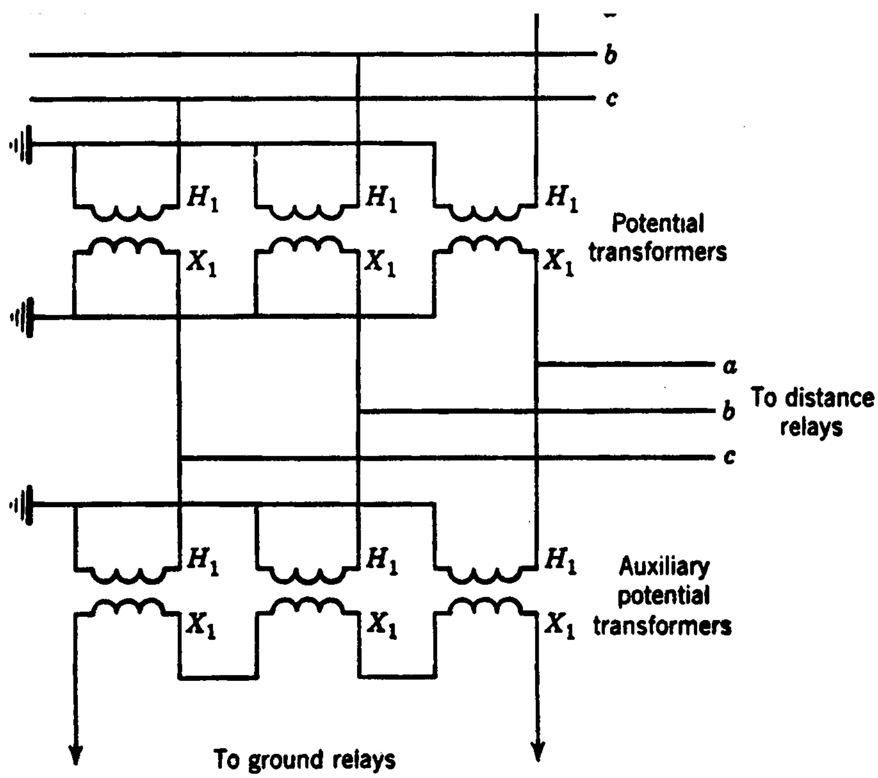

Fig. 14. Potential-transformer connections for distance and ground relays.

The connection of Fig. 15 cannot always be duplicated with bushing potential devices because at least some of the capacitance corresponding to the auxiliary capacitor C_2 might be an integral part of the bushing and could not be separated from it. The capacitance to ground of interconnecting cable may also have a significant effect.

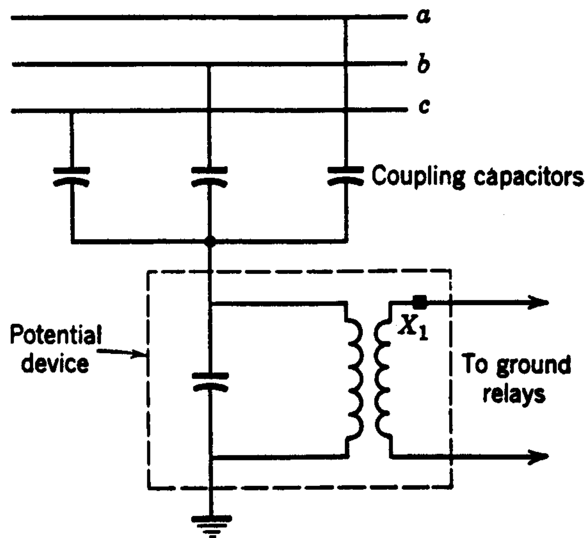

Fig. 16. Connection of three coupling capacitors and one potential device for providing polarizing voltage for directional-ground relays.

The three capacitance tape may be connected together, and a special potential device may be connected across the tap voltage as shown in Fig. 16, but the rated burden may be less than that of Table 1.

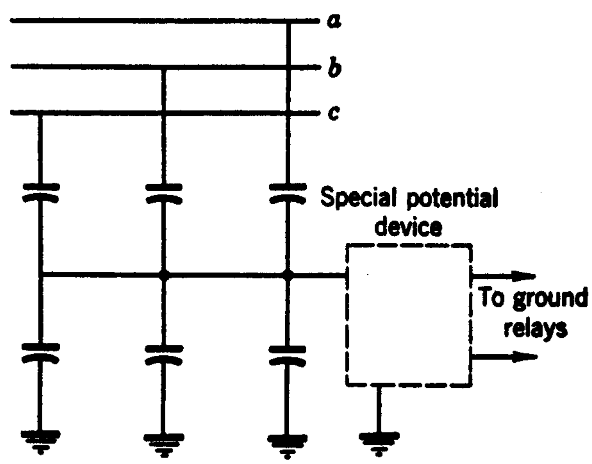

Fig. 16. Use of one potential device with three capacitance bushings.

Incidentally, a capacitance bushing cannot be wed to couple carrier current to a line because there is no way to insert the required carrier-current choke coil in series with the bushing capacitance between the tap and ground, to prevent short-circuiting the output of the carrier-current transmitter.

PROBLEM

1. Given a wye-delta power transformer with standard connections. According to the definitions of this chapter, draw the connection diagram and the three-phase voltage vector diagram for the HV and the LV sides, labeling the HV phases *a*, *b*, and *c* and the corresponding LV phases *a´*, *b´*, and *c´*, (1) for positive-phase-sequence voltage applied to the HV side, and (2) for negative-phase-sequence voltage applied to the HV side. When positive-phase-sequence voltage is applied to the HV side, the phase sequence is *a-b-c*. When negative voltage is applied, there is no change in connections, but the phase sequence is *a-c-b*.

BIBLIOGRAPHY

1. "American Standard Requirements, Terminology, and Test Code for Instrument Transformers," *Publ. C57.13-1954,* American Standards Association, Inc., 70 East 45th Street, New York 17, N. Y.

2. "Outdoor Coupling Capacitors and Capacitance Potential Device," *Publ. 31,* American Institute of Electrical Engineers, 33 West 39th Street, New York 18, N. Y.

"Standards for Coupling Capacitors and Potential Devices," *Publ. 47-123,* National Electrical Manufacturers Association, 155 East 44th Street, New York 17, N. Y.

3. "Application of Capacitance Potential Devices," by J. E. Clem, *AIEE Trans., 48* (1939), pp. 1-8. Discussions, pp. 8-10.

4. *Transient Performance of Electric Power Systems,* by R. Rudenberg, McGraw-Hill Book Co., New York, 1950.

5. "The Effects of Coupling-Capacitor Potential-Device Transients on Protective-Relay Operation," *AIEE Committee Report, AIEE Trans., 70* (1951), pp. 2089-2096. Discussions, p. 2096.

"Transient and Steady-State Performance of Potential Devices," by E. L Harder, P. O. Langguth,, and C. A. Woods, Jr., *AIEE Trans., 59* (1940), pp. 91-99 Discussions, pp. 99-102.