BIRZEIT UNIVERSITY
FACULTY OF ENGINEERING
AND TECHNOLOGY

PROTECTION AND AUTOMATION IN ELECTRICAL POWER SYSTEMS

IMPEDANCE (DISTANCE) RELAYS
&
DIFFERENTIAL RELAYS

By

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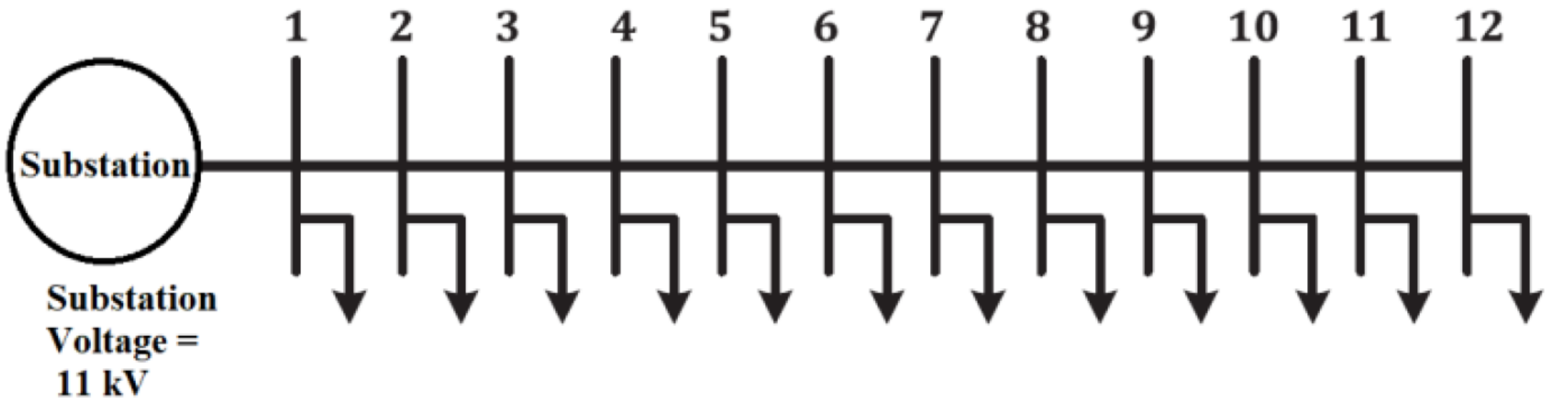
DISTANCE RELAYS

- Coordinating time-delay overcurrent relays can also be difficult for some radial systems. If there are too many radial lines and buses, the time delay for the breaker closest to the source becomes excessive.
- Also, directional overcurrent relays are difficult to coordinate in transmission loops with multiple sources.



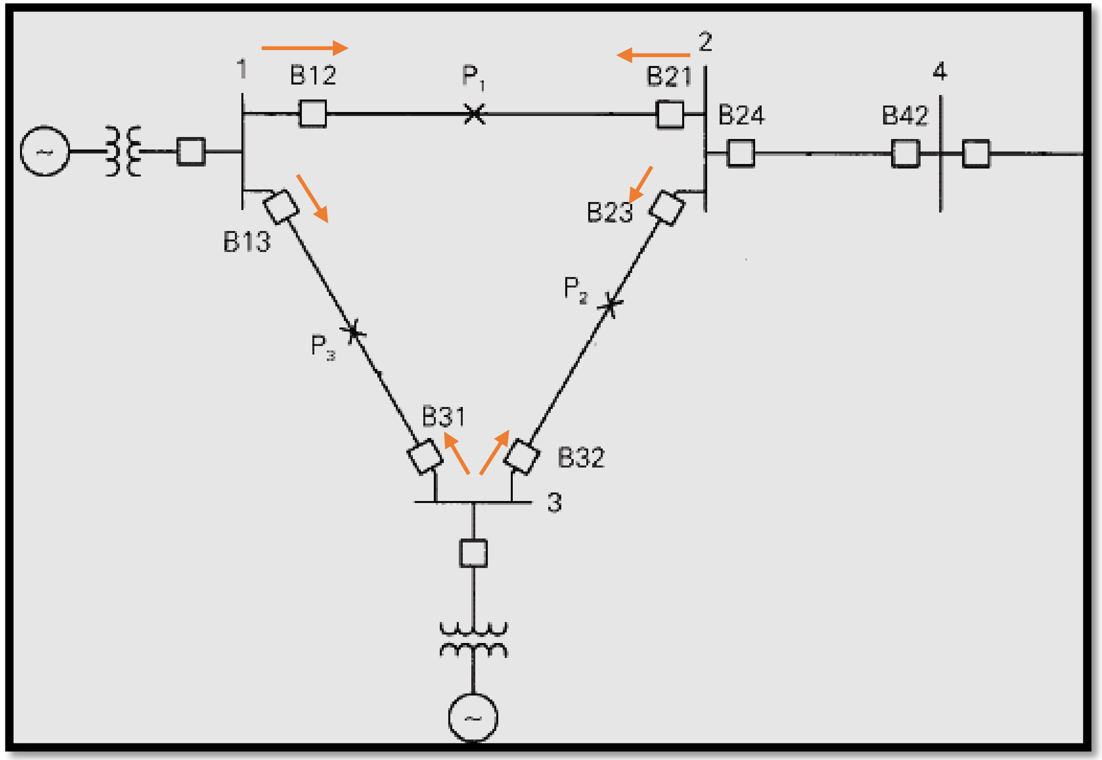
DISTANCE RELAYS

- For a fault at P1, we want the B21 relay to operate faster than the B32 relay. For a fault at P2, we want B32 faster than B13. And for a fault at P3, we want B13 faster than B21.

- Proper coordination, which depends on the magnitudes of the fault currents, becomes a tedious process. Furthermore, when consideration is given to various lines or sources out of service, coordination becomes extremely difficult.

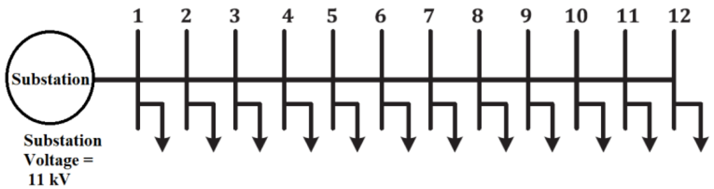
- To overcome these problems, relays that respond to a voltage-to current

  ratio can be used.



DISTANCE RELAYS

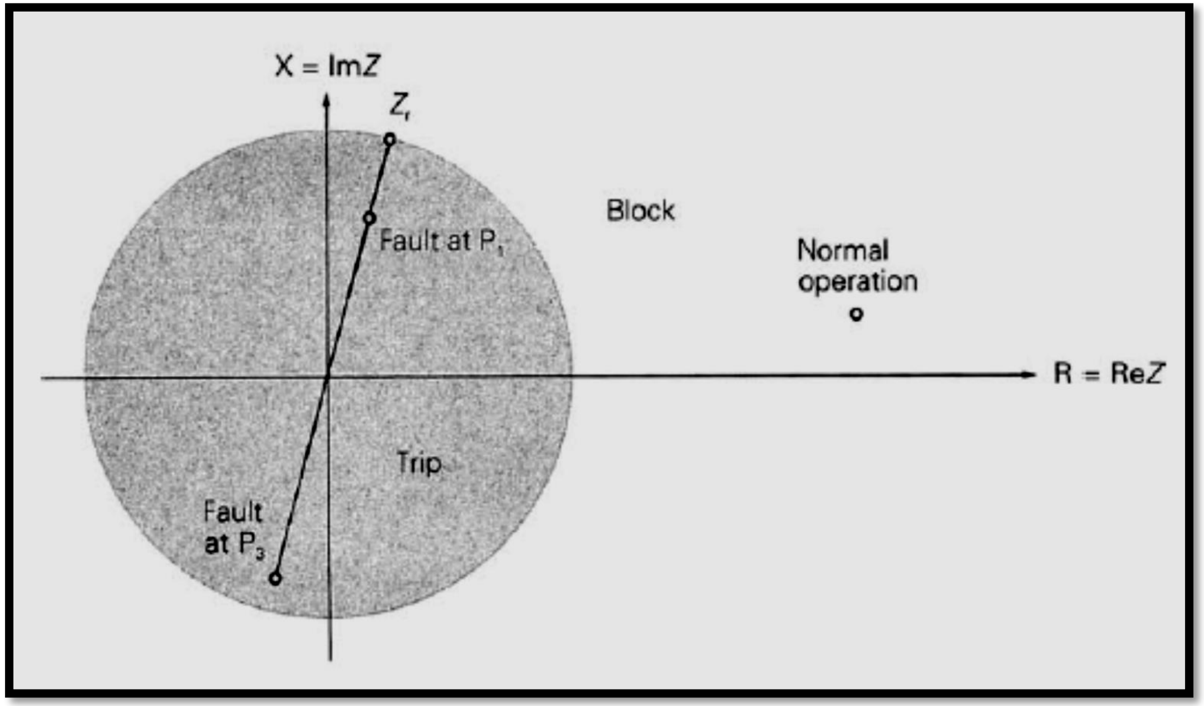
- During a three-phase fault, current increases while bus voltages close to the fault decrease. H.W: (Voltage Profile), ($V_i/I_{i,entered}$ Vs. bus #), (fault current Vs. fault location), (faulted bus voltage Vs. fault location), (V/I ratio Vs. fault location), (fault at bus 12: $V_i/I_{i,entered}$ Vs. bus #), (your conclusion for each plot)



- If, for example, current increases by a factor of 5 while voltage decreases by a factor of 2, then the voltage-to current ratio decreases by a factor of 10.
- That is, the voltage-to-current ratio is more sensitive to faults than current alone. A relay that operates on the basis of voltage-to-current ratio is called an impedance relay. It is also called a distance relay or a ratio relay.

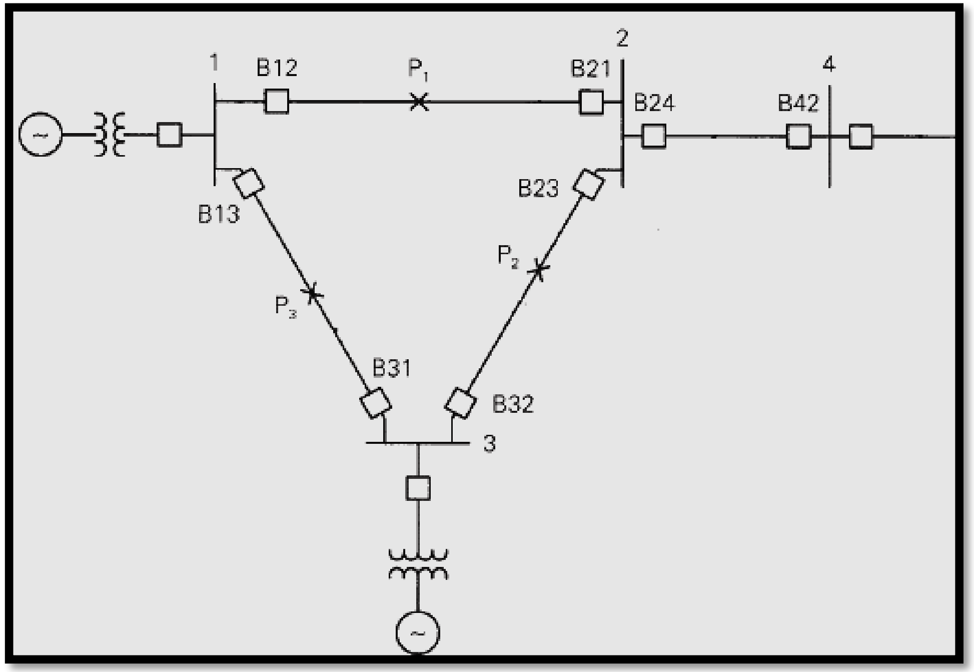
DISTANCE RELAYS

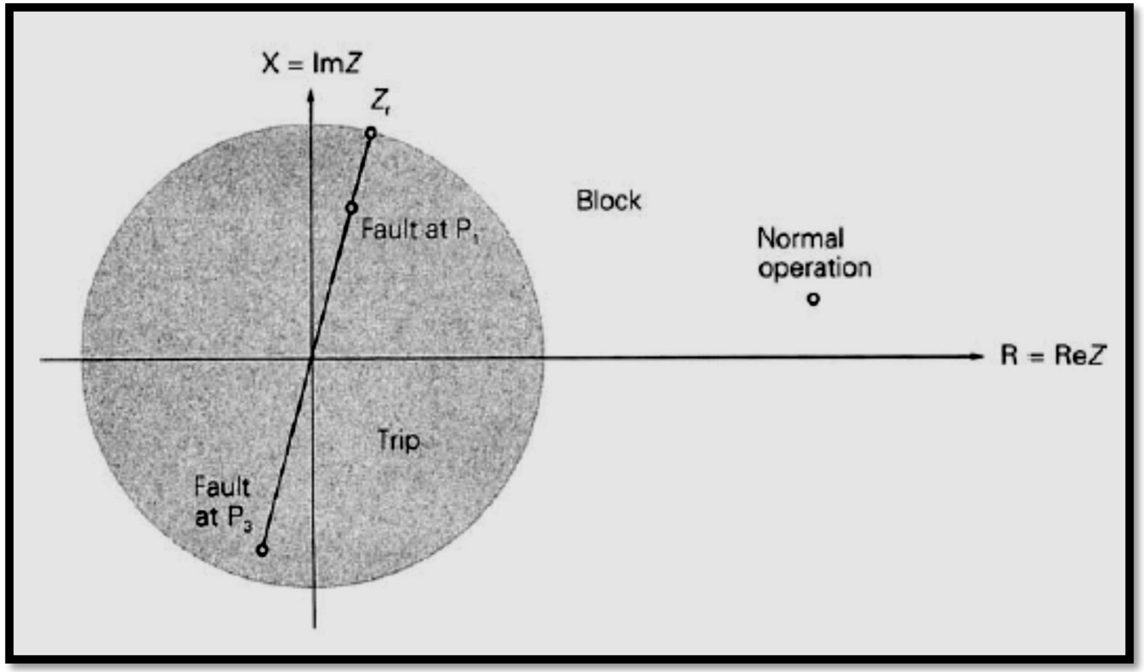
Impedance relay block and trip regions are shown in Figure below, where the impedance Z is defined as the voltage-to-current ratio at the relay location. The relay trips for $|Z| < |Z_r|$, where Z_r is an adjustable relay setting. The impedance circle that defines the border between the block and trip regions passes through Z_r.



DISTANCE RELAYS

Consider an impedance relay for breaker B12 in Figure below, for which $Z = V_1/I_{12}$. During normal operation, load currents are usually much smaller than fault currents, and the ratio Z has a large magnitude (and some arbitrary phase angle). Therefore, Z will lie outside the circle, and the relay will not trip during normal operation.

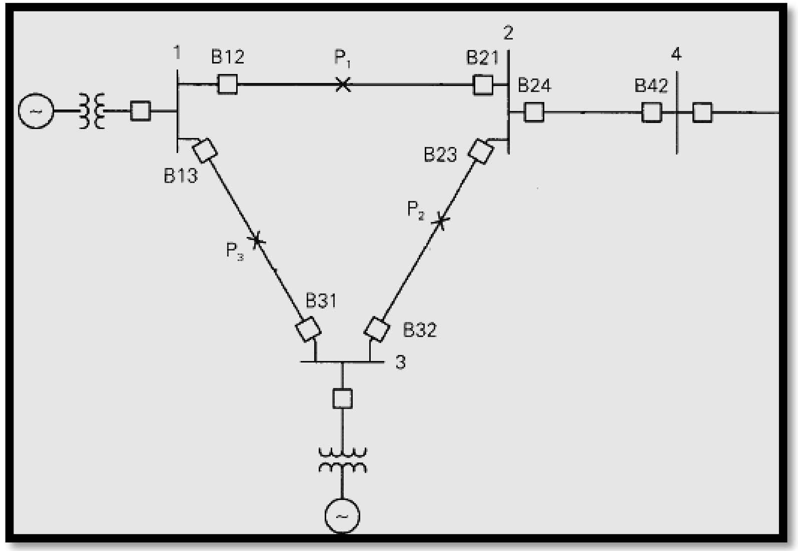


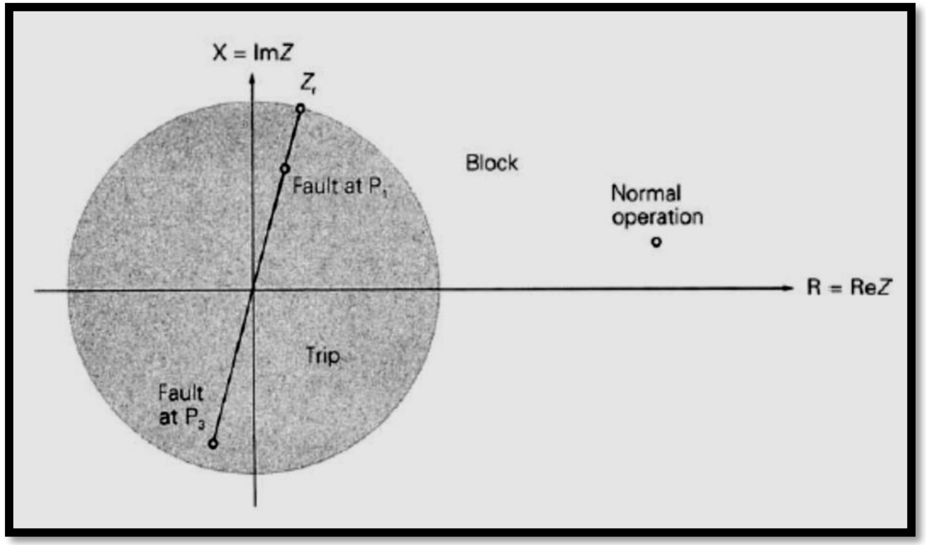


DISTANCE RELAYS

- During a three-phase fault at P1, however, Z appears to relay B12 to be the line impedance from the B12 relay to the fault. If $|\boldsymbol{Z_r}|$ in Figure below is set to be larger than the magnitude of this impedance, then the B12 relay will trip. Also, during a three-phase fault at P3, Z appears to relay B12 to be the negative of the line impedance from the relay to the fault. If $|\boldsymbol{Z_r}|$ is larger than the magnitude of this impedance, the B12 relay will trip.

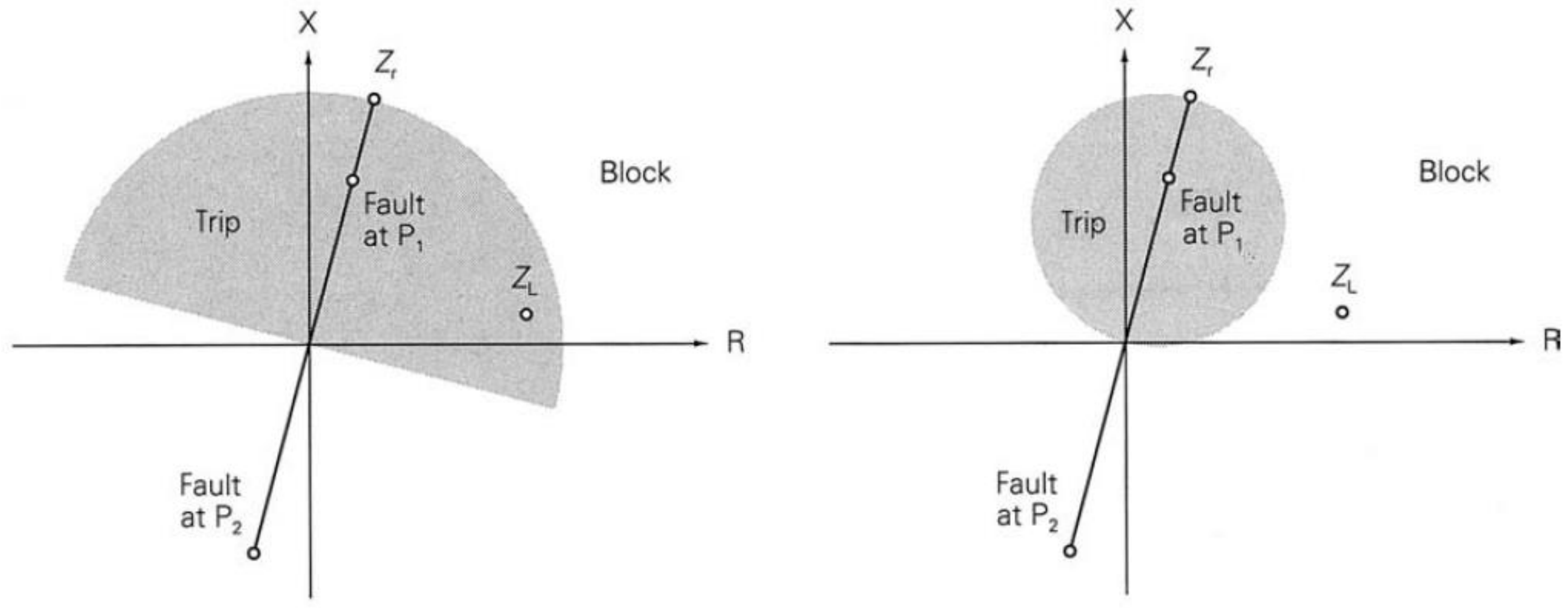
- Thus, the impedance relay of this Figure is not directional; a fault to the left or right of the relay can cause a trip.





DISTANCE RELAYS

Two ways to include directional capability with an impedance relay are:



(a) Impedance relay with directional restraint

(b) Modified impedance relay (mho relay)

DISTANCE RELAYS

- An impedance relay with directional restraint is obtained by including a directional relay in series with an impedance relay, just as was done previously with an overcurrent relay

- A modified impedance relay is obtained by offsetting the center of the impedance circle from the origin. This modified impedance relay is sometimes called an mho relay.

- If either of these relays is used at B12, a fault at P1 will result in a trip decision, but a fault at P3 will result in a block decision.

THE REACH OF AN IMPEDANCE RELAY

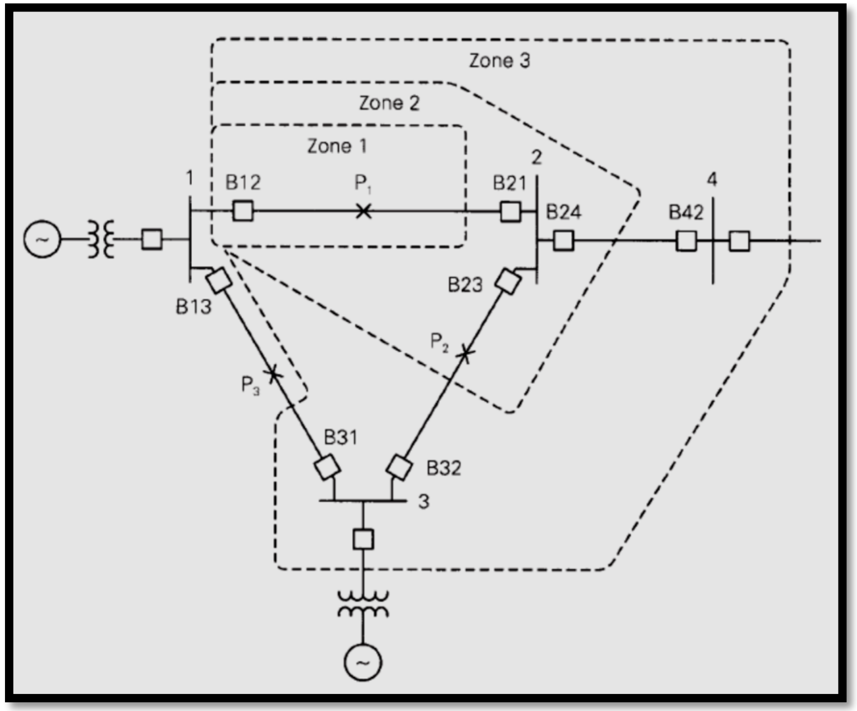
- The reach of an impedance relay denotes how far down the line the relay detects faults. For example, an 80% reach means that the relay will detect any (solid three-phase) fault between the relay and 80% of the line length. This explains the term distance relay.

- It is common practice to use three directional impedance relays per phase, with increasing reaches and longer time delays.

THE REACH OF AN IMPEDANCE RELAY

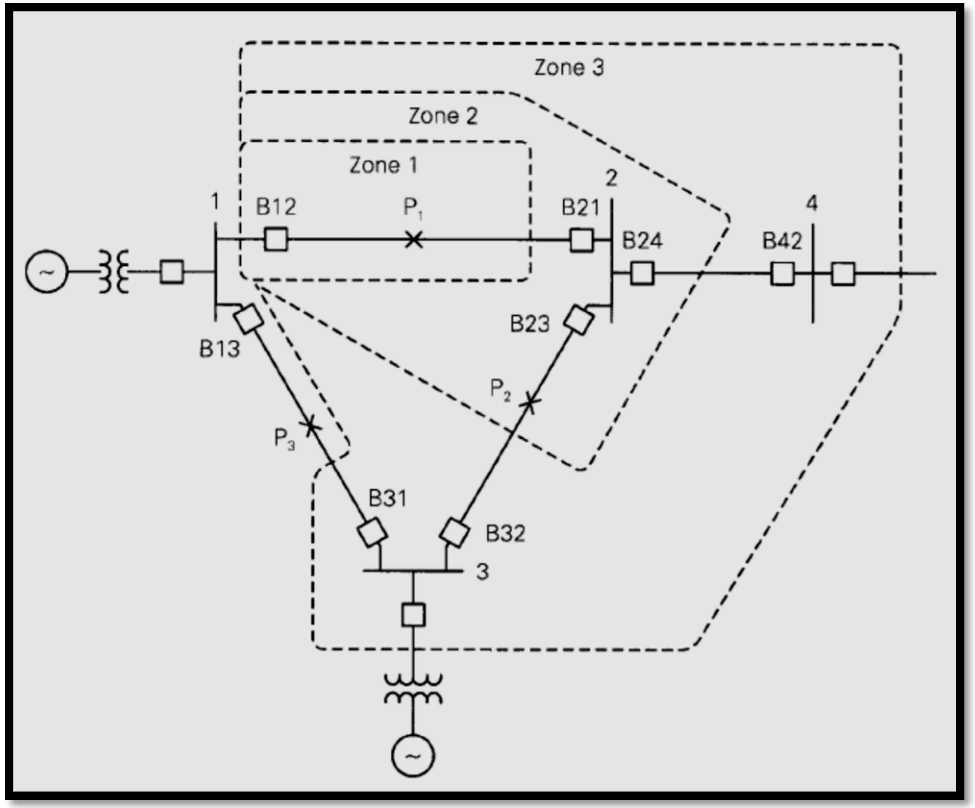
For example, The next Figure shows three protection zones for B12.

- ✓ The zone 1 relay is typically set for an **80%** reach and instantaneous operation, in order to provide primary protection for line 1–2.
- ✓ The zone 2 relay is set for about **120%** reach, extending beyond bus 2, with a typical time delay of 0.2 to 0.3 seconds. The zone 2 relay provides backup protection for faults on line 1–2 as well as remote backup for faults on line 2–3 or 2–4 in zone 2.
- ✓ Reach for the zone 3 B12 relay is typically set to extend beyond buses 3 and 4 in Figure 10.27, in order to provide remote backup for neighboring lines. As such, the zone 3 reach is set for **100%** of line 1–2 **plus 120%** of either line 2–3 or 2–4, whichever is longer, with an even larger time delay, typically one second.



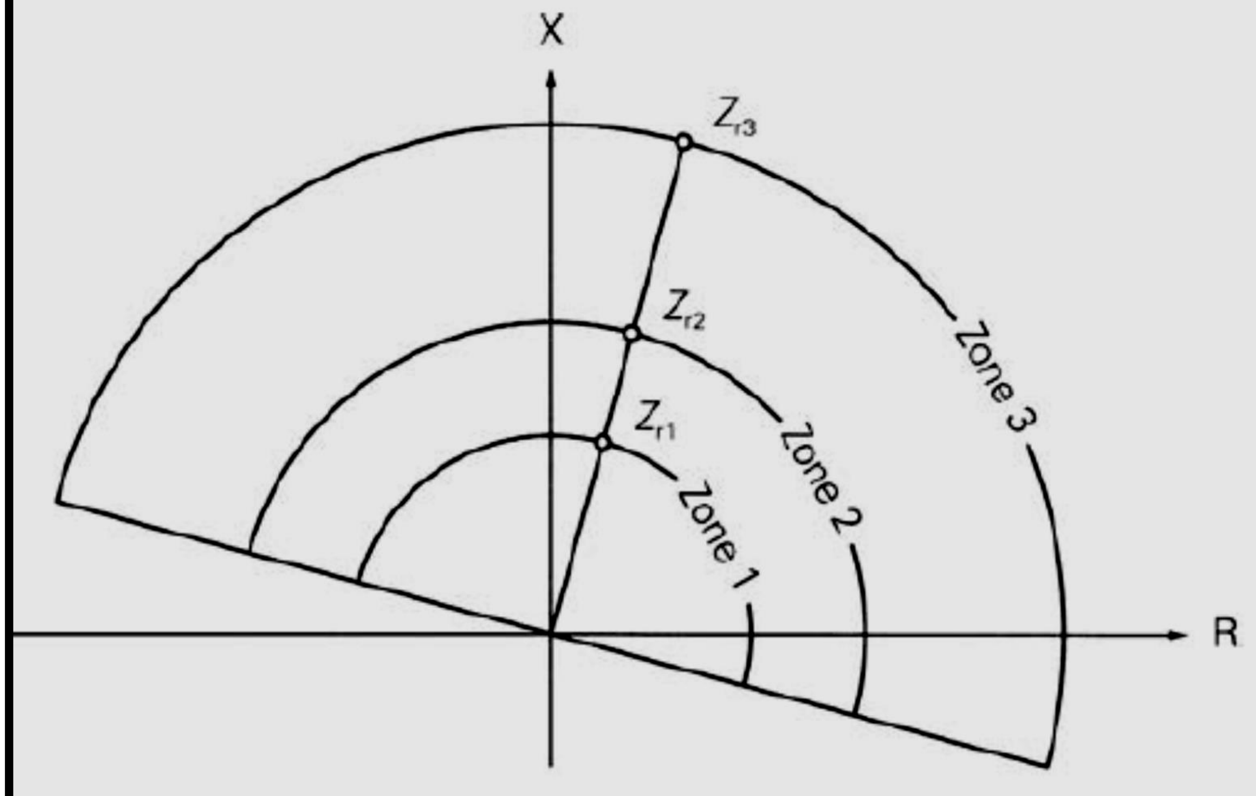
THE REACH OF AN IMPEDANCE RELAY

Note that in the case of a fault on line 2–3 we want the B23 relay to trip, not the B12 relay. Since the impedance seen by B12 for faults near bus 2, either on line 1–2 or line 2–3, is essentially the same, we cannot set the B12 zone 1 relay for 100% reach. Instead, an 80% reach is selected to avoid instantaneous operation of B12 for a fault on line 2–3 near bus 2. For example, if there is a fault at P2 on line 2–3, B23 should trip instantaneously; if it fails, B12 will trip after time delay. Other faults at or near bus 2 also cause tripping of the B12 zone 2 relay after time delay.

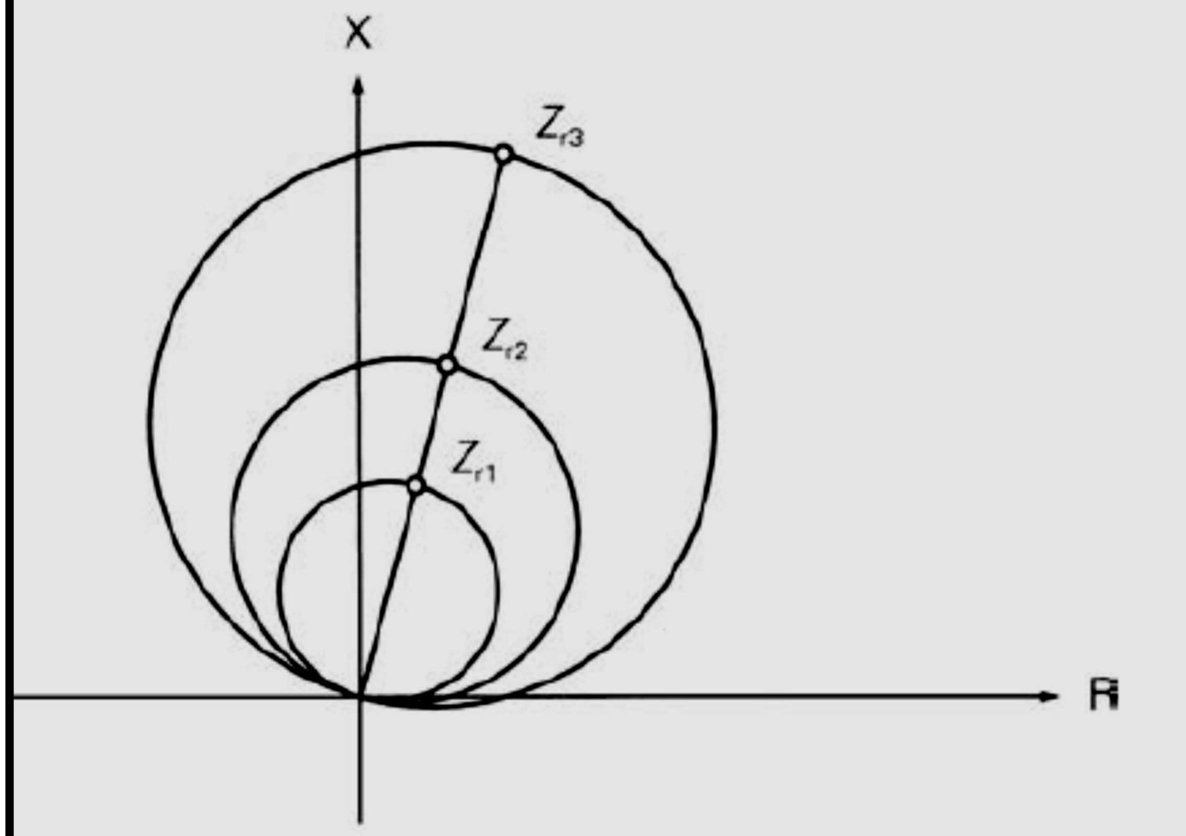


DISTANCE RELAYS

Three-zone, directional impedance relay



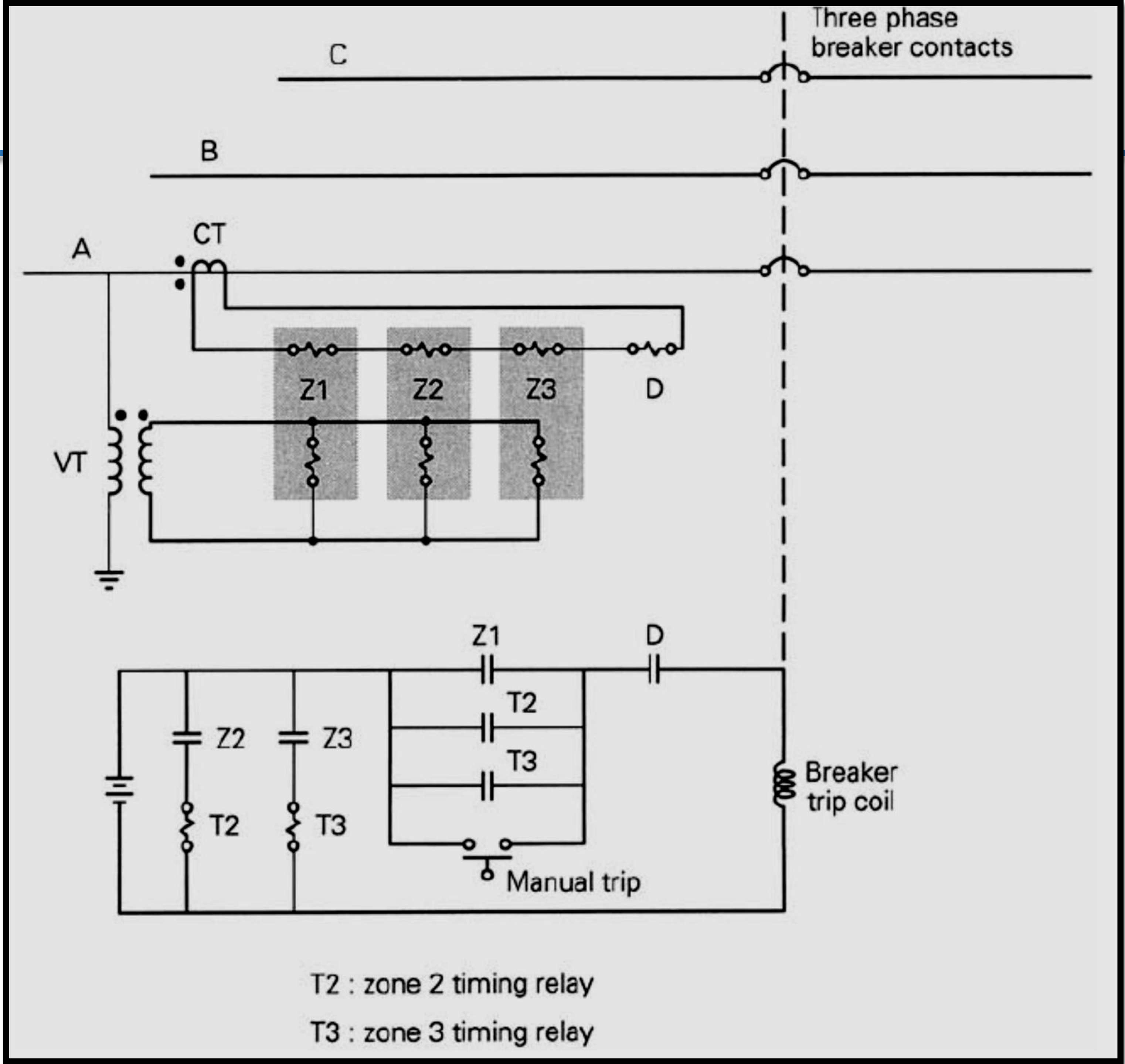
(a) Impedance relay with directional restraint



(b) Modified impedance relay (mho relay)

DISTANCE RELAYS

- **Relay connections for a three-zone directional impedance relay (only phase A is shown)**



EXAMPLE 10.8 Three-zone impedance relay settings

Table 10.8 gives positive-sequence line impedances as well as CT and VT ratios at B12 for the 345-kV system shown in Figure 10.27. (a) Determine the settings Z_{r1}, Z_{r2}, and Z_{r3} for the B12 three-zone, directional impedance relays connected as shown in Figure 10.31. Consider only solid, three-phase faults.

TABLE 10.8

Data for Example 10.8

Line	Positive-Sequence Impedance Ω
1–2	$8 + j50$
2–3	$8 + j50$
2–4	$5.3 + j33$
1–3	$4.3 + j27$

Breaker	CT Ratio	VT Ratio
B12	1500: 5	3000 : 1

(b) Maximum current for line 1–2 during emergency loading conditions is 1500 A at a power factor of 0.95 lagging. Verify that B12 does not trip during normal and emergency loadings.

DISTANCE RELAYS

SOLUTION

a. Denoting V_{LN} as the line-to-neutral voltage at bus 1 and I_L as the line current through B12, the primary impedance Z viewed at B12 is

$$Z = \frac{V_{LN}}{I_L}\ \Omega$$

Using the CT and VT ratios given in Table 10.8, the secondary impedance viewed by the B12 impedance relays is

$$Z' = \frac{V_{LN} \Big/ \left(\frac{3000}{1}\right)}{I_L \Big/ \left(\frac{1500}{5}\right)} = \frac{Z}{10}$$

We set the B12 zone 1 relay for 80% reach, that is, 80% of the line 1–2 (secondary) impedance:

$$Z_{r1} = 0.80(8 + j50)/10 = 0.64 + j4 = 4.05\underline{/80.9^\circ}\ \Omega \quad \text{secondary}$$

DISTANCE RELAYS

Setting the B12 zone 2 relay for 120% reach:

$$Z_{r2} = 1.2(8 + j50)/10 = 0.96 + j6 = 6.08\underline{/80.9^\circ}\ \Omega \quad \text{secondary}$$

From Table 10.8, line 2–4 has a larger impedance than line 2–3. Therefore, we set the B12 zone 3 relay for 100% reach of line 1–2 plus 120% reach of line 2–4.

$$\begin{aligned} Z_{r3} &= 1.0(8 + j50)/10 + 1.2(5.3 + j33)/10 \\ &= 1.44 + j8.96 = 9.07\underline{/80.9^\circ}\ \Omega \quad \text{secondary} \end{aligned}$$

DISTANCE RELAYS

The secondary impedance viewed by B12 during emergency loading, using $V_{\mathrm{LN}} = 345/\sqrt{3}\angle 0^\circ = 199.2\angle 0^\circ$ kV and $I_{\mathrm{L}} = 1500\angle -\cos^{-1}(0.95) = 1500\angle -18.19^\circ$ A, is

$$Z' = Z/10 = \left(\frac{199.2 \times 10^3}{1500\angle -18.19^\circ}\right)\Big/ 10 = 13.28\angle 18.19^\circ\ \Omega \quad \text{secondary}$$

Since this impedance exceeds the zone 3 setting of $9.07\angle 80.9^\circ\ \Omega$, the impedance during emergency loading lies outside the trip regions of the three-zone, directional impedance relay. Also, lower line loadings during normal operation will result in even larger impedances farther away from the trip regions. B12 will trip during faults but not during normal and emergency loadings. ■

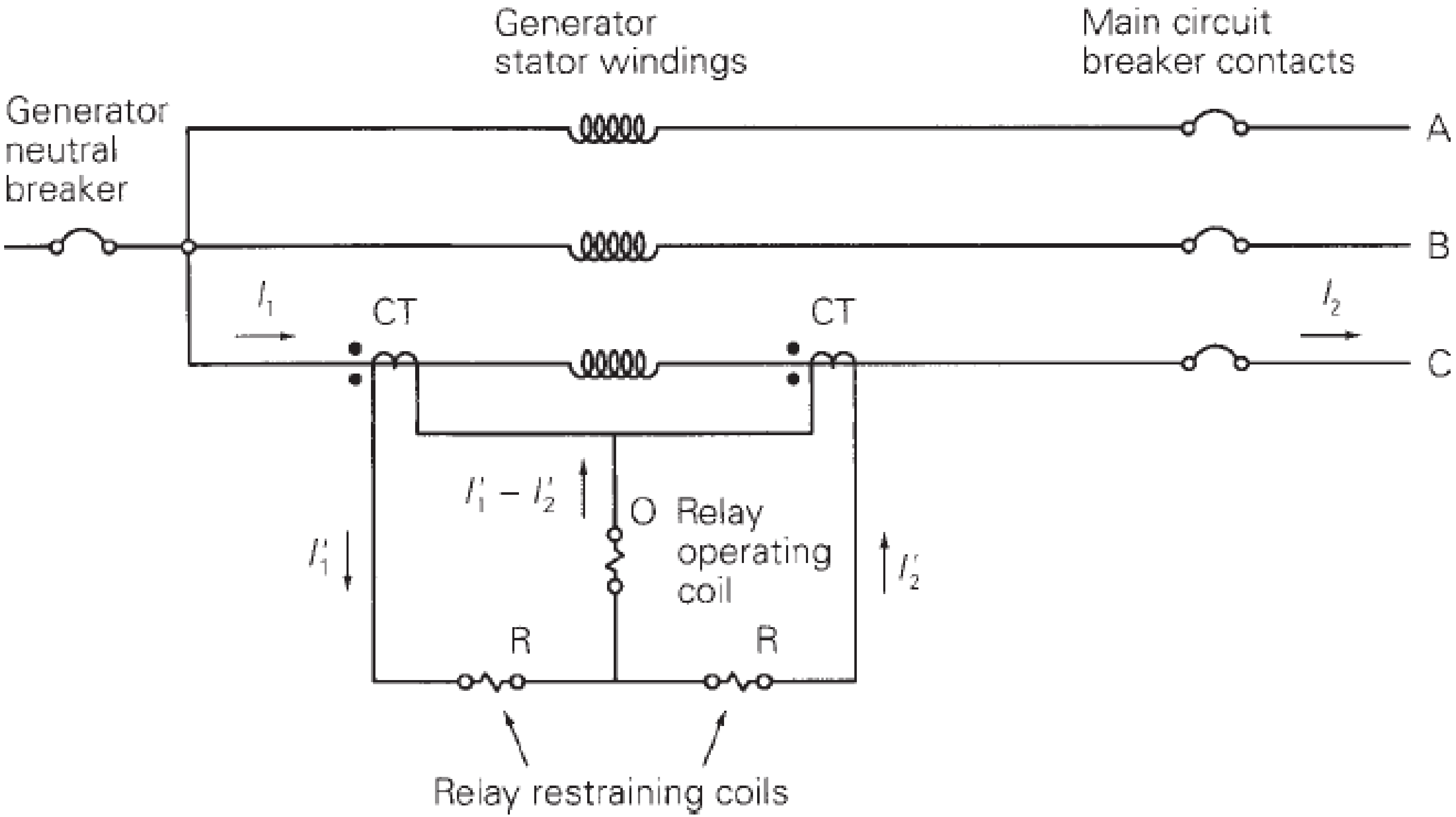
DIFFERENTIAL RELAYS

- **Differential relays are commonly used to protect generators, buses, and transformers**

- **Since the relay operation depends on a difference current flows in the relay operating coil, it is called a differential relay.**

DIFFERENTIAL RELAYS

Differential relaying for generator protection



DIFFERENTIAL RELAYS

The protection of only one phase is shown. The method is repeated for the other two phases. When the relay in any one phase operates, all three phases of the main circuit breaker will open, as well as the generator neutral.

DIFFERENTIAL RELAYS

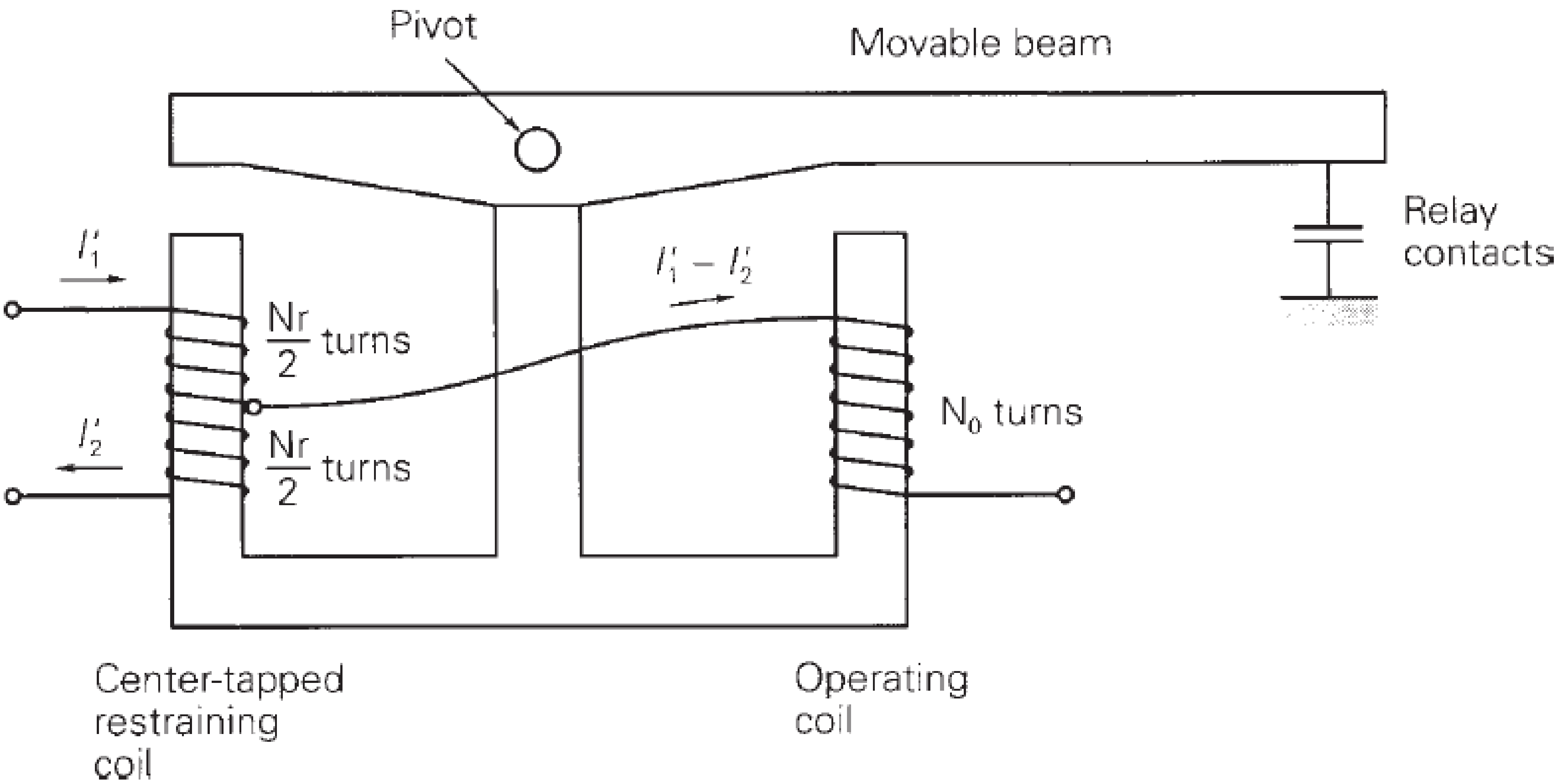
For the case of no internal fault within the generator windings, $I_1 = I_2$, and, assuming identical CTs, $I_1' = I_2'$. For this case the current in the relay operating coil is zero, and the relay does not operate. On the other hand, for an internal fault such as a phase-to-ground or phase-to-phase short within the generator winding, $I_1 \neq I_2$, and $I_1' \neq I_2'$. Therefore, a difference current $I_1' - I_2'$ flows in the relay operating coil, which may cause the relay to operate. Since this relay operation depends on a *difference* current, it is called a *differential* relay.

DIFFERENTIAL RELAYS

An electromechanical differential relay called a *balance beam* relay is shown in Figure 10.33. The relay contacts close if the downward force on the right side exceeds the downward force on the left side. The electromagnetic force on the right, operating coil is proportional to the square of the operating coil mmf—that is, to $[N_0(I_1' - I_2')]^2$. Similarly, the electromagnetic force on the left, restraining coil is proportional to $[N_r(I_1' + I_2')/2]^2$. The condition for relay operation is then

$$[N_0(I_1' - I_2')]^2 > [N_r(I_1' + I_2')/2]^2$$

DIFFERENTIAL RELAYS



DIFFERENTIAL RELAYS

$$[N_0(I_1' - I_2')]^2 > [N_r(I_1' + I_2')/2]^2 \tag{10.10.1}$$

Taking the square root:

$$|I_1' - I_2'| > k|(I_1' + I_2')/2| \tag{10.10.2}$$

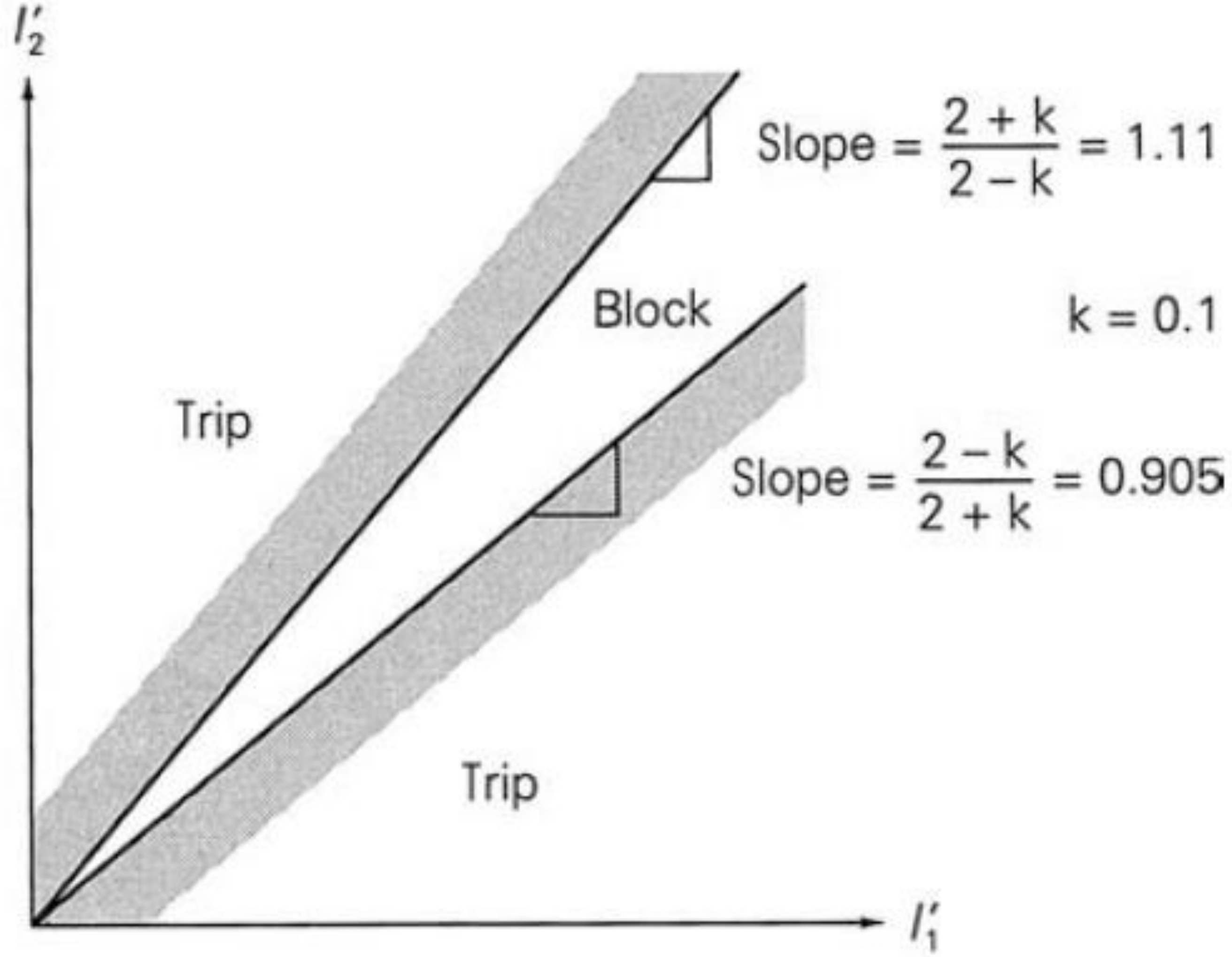
where

$$k = N_r/N_0 \tag{10.10.3}$$

Assuming I_1' and I_2' are in phase, (10.10.2) is solved to obtain

$$\begin{aligned} I_2' &> \frac{2+k}{2-k} I_1' \quad \text{for } I_2' > I_1' \\ I_2' &< \frac{2-k}{2+k} I_1' \quad \text{for } I_2' < I_1' \end{aligned} \tag{10.10.4}$$

DIFFERENTIAL RELAYS

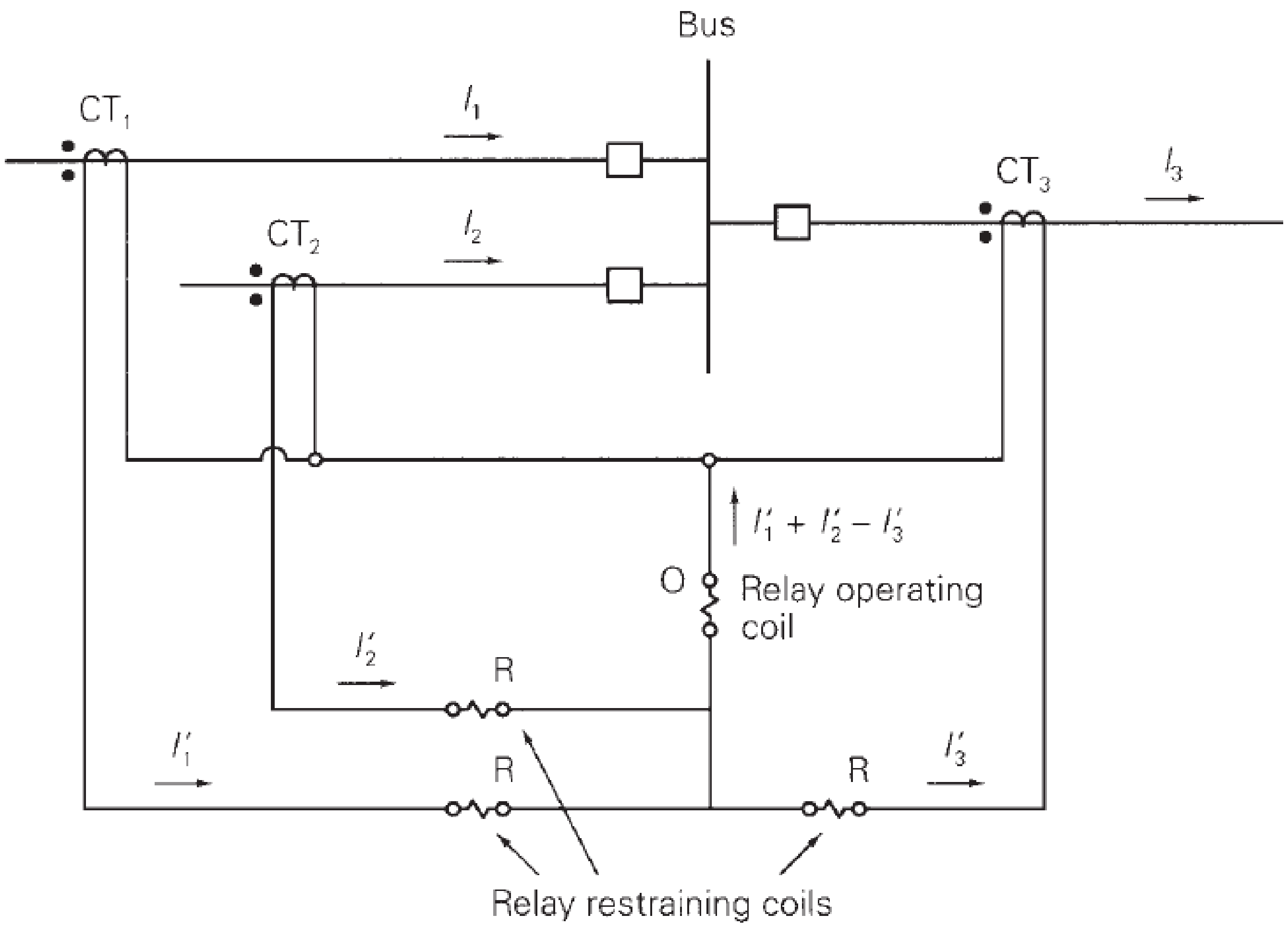


DIFFERENTIAL RELAYS

Equation (10.10.4) is plotted in Figure 10.34 to obtain the block and trip regions of the differential relay for k = 0.1. Note that as k increases, the block region becomes larger; that is, the relay becomes less sensitive. In practice, no two CTs are identical, and the differential relay current $I_1' - I_2'$ can become appreciable during external faults, even though $I_1 = I_2$. The balanced beam relay solves this problem without sacrificing sensitivity during normal currents, since the block region increases as the currents increase, as shown in Figure 10.34. Also, the relay can be easily modified to enlarge the block region for very small currents near the origin, in order to avoid false trips at low currents.

DIFFERENTIAL RELAYS

BUS PROTECTION WITH DIFFERENTIAL RELAYS

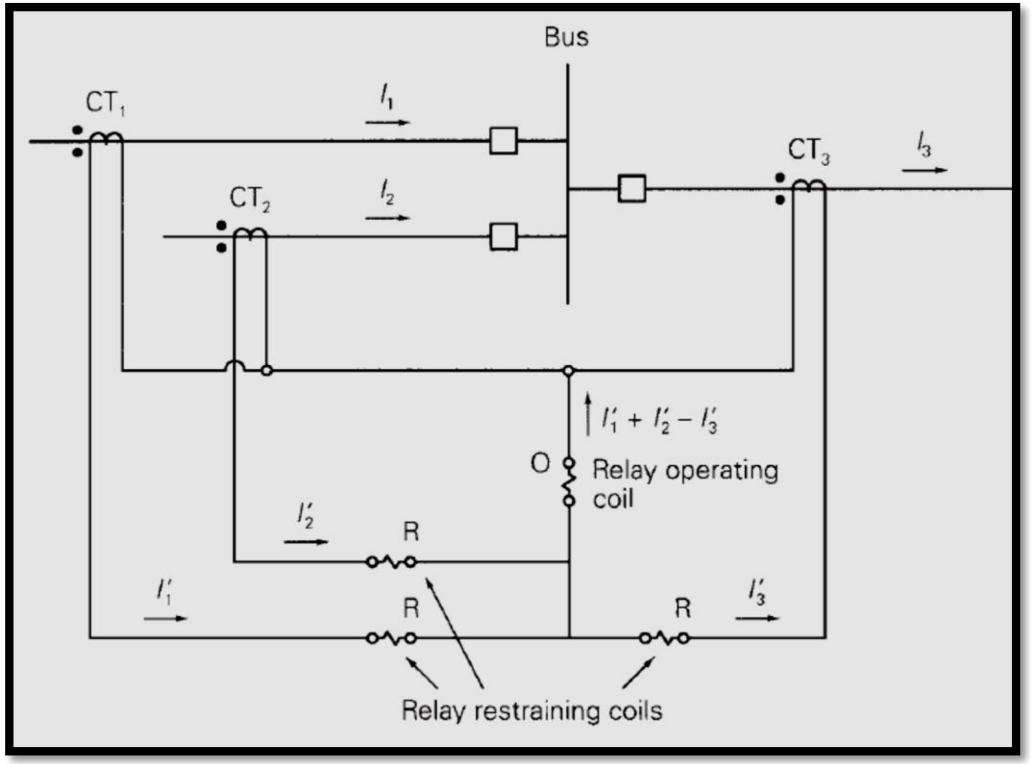


- **Differential bus protection is illustrated by the single-line diagram of this Figure. In practice, three differential relays are required, one for each phase. Operation of any one relay would cause all of the three-phase circuit breakers connected to the bus to open, thereby isolating the three phase bus from service.**

DIFFERENTIAL RELAYS

For the case of no internal fault between the CTs—that is, no bus fault—$I_1 + I_2 = I_3$. Assuming identical CTs, the differential relay current $I_1' + I_2' - I_3'$ equals zero, and the relay does not operate. However, if there is a bus fault, the differential current $I_1' + I_2' - I_3'$, which is not zero, flows in the operating coil to operate the relay. Use of the restraining coils overcomes the problem of nonidentical CTs.

- **Most transformer differential relays have taps that provide for differences in restraining windings in the order of 2 or 3 to 1.**



DIFFERENTIAL RELAYS

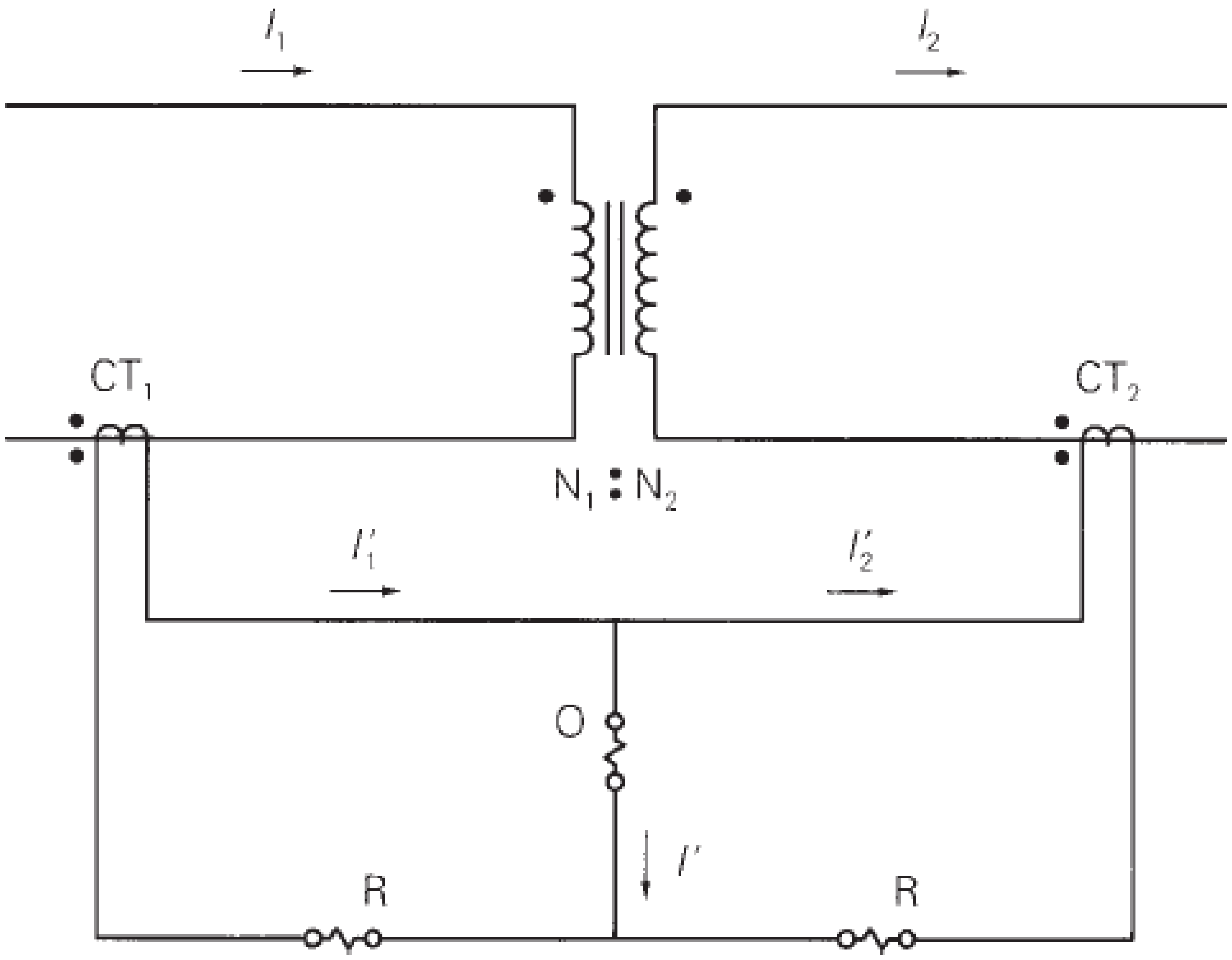
A problem with differential bus protection can result from different levels of fault currents and varying amounts of CT saturation. For example, consider an external fault at point P in Figure 10.35. Each of the CT_1 and CT_2 primaries carries part of the fault current, but the CT_3 primary carries the sum $I_3 = I_1 + I_2$. CT_3, energized at a higher level, will have more saturation, such that $I_3' \neq I_1' + I_2'$. If the saturation is too high, the differential current in the relay operating coil could result in a false trip. This problem becomes more difficult when there are large numbers of circuits connected to the bus. Various schemes have been developed to overcome this problem [1].

DIFFERENTIAL RELAYS

TRANSFORMER PROTECTION WITH DIFFERENTIAL RELAYS

- **The protection method used for power transformers depends on the transformer MVA rating. Fuses are often used to protect transformers with small MVA ratings, whereas differential relays are commonly used to protect transformers with ratings larger than 10 MVA.**

DIFFERENTIAL RELAYS



DIFFERENTIAL RELAYS

The differential protection method is illustrated in Figure 10.36 for a single-phase, two-winding transformer. Denoting the turns ratio of the primary and secondary CTs by $1/n_1$ and $1/n_2$, respectively (a CT with 1 primary turn and n secondary turns has a turns ratio $a = 1/n$), the CT secondary currents are

$$I_1' = \frac{I_1}{n_1} \qquad I_2' = \frac{I_2}{n_2} \tag{10.12.1}$$

and the current in the relay operating coil is

$$I' = I_1' - I_2' = \frac{I_1}{n_1} - \frac{I_2}{n_2} \tag{10.12.2}$$

DIFFERENTIAL RELAYS

For the case of no fault between the CTs—that is, no internal transformer fault—the primary and secondary currents for an ideal transformer are related by

$$I_2 = \frac{N_1 I_1}{N_2} \qquad (10.12.3)$$

Using (10.12.3) in (10.12.2),

$$I' = I_1' - I_2' = \frac{I_1}{n_1} - \frac{I_2}{n_2} \quad \Longrightarrow \quad I' = \frac{I_1}{n_1}\left(1 - \frac{N_1/N_2}{n_2/n_1}\right) \qquad (10.12.4)$$

To prevent the relay from tripping for the case of no internal transformer fault, where (10.12.3) and (10.12.4) are satisfied, the differential relay current I' must be zero. Therefore, from (10.12.4), we select

$$\frac{n_2}{n_1} = \frac{N_1}{N_2} \qquad (10.12.5)$$

DIFFERENTIAL RELAYS

If an internal transformer fault between the CTs does occur, (10.12.3) is not satisfied and the differential relay current $I' = I_1' - I_2'$ is not zero. The relay will trip if the operating condition given by (10.10.4) is satisfied. Also, the value of k in (10.10.4) can be selected to control the size of the block region shown in Figure 10.34, thereby controlling relay sensitivity.

$$I_2 = \frac{N_1 I_1}{N_2} \qquad (10.12.3)$$

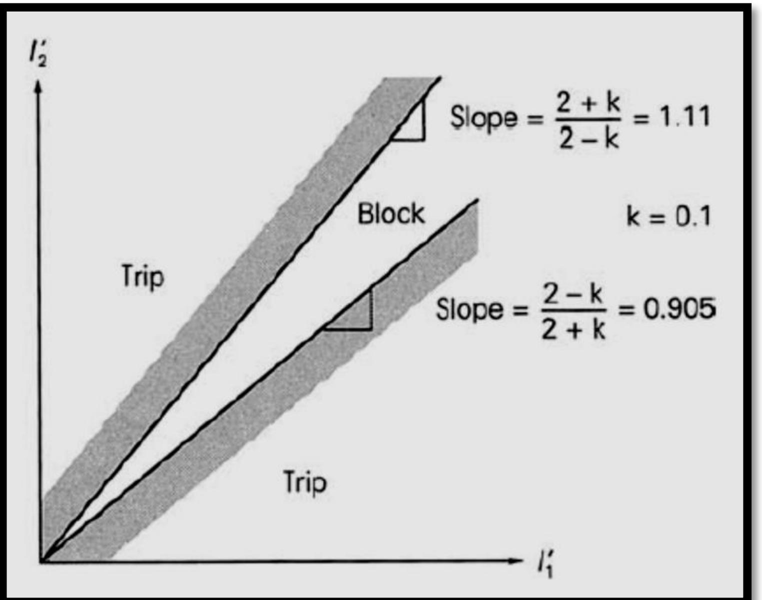
$$I' = \frac{I_1}{n_1}\left(1 - \frac{N_1/N_2}{n_2/n_1}\right) \qquad (10.12.4)$$

$$I_2' > \frac{2+k}{2-k} I_1' \quad \text{for } I_2' > I_1'$$

$$I_2' < \frac{2-k}{2+k} I_1' \quad \text{for } I_2' < I_1'$$

- **Transformer differential relays typically have their block regions adjusted between 20% and 60% (by adjusting k in this figure)**

$$k = N_r/N_0$$



DIFFERENTIAL RELAYS

EXAMPLE 10.9 Differential relay protection for a single-phase transformer

A single-phase two-winding, 10-MVA, 80 kV/20 kV transformer has differential relay protection. Select suitable CT ratios. Also, select k such that the relay blocks for up to 25% mismatch between I_1' and I_2'.

TABLE 10.2	Current Ratios						
Standard CT ratios	50:5	100:5	150:5	200:5	250:5	300:5	400:5
	450:5	500:5	600:5	800:5	900:5	1000:5	1200:5
	1500:5	1600:5	2000:5	2400:5	2500:5	3000:5	3200:5
	4000:5	5000:5	6000:5				

DIFFERENTIAL RELAYS

EXAMPLE 10.9 **Differential relay protection for a single-phase transformer**

SOLUTION The transformer-rated primary current is

$$I_{1\text{rated}} = \frac{10 \times 10^6}{80 \times 10^3} = 125 \text{ A}$$

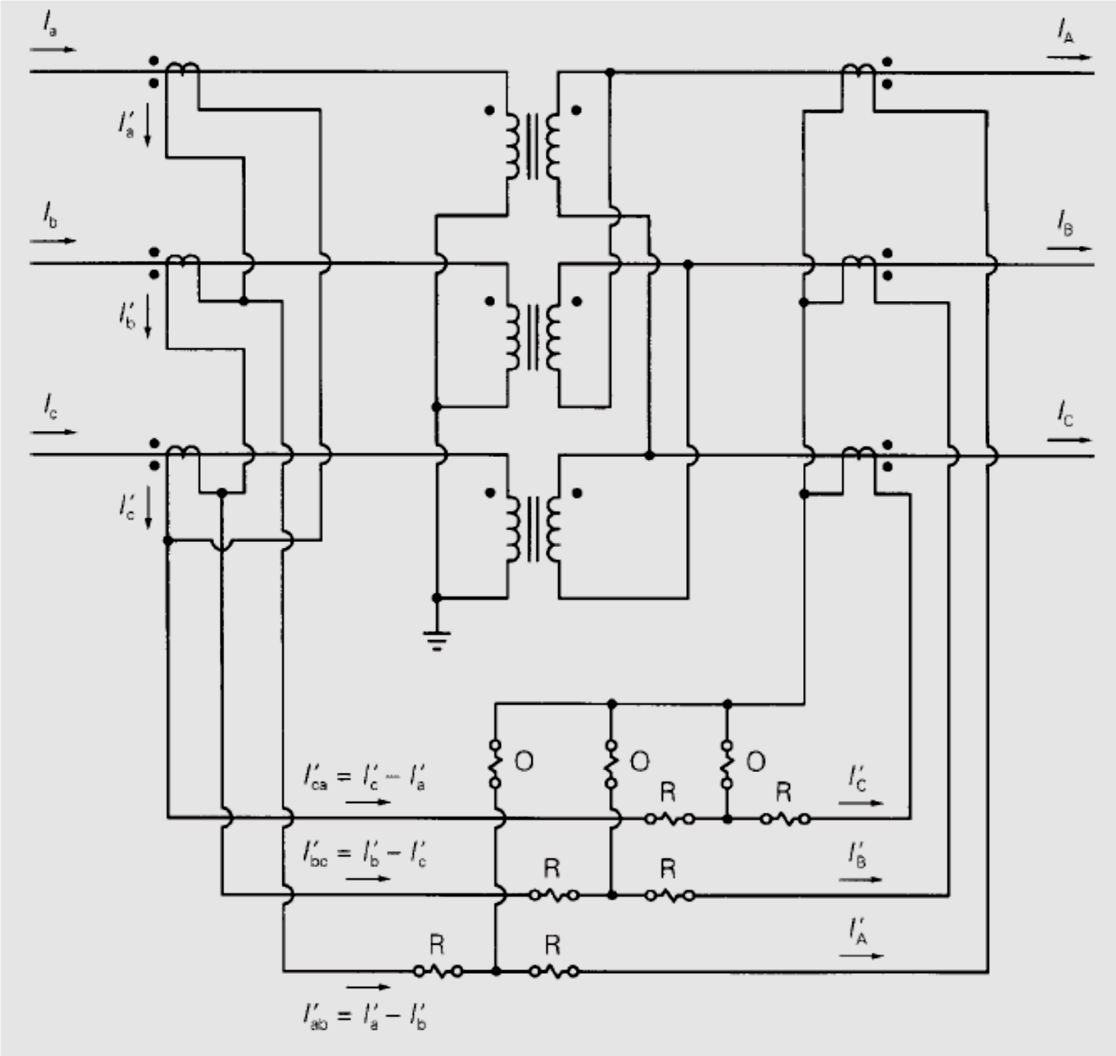
From Table 10.2, select a 150:5 primary CT ratio to give $I_1' = 125(5/150) = 4.17$ A at rated conditions. Similarly, $I_{2\text{rated}} = 500$ A. Select a 600:5 secondary CT ratio to give $I_2' = 500(5/600) = 4.17$ A and a differential current $I' = I_1' - I_2' = 0$ (neglecting magnetizing current) at rated conditions. Also, for a 25% mismatch between I_1' and I_2', select a 1.25 upper slope in Figure 10.34. That is,

$$\frac{2+k}{2-k} = 1.25 \qquad k = 0.2222$$

■

DIFFERENTIAL RELAYS

Differential protection of a three-phase Y– Δ two-winding transformer.



DIFFERENTIAL RELAYS

- **Note that a Y– Δ transformer produces 30° phase shifts in the line currents. The CTs must be connected to compensate for the 30° phase shifts, such that the CT secondary currents as seen by the relays are in phase. The correct phase-angle relationship is obtained by connecting CTs on the Y side of the transformer in Δ , and CTs on the Δ side in Y.**

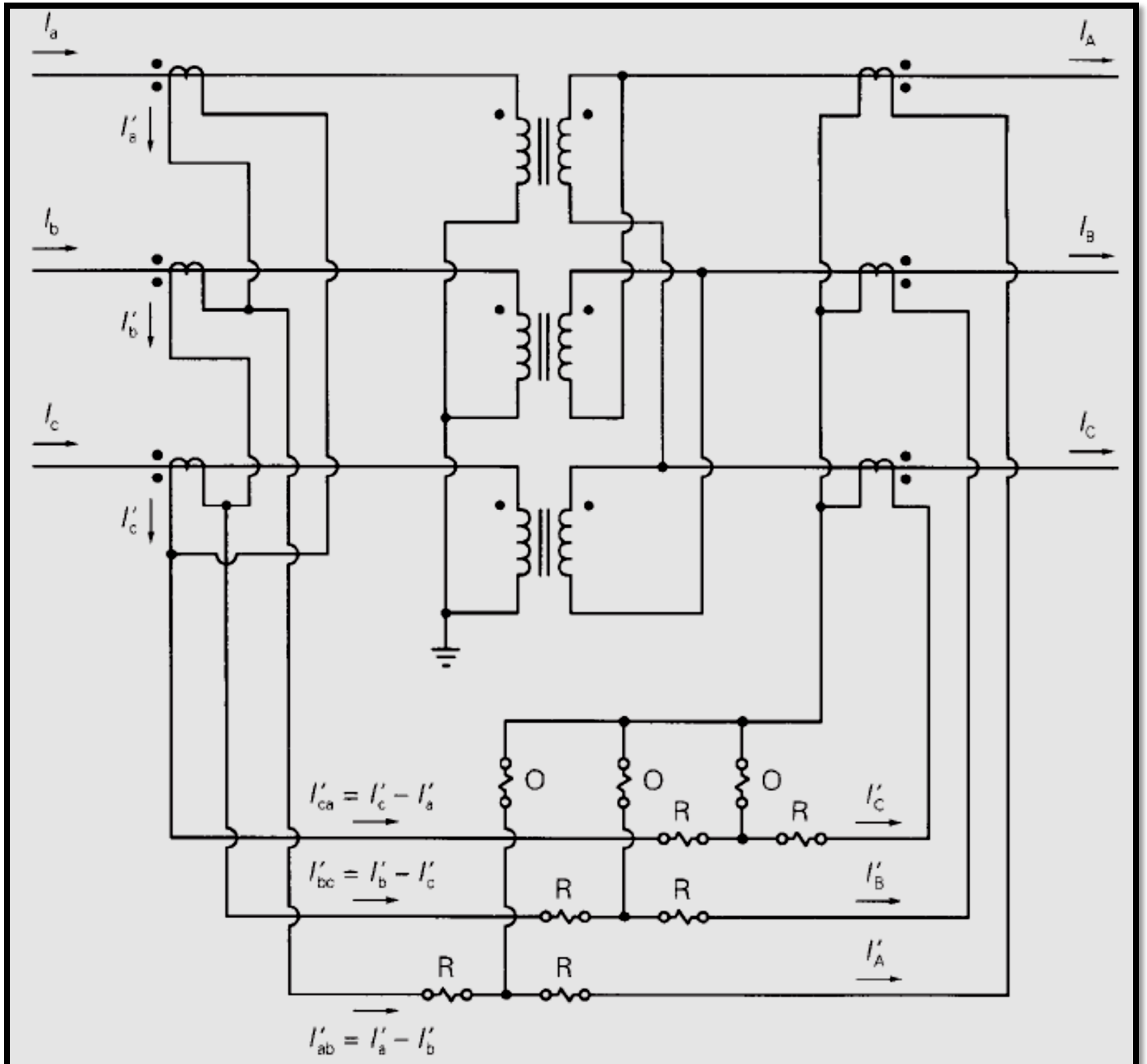
- **For three-phase transformers (Y–Y, Y–Δ, Δ–Y, Δ–Δ), the general rule is to connect CTs on the Y side in Δ and CTs on the Δ side in Y. This arrangement compensates for the 30° phase shifts in Y–Δ or Δ–Y banks..**

- **Most transformer differential relays have taps that provide for differences in restraining windings in the order of 2 or 3 to 1.**

DIFFERENTIAL RELAYS

EXAMPLE 10.10 Differential relay protection for a three-phase transformer

A 30-MVA, 34.5 kV Y/138 kV Δ transformer is protected by differential relays with taps. Select CT ratios, CT connections, and relay tap settings. Also determine currents in the transformer and in the CTs at rated conditions. Assume that the available relay tap settings are 5:5, 5:5.5, 5:6.6, 5:7.3, 5:8, 5:9, and 5:10, giving relay tap ratios of 1.00, 1.10, 1.32, 1.46, 1.60, 1.80, and 2.00.



I_a
I'_a
I_b
I'_b
I_c
I'_c
I_A
I_B
I_C
O
O
O
R
R
R
R
R
R
I'_C
I'_B
I'_A
$I'_{ca} = I'_c - I'_a$
$I'_{bc} = I'_b - I'_c$
$I'_{ab} = I'_a - I'_b$

DIFFERENTIAL RELAYS

SOLUTION As shown in Figure 10.37, CTs are connected in Δ on the (34.5-kV) Y side of the transformer, and CTs are connected in Y on the (138-kV) Δ side, in order to obtain the correct phasing of the relay currents.

Rated current on the 138-kV side of the transformer is

$$I_{A\,\text{rated}} = \frac{30 \times 10^6}{\sqrt{3}(138 \times 10^3)} = 125.51 \text{ A}$$

Select a 150:5 CT on the 138-kV side to give $I'_A = 125.51(5/150) = 4.184$ A in the 138-kV CT secondaries and in the righthand restraining windings of Figure 10.37.

DIFFERENTIAL RELAYS

Next, rated current on the 34.5-kV side of the transformer is

$$I_{a\,\text{rated}} = \frac{30 \times 10^6}{\sqrt{3}(34.5 \times 10^3)} = 502.04 \text{ A}$$

Select a 500:5 CT on the 34.5-kV side to give $I'_a = 502.0(5/500) = 5.02$ A in the 34.5-kV CT secondaries and $I'_{ab} = 5.02\sqrt{3} = 8.696$ A in the lefthand restraining windings of Figure 10.37.

DIFFERENTIAL RELAYS

Finally, select relay taps to balance the currents in the restraining windings. The ratio of the currents in the left- to righthand restraining windings is

$$\frac{I'_{ab}}{I'_{A}} = \frac{8.696}{4.184} = 2.078$$

The closest relay tap ratio is $T'_{AB}/T'_{A} = 2.0$, corresponding to a relay tap setting of $T'_{A} : T'_{ab} = 5 : 10$. The percentage mismatch for this tap setting is

$$\left|\frac{(I'_{A}/T'_{A}) - (I'_{ab}/T'_{ab})}{(I'_{ab}/T'_{ab})}\right| \times 100 = \left|\frac{(4.184/5) - (8.696/10)}{(8.696/10)}\right| \times 100 = 3.77\%$$

This is a good mismatch; since transformer differential relays typically have their block regions adjusted between 20% and 60% (by adjusting k in Figure 10.34), a 3.77% mismatch gives an ample safety margin in the event of CT and relay differences. ■

PILOT RELAYING

- **Pilot relaying refers to a type of differential protection that compares the quantities at the terminals via a communication channel rather than by a direct wire interconnection of the relays**

- **Differential protection of generators, buses, and transformers considered in previous sections does not require pilot relaying because each of these devices is at one geographical location where CTs and relays can be directly interconnected. However, differential relaying of transmission lines requires pilot relaying because the terminals are widely separated (often by many kilometers). In actual practice, pilot relaying is typically applied to short transmission lines (up to 80 km) with 69 to 115 kV ratings.**