# Power System Protection

## EE454

Lecture ppt. # 5
ODL Week
Nov. 30 – Dec. 4

- **Note:**

  **The materials in this presentation are only for the use of students enrolled in this course in the specific campus; these materials are for purposes associated with this course and may not be further disseminated or retained after expiry of the course.**

| **Session No.** | **Content of the Lecture presentation (which students should cover and can discuss in the Q/A session)** | |
|---|---|---|
| - | Slide 4 – 9 | Intro. to Distance/Stepped Distance Protection – Intro. to RX diagram<br>Discussed in – in-class lecture on 24th Nov and then online lecture on 27th Nov. |
| 1 | Slide 10 - 16 | Example of RX diagram<br>Three phase distance relays – LL, LLG and LLL faults - theory |
| 2 | Slide 17 - 21 | Three phase distance relays – LG faults – theory<br>Example (5.4) LLL and LL faults |
| 3 | Slide 22 - 24 | Example (5.4) LG fault – Effect of fault resistance on distance relays - Distance relay types |


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# 5

# Nonpilot distance protection of transmission lines

## 5.1 Introduction

Distance relays are normally used to protect transmission lines.[1] They respond to the impedance between the relay location and the fault location. As the impedance per mile of a transmission line is fairly constant, these relays respond to the distance to a fault on the transmission line – and hence their name.

## 5.2 Stepped distance protection

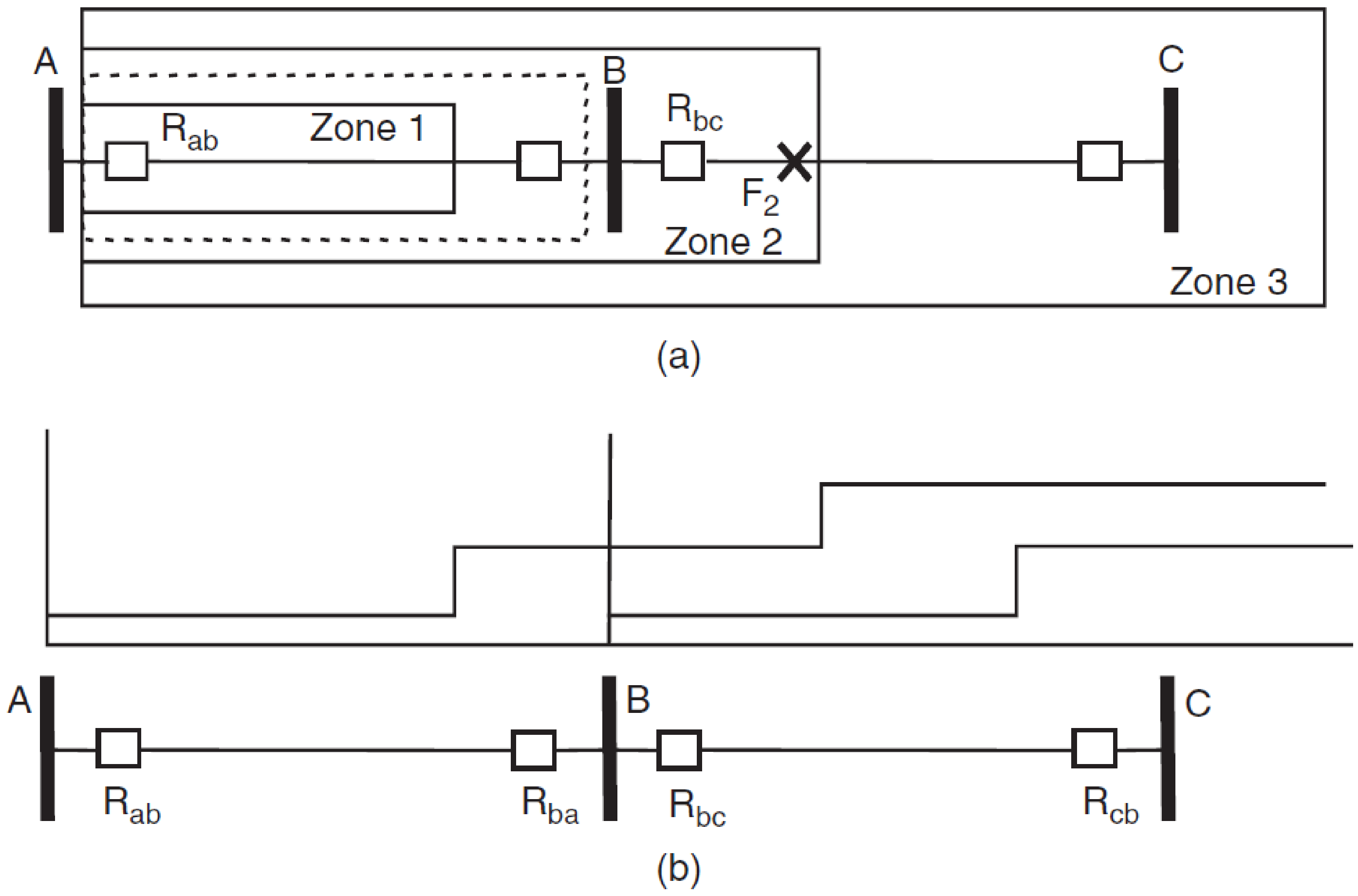



**Figure 5.1** Three-zone step distance relaying to protect 100 % of a line, and back up the neighboring line

It is customary to set zone 1 between 85 and 90 % of the line length

The reach of the second zone is generally set at 120–150 % of the line length AB.

This **coordination delay** for zone 2 is usually of the order of 0.3 s, for the reasons explained in Chapter 4.

It must be borne in mind that zone 2 of relay $R_{ab}$ must not reach beyond zone 1 of relay $R_{bc}$, otherwise some faults may exist simultaneously in the second zones of $R_{ab}$ and $R_{bc}$, and may lead to unnecessary tripping of both lines.

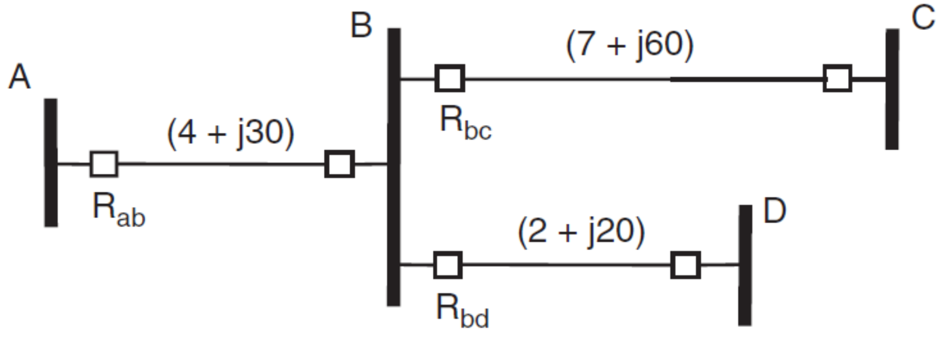
In order to provide a backup function for the entire line, it is customary to provide yet another zone of protection for the relay at A. This is known as the third zone of protection, and usually extends to 120–180 % of the next line section. The third zone must coordinate in time and distance with the second zone of the neighboring circuit, and usually the operating time of the third zone is of the order of 1 s.

'Underreaching' protection is a form of protection in which the relays at a given terminal do not operate for faults at remote locations on the protected equipment.[2]

The distance relay is set to underreach the remote terminal.

**Example 5.1**

Consider the transmission system shown in Figure 5.2. The relay $R_{ab}$ is to be set to protect the line AB, and back up the two lines BC and BD. The impedances of the three lines are as shown in Figure 5.2. (Note that these impedances are in primary ohms – i.e. actual ohms of the transmission lines. Normally, the settings are expressed in secondary ohms, as will be explained in section 5.3.) Zone 1 setting for $R_{ab}$ is $0.85 \times (4 + j30)$, or $(3.4 + j25.5)\ \Omega$. Zone 2 is set at $1.2 \times (4 + j30)$, or $(4.8 + j36)\ \Omega$. Since the relay $R_{ab}$ must back up relays $R_b$ and $R_{bd}$, it must reach beyond the longer of the two lines. Thus, zone 3 is set at $[(4 + j30) + 1.5 \times (7 + j60)]$, or at $(14.5 + j120)\ \Omega$. The time delays associated with the second and third zones should be set at about 0.3 and 1.0 s, respectively.



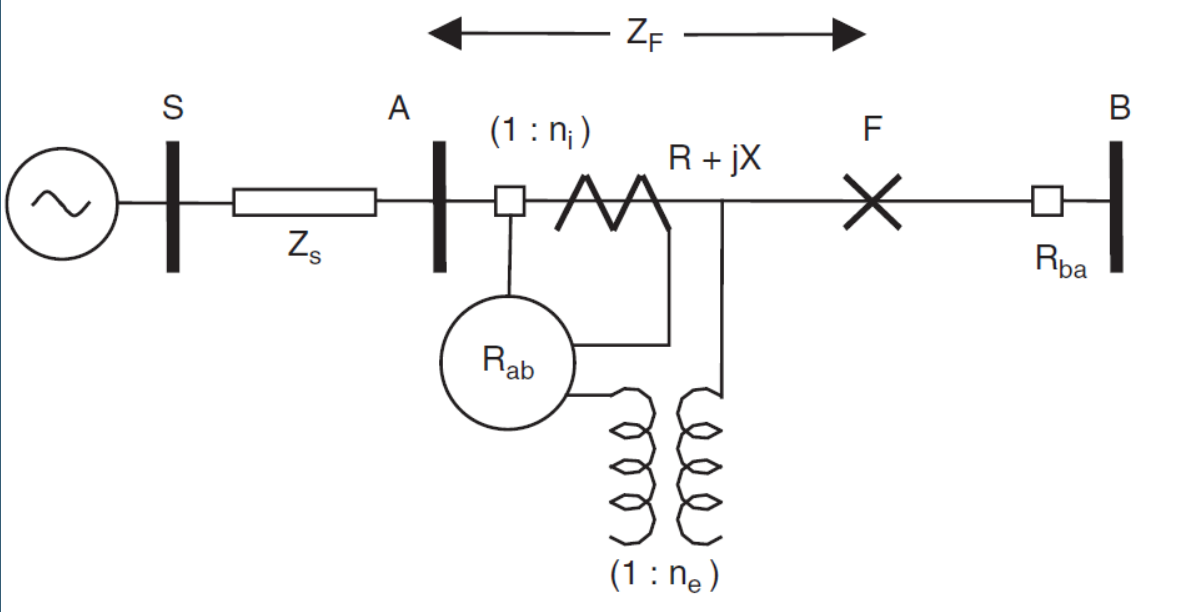

It should be noted that if one of the neighboring lines, such as line BD, is too short, then the zone 2 setting of the relay $R_{ab}$ may reach beyond its far end. For the present case, this would happen if the impedance of line BD is smaller than $[(4.8 + j36) - (4.0 + j30)] = (0.8 + j6)\ \Omega$. In such a case, one must set zone 2 to be a bit shorter, to make sure that it does not overreach zone 1 of $R_{bd}$, or, if this is not possible, zone 2 of the relay $R_{ab}$ may be set longer than zone 2 of relay $R_{bd}$ or it may be dispensed with entirely and only zone 3 may be employed as a backup function for the two neighboring lines.

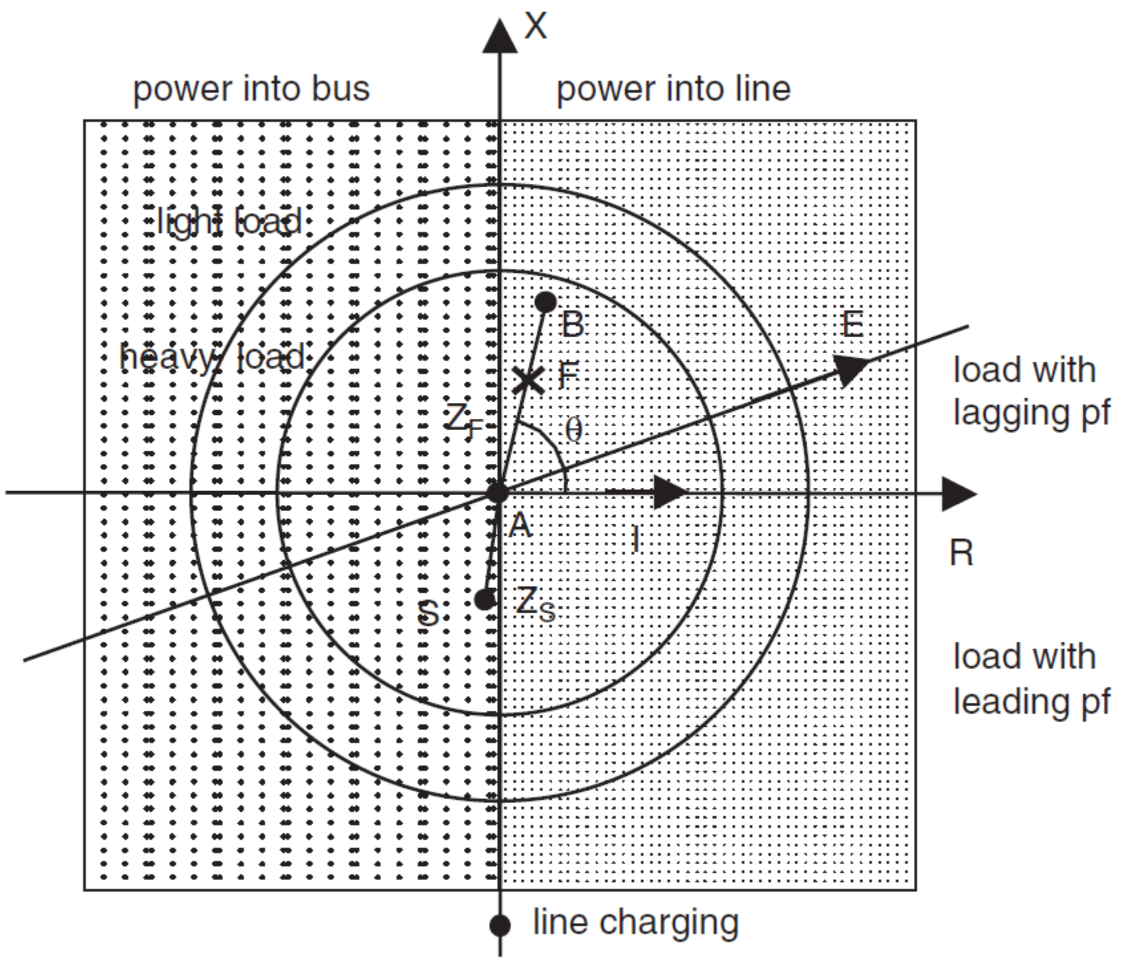
The three distance measuring elements $Z_1$, $Z_2$ and $Z_3$ close their contacts if the impedance seen by the relay is inside their respective zones. The zone 1 contact activates the breaker trip coil(s) immediately (i.e. with no intentional time delay), whereas the zones 2 and 3 contacts energize the two timing devices $T_2$ and $T_3$, respectively. Once energized, these timing devices close their contacts after their timer settings have elapsed. These timer contacts also energize the breaker trip coil(s). Should the fault be cleared before the timers run out, $Z_2$, $Z_3$, $T_2$ and $T_3$ will reset as appropriate in a relatively short time (about 1–4 ms).

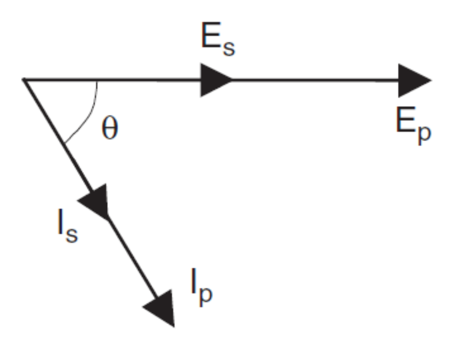
# 5.3 $R - X$ diagram

Consider an ideal (zero resistance) short circuit at location F in the single-phase system shown in Figure 5.4. The distance relay under consideration is located at line terminal A. The primary voltage and current at the relay location are related by

$$Z_{f,p} = \frac{E_p}{I_p}$$




$$Z_{f,s} = \frac{E_s}{I_s} = Z_{f,p}\frac{n_i}{n_e}$$

Audio correction – around time 7mins 10s – I am saying 30MVA load – this is wrong – it is actually 80MVA load.

**Example 5.2**

Consider a distance relaying system utilizing a CT with a turns ratio of 500 : 5 and a VT with a turns ratio of 20 000 : 69.3. Thus, the CT ratio $n_i$ is 100, while the VT ratio $n_e$ is 288.6. The impedance conversion factor $n_i/n_e$ for this case is (100/288.6), or 0.3465. All primary impedances must be multiplied by this factor to obtain their secondary values. Thus, the line in Example 5.1 with an impedance of $(4 + j30)\ \Omega$ primary would appear to be $(1.386 + j10.395)\ \Omega$ secondary.

The zone 1 setting for this line would be 85 % of this impedance, or $(1.17 + j8.84)\ \Omega$ secondary. Of course, the actual setting used would depend upon the nearest value which is available on a given relay.

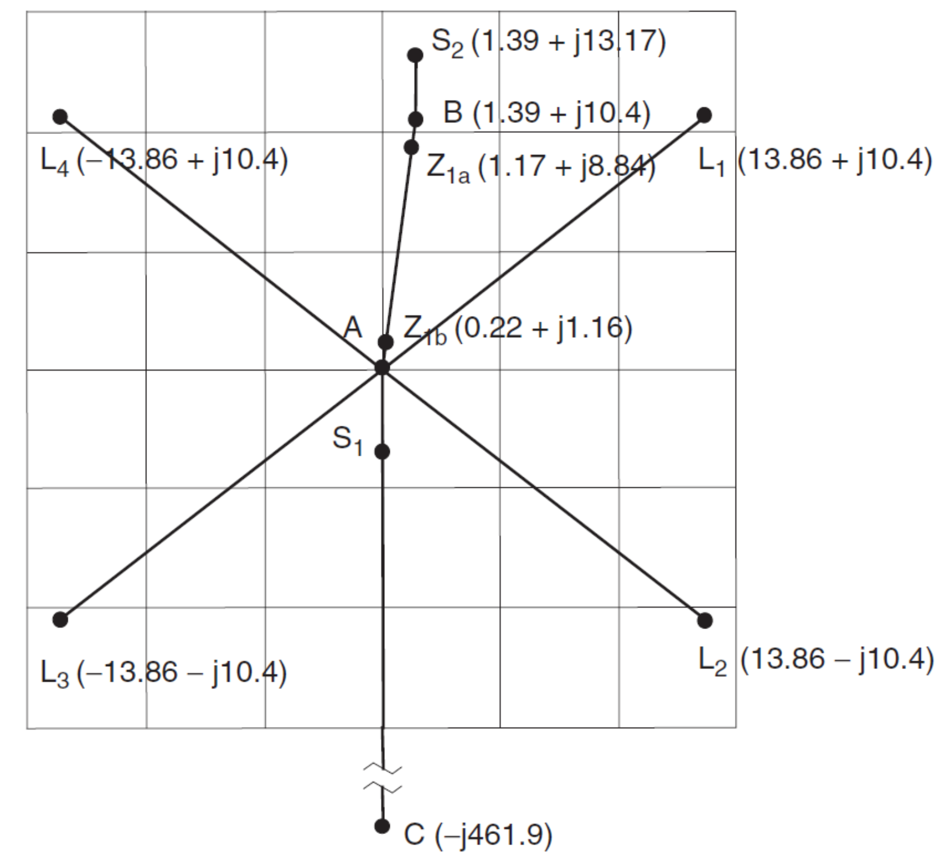
$$Z_{f,p} = \frac{E_p}{I_p}$$

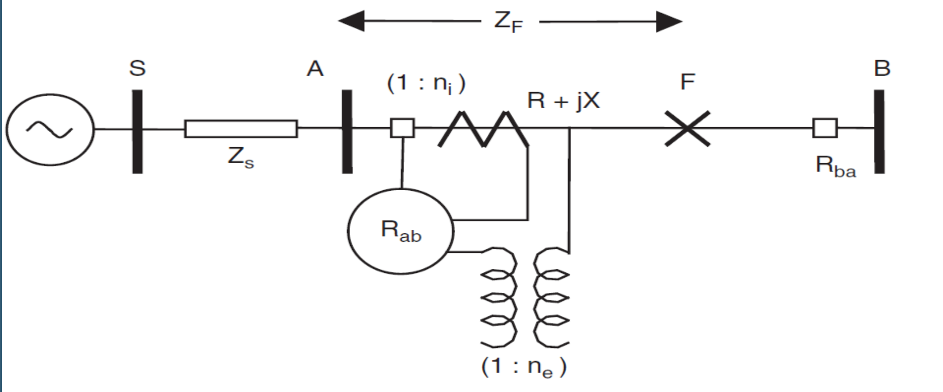
$$Z_{f,s} = \frac{E_s}{I_s} = Z_{f,p}\frac{n_i}{n_e}$$

**Example 5.3**

Let the rated load for the transmission line shown in Figure 5.4 be 8 MVA. This corresponds to 400 A at the rated voltage of 20 000 V. The apparent impedance corresponding to this load is (20 000/400) = 50 Ω primary. In terms of secondary ohms, this impedance becomes 50 × 0.3465 = 17.32 Ω. Thus, a load of 8 MVA at 0.8 pf lagging is 17.32 × (0.8 + j0.6) = (13.86 + j10.4) Ω secondary. This is shown as $L_1$ in Figure 5.6. A load of 8 MVA with a leading power factor of 0.8 is (13.86 – j10.4) Ω secondary, which maps as point $L_2$. Similarly, 8 MVA flowing from B to A maps into $L_3$ and $L_4$ for leading and lagging power factors, respectively.

The line impedance of (1.39 + j10.4) Ω secondary maps into point B while the zone 1 setting of (1.17 + j8.84) Ω maps into the point $Z_{1a}$. A similar relay located at B would have its zone 1 map at $Z_{1b}$. If we assume the equivalent source impedances as seen at buses A and B to be j10 and j8 Ω primary respectively, they will be j3.46 and j2.77 Ω secondary respectively, as shown by points $S_1$ and $S_2$ in Figure 5.6. If the line-charging current is 15 A, the apparent impedance seen by the relay at A when the breaker at terminal B is open is –j(20 000/15) = –j1333 Ω primary, or –j461.9 Ω secondary. This is shown as the point C, on a telescoped $y$ axis in Figure 5.6. The zones of protection of a relay are defined in terms of its impedance, and hence it is necessary that they cover areas in the immediate neighborhood of the line AB. As the load on the system increases, the possibility of it encroaching upon the protection zones becomes greater. Ultimately, at some values of the load, the relay is in danger of tripping. The $R$–$X$ diagram offers a convenient method of analyzing whether this is the case. A fuller account of the loadability of a distance relay is considered in section 5.11.

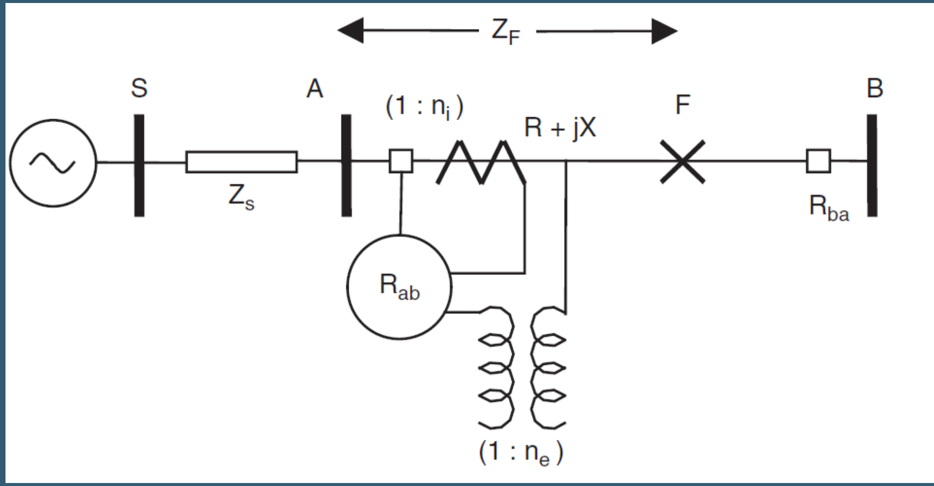


## 5.4 Three-phase distance relays

. It is a fundamental principle of distance relaying that, regardless of the type of fault involved, the voltage and current used to energize the appropriate relay are such that the relay will measure the positive sequence impedance to the fault.[5]

## *5.4.1 Phase-to-phase faults*



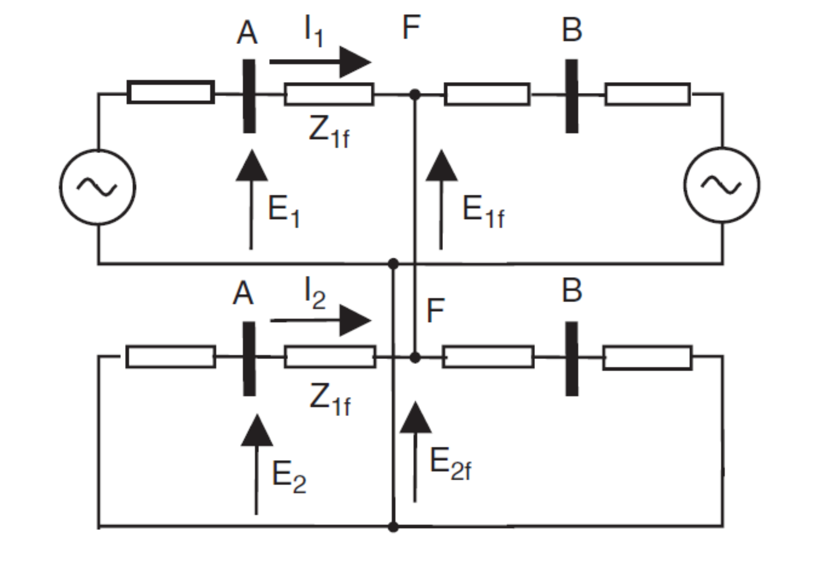
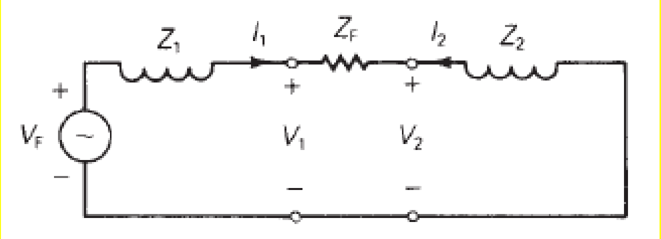




**Figure 5.7** Symmetrical component circuit for b–c fault




(b) Interconnected sequence networks

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (8.1.1)$$

$$E_{1\mathrm{f}} = E_{2\mathrm{f}} = E_1 - Z_{1\mathrm{f}} I_1 = E_2 - Z_{1\mathrm{f}} I_2 \quad (5.3)$$

$$\frac{E_1 - E_2}{I_1 - I_2} = Z_{1\mathrm{f}} \quad (5.4)$$

$$E_\mathrm{b} = E_0 + \alpha^2 E_1 + \alpha E_2 \text{ and } E_\mathrm{c} = E_0 + \alpha E_1 + \alpha^2 E_2 \quad (5.5)$$

$$(E_\mathrm{b} - E_\mathrm{c}) = (\alpha^2 - \alpha)(E_1 - E_2) \text{ and } (I_\mathrm{b} - I_\mathrm{c}) = (\alpha^2 - \alpha)(I_1 - I_2) \quad (5.6)$$

$$\frac{E_\mathrm{b} - E_\mathrm{c}}{I_\mathrm{b} - I_\mathrm{c}} = \frac{E_1 - E_2}{I_1 - I_2} = Z_{1\mathrm{f}} \quad (5.7)$$

Thus, a distance relay, to which the line-to-line voltage between phases b and c is connected, and which is supplied by the difference between the currents in the two phases, will measure the positive sequence impedance to the fault, when a fault between phases b and c occurs.

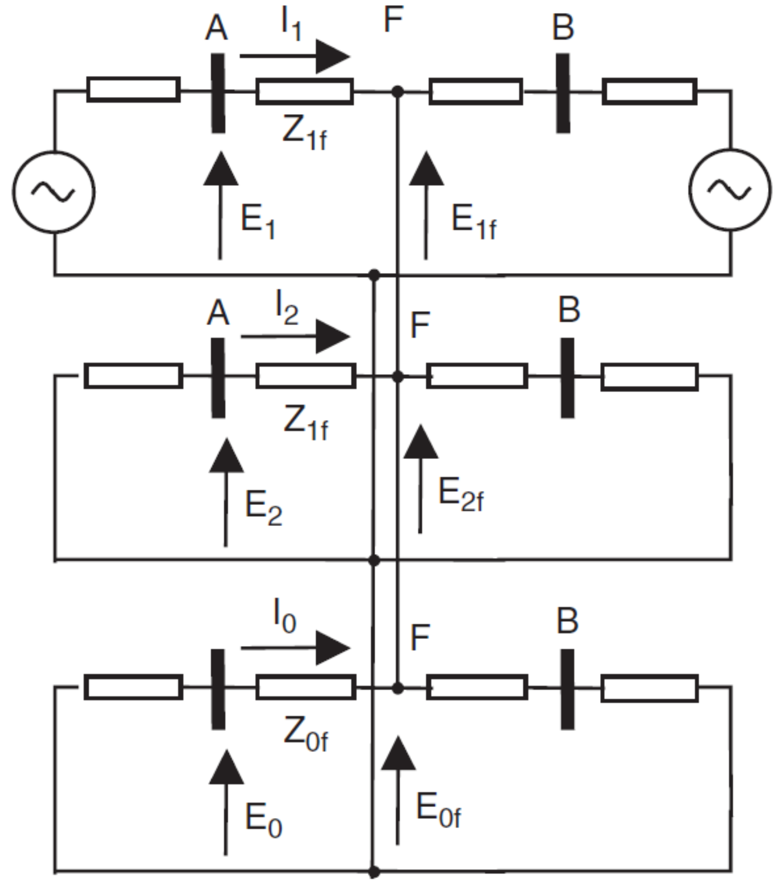



**Figure 5.8** Symmetrical component circuit for b–c–g fault

$$E_{1f} = E_{2f} = E_1 - Z_{1f} I_1 = E_2 - Z_{1f} I_2 \quad (5.3)$$

$$\frac{E_1 - E_2}{I_1 - I_2} = Z_{1f} \quad (5.4)$$

$$E_b = E_0 + \alpha^2 E_1 + \alpha E_2 \text{ and } E_c = E_0 + \alpha E_1 + \alpha^2 E_2 \quad (5.5)$$

$$(E_b - E_c) = (\alpha^2 - \alpha)(E_1 - E_2) \text{ and } (I_b - I_c) = (\alpha^2 - \alpha)(I_1 - I_2) \quad (5.6)$$

$$\frac{E_b - E_c}{I_b - I_c} = \frac{E_1 - E_2}{I_1 - I_2} = Z_{1f} \quad (5.7)$$

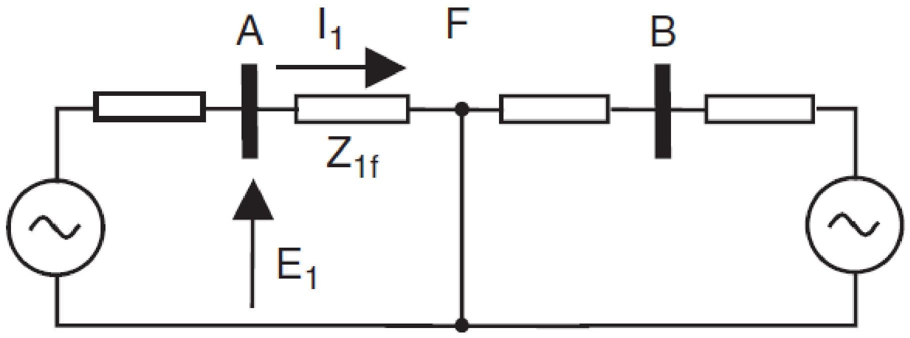



**Figure 5.9** Symmetrical component circuit for a three-phase fault

$$E_1 = E_a = Z_{1f} I_1 = Z_{1f} I_a$$

$$E_2 = E_0 = 0$$

$$I_2 = I_0 = 0$$

$$\frac{E_a - E_b}{I_a - I_b} = \frac{E_b - E_c}{I_b - I_c} = \frac{E_c - E_a}{I_c - I_a} = Z_{1f}$$

$$E_a = E_1,\ E_b = \alpha^2 E_1$$

So,

$(Ea - Eb)/(Ia - Ib)$

$= (E_1 - a^2E_1) / (I_1 - a^2I_1)$

$= E_1 (1 - a^2) / I_1 (1 - a^2)$

$= E_1/I_1$

$= Ea/Ia$

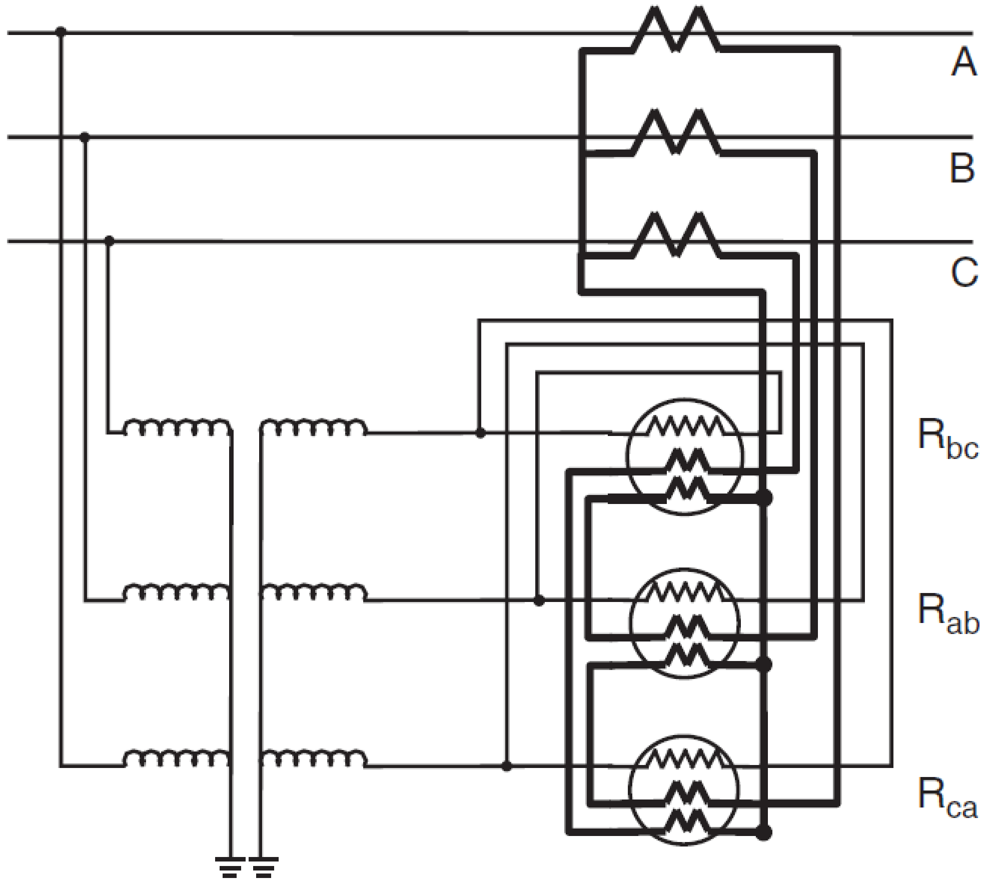



**Figure 5.10** Current transformer and voltage transformer connections for distance relays for phase faults

The three distance relays cover all seven phase faults (Double Line, Double Line to Ground and Triple line fault)

### *5.4.2 Ground faults*

$$E_{1f} = E_1 - Z_{1f} I_1$$

$$E_{2f} = E_2 - Z_{1f} I_2$$

$$E_{0f} = E_0 - Z_{0f} I_0$$

$$\begin{aligned} E_{af} &= E_{0f} + E_{1f} + E_{2f} \\ &= (E_0 + E_1 + E_2) - Z_{1f}(I_1 + I_2) - Z_{0f} I_0 = 0 \\ &= E_a - Z_{1f} I_a - (Z_{0f} - Z_{1f}) I_0 = 0 \end{aligned}$$

$$I'_a = I_a + \frac{Z_{0f} - Z_{1f}}{Z_{1f}} I_0 = I_a + \frac{Z_0 - Z_1}{Z_1} I_0 = I_a + m I_0$$

$$\frac{E_a}{I'_a} = Z_{1f}$$

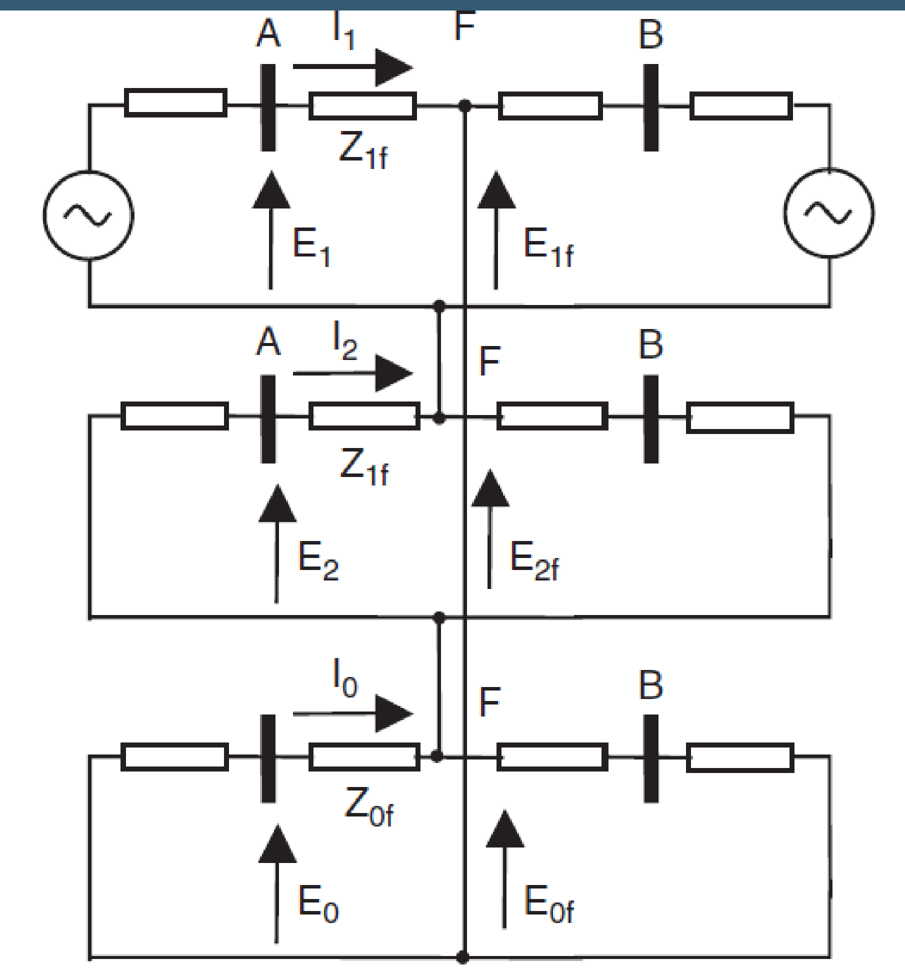



**Figure 5.11** Symmetrical component circuit for an a–g fault

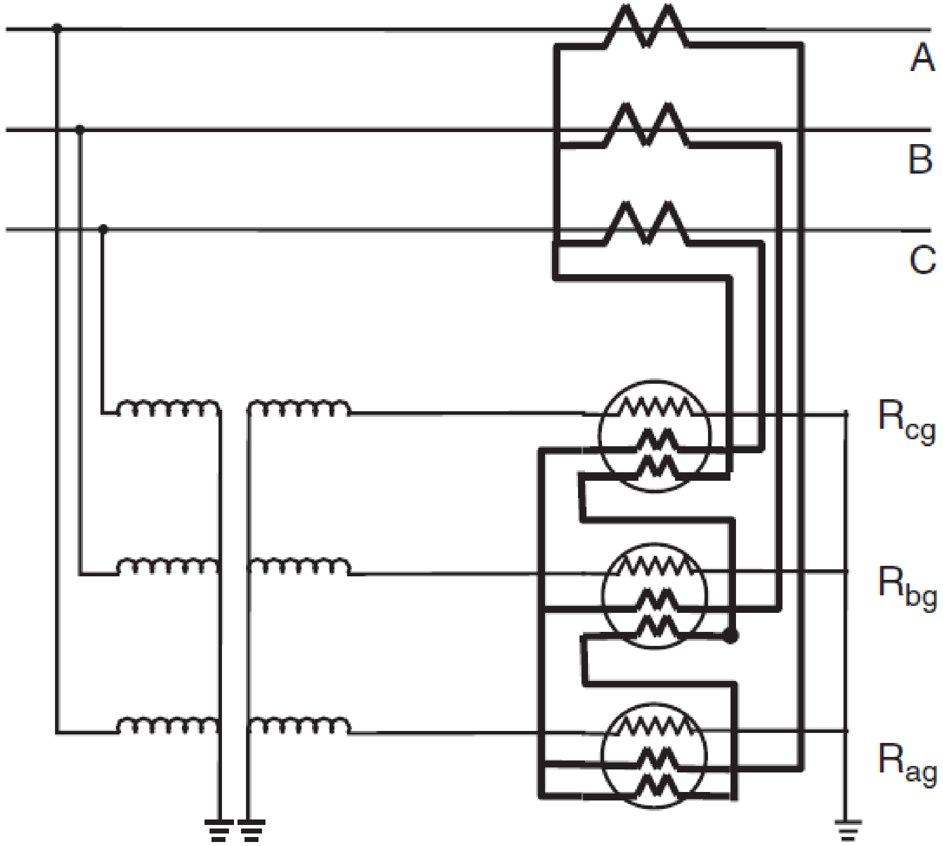



**Figure 5.12** Current transformer and voltage transformer connections for distance relays for ground faults

The factor $m$ for most overhead transmission lines is a real number, and varies between 1.5 and 2.5. A good average value for $m$ is 2.0, which corresponds to $Z_0$ of a transmission line being equal to $3Z_1$.

A full complement of phase and ground distance relays will require six distance measuring elements connected as shown in Figures 5.10 and 5.12.

**Example 5.4**

Consider the simple system represented by the one-line diagram in Figure 5.13. The system nominal voltage is 13.8 kV, and the positive and zero sequence impedances of the two elements are as shown in the figure. The zero sequence impedances are given in parentheses. We will verify the distance calculation equations (5.9) and (5.14) for three-phase, phase-to-phase and phase-to-ground faults.

**Three-phase fault**

For this case, only the positive sequence current exists, and is also the phase a current. It is given by

$$I_a = I_1 = \frac{7967.4}{4 + j45} = 176.36\angle 84.92^\circ$$

$7967.4 = (13\,800/\sqrt{3})$ is the phase-to-neutral voltage. The phase a voltage at the relay location is given by

$$E_a = E_1 = 7967.4 - j5 \times 176.36\angle 84.92^\circ = 7089.49\angle -0.63^\circ$$

Thus, the fault impedance seen by the relay in this case is

$$Z_f = \frac{E_a - E_b}{I_a - I_b} = \frac{E_a}{I_a} = \frac{7089.49\angle -0.63^\circ}{176.36\angle -84.92^\circ} = 4 + j40\ \Omega$$

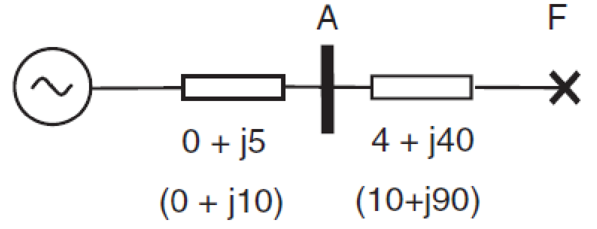


**Figure 5.13** System for fault impedance calculation

$$\frac{E_a - E_b}{I_a - I_b} = \frac{E_b - E_c}{I_b - I_c} = \frac{E_c - E_a}{I_c - I_a} = Z_{1f}$$

$$\frac{E_a - E_b}{I_a - I_b} = \frac{E_b - E_c}{I_b - I_c} = \frac{E_c - E_a}{I_c - I_a} = Z_{1f}$$

**Phase-to-phase fault**

For a b–c fault

$$I_1 = -I_2 = \frac{7967.4}{2 \times (4 + j45)} = 88.18\angle 84.92^\circ$$

Also, $I_b = -I_c = I_1(\alpha_2 - \alpha) = -j\sqrt{(3)}I_1 = 152.73\angle - 174.92^\circ$. And, $(I_b - I_c) = 305.46\angle - 174.92^\circ$. The positive and negative sequence voltages at the relay location are given by

$$E_1 = 7967.4 - j5 \times 88.18\angle - 84.92^\circ = 7528.33\angle - 0.3^\circ$$

$$E_2 = j5 \times 88.18\angle - 84.92^\circ = 440.90\angle 5.08^\circ$$

and the phase b and c voltages at the relay location are

$$E_b = \alpha^2 E_1 + \alpha E_2 = 7528.33\angle - 120.3^\circ + 440.90\angle 125.08^\circ$$

$$= -4051.3 - j6139.3$$

$$E_c = \alpha E_1 + \alpha^2 E_2 = 7528.33\angle 119.7^\circ + 440.90\angle - 114.9^\circ$$

$$= -3916.09 + j6139.3$$

Thus, $E_b - E_c = 12279.37\angle - 90.63^\circ$, and

$$\frac{E_b - E_c}{I_b - I_c} = \frac{12\,279.37\angle - 90.63^\circ}{305.46\angle - 174.92^\circ} = 4 + j40\ \Omega$$

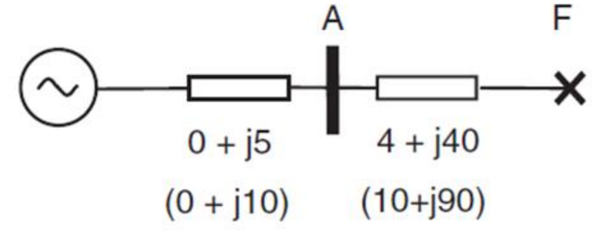



**Figure 5.13** System for fault impedance calculation

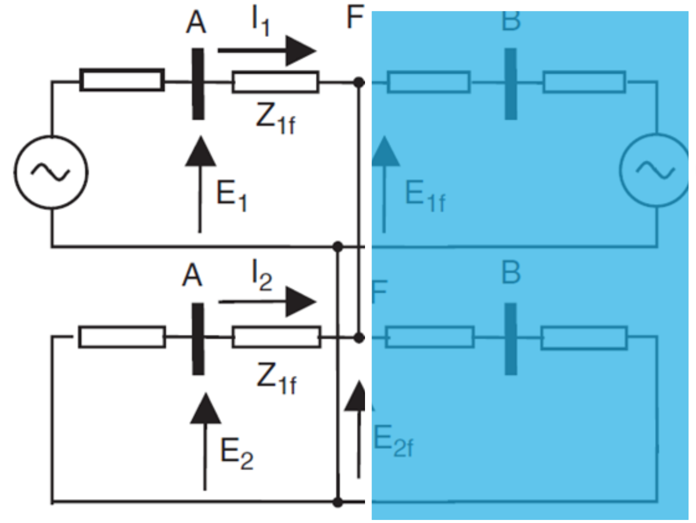



**Figure 5.7** Symmetrical component circuit for b–c fault

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (8.1.1)$$

$$\frac{E_a - E_b}{I_a - I_b} = \frac{E_b - E_c}{I_b - I_c} = \frac{E_c - E_a}{I_c - I_a} = Z_{1f}$$

**Phase-to-phase fault**

For a b–c fault

$$I_1 = -I_2 = \frac{7967.4}{2 \times (4 + j45)} = 88.18\angle 84.92^\circ$$

Mistake in book – angle is - 84.92°

Also, $I_b = -I_c = I_1(\alpha_2 - \alpha) = -j\sqrt{(3)}I_1 = 152.73\angle -174.92^\circ$. And, $(I_b - I_c) = 305.46\angle -174.92^\circ$. The positive and negative sequence voltages at the relay location are given by

$$E_1 = 7967.4 - j5 \times 88.18\angle -84.92^\circ = 7528.33\angle -0.3^\circ$$

$$E_2 = j5 \times 88.18\angle -84.92^\circ = 440.90\angle 5.08^\circ$$

and the phase b and c voltages at the relay location are

$$E_b = \alpha^2 E_1 + \alpha E_2 = 7528.33\angle -120.3^\circ + 440.90\angle 125.08^\circ$$

$$= -4051.3 - j6139.3$$

$$E_c = \alpha E_1 + \alpha^2 E_2 = 7528.33\angle 119.7^\circ + 440.90\angle -114.9^\circ$$

$$= -3916.09 + j6139.3$$

Thus, $E_b - E_c = 12279.37\angle -90.63^\circ$, and

$$\frac{E_b - E_c}{I_b - I_c} = \frac{12\,279.37\angle -90.63^\circ}{305.46\angle -174.92^\circ} = 4 + j40\ \Omega$$

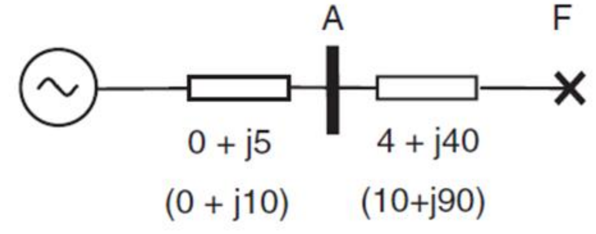



**Figure 5.13** System for fault impedance calculation

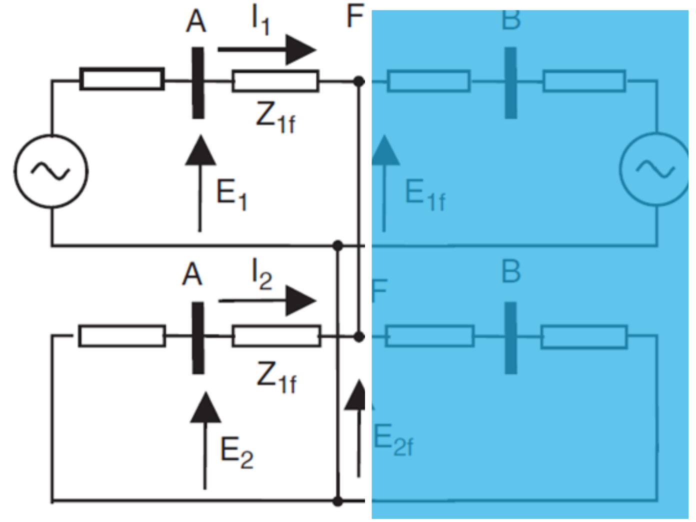



**Figure 5.7** Symmetrical component circuit for b–c fault

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (8.1.1)$$

**Phase-a-to-ground fault**

$$\boxed{\frac{E_a}{I'_a} = Z_{1f}}$$

For this fault, the three symmetrical components of the current are equal:

$$I_1 = I_2 = I_0 = \frac{7967.4}{(0 + j10) + 2 \times (0 + j5) + (10 + j90) + 2 \times (4 + j40)}$$
$$= 41.75\angle - 84.59^\circ$$

The symmetric components of the voltages at the relay location are

$$E_1 = 7967.4 - j5 \times 41.75\angle - 84.59^\circ = 7759.58 - j19.68$$
$$E_2 = -j5 \times 41.75\angle - 84.59^\circ = -207.82 - j19.68$$
$$E_0 = -(0 + j10) \times 41.75\angle - 84.59^\circ = -415.64 - j39.36$$

And the phase a voltage and current at the relay location are

$$E_a = E_1 + E_2 + E_0 = 7136.55\angle - 0.63^\circ$$
$$I_a = I_1 + I_2 + I_0 = 125.25\angle - 84.59^\circ$$

The zero sequence current compensation factor $m$ is given by

$$m = \frac{Z_0 - Z_1}{Z_1} = \frac{1 - j90 - 4 - j40}{4 + j40} = 1.253\angle - 1.13^\circ$$

and the compensated phase a current is $I'_a = I_a + mI_0 = 177.54\angle - 84.92^\circ$; and, finally

$$\frac{E_a}{I'_a} = \frac{7136.55\angle - 0.63^\circ}{177.54\angle - 84.92^\circ} = 4 + j40\ \Omega$$

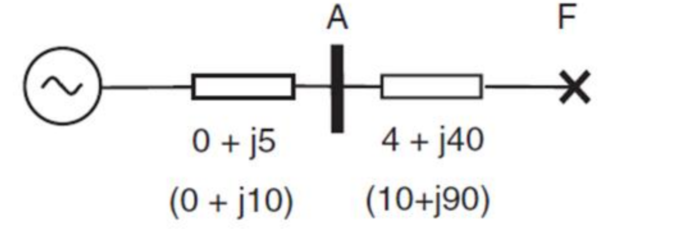



**Figure 5.13** System for fault impedance calculation

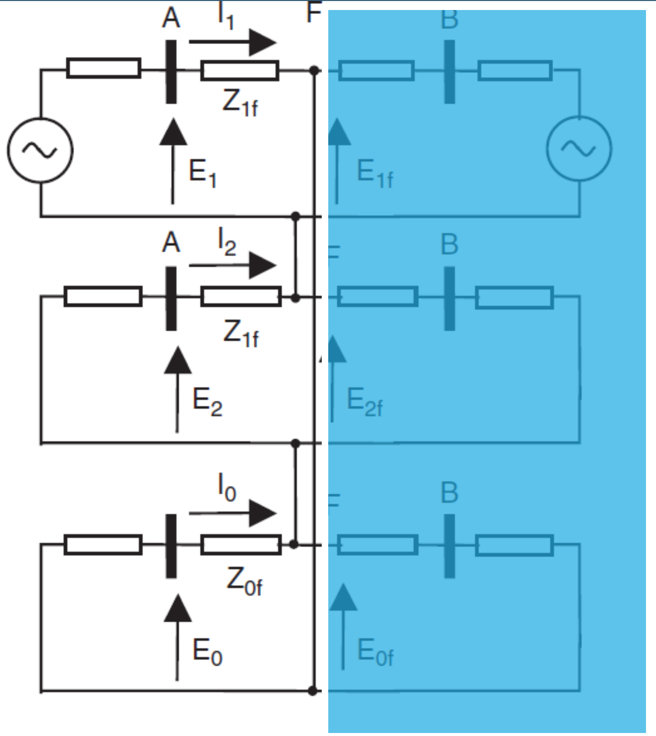



**Figure 5.11** Symmetrical component circuit for an a–g fault

## 5.4.4 Fault resistance

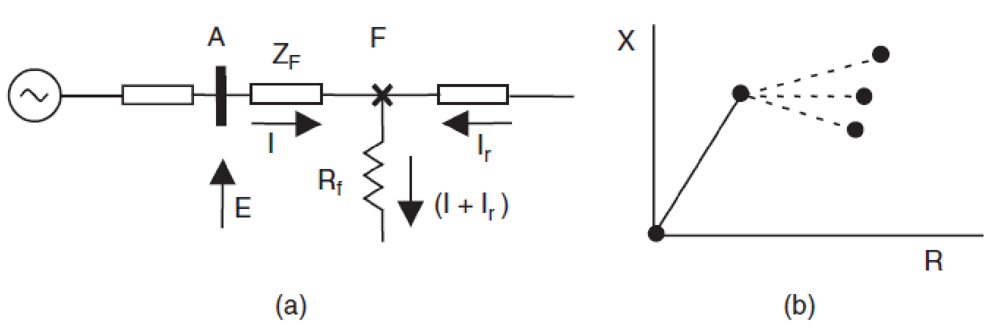



**Figure 5.15** Fault path resistance, and its effect on the $R-X$ diagram

$$E = Z_f I + R_f(I + I_r) \tag{5.16}$$

The apparent impedance $Z_a$ seen by the relay is

$$Z_a = E/I = Z_f + R_f\left(\frac{I_r}{I} + 1\right) \tag{5.17}$$

The fault resistance introduces an error in the fault distance estimate, and hence may create an unreliable operation of a distance relay. Consider the single-phase transmission system shown in Figure 5.15(a), and assume that the fault resistance is equal to $R_f$.

In order to accommodate the resistance in the fault path, it is necessary to shape the trip zone of a distance relay in such a manner that the region surrounding the apparent impedance is included inside the zone. It will be seen in section 5.11 that different types of distance relay have differing ability of accommodating the fault resistance.

**Example 5.5**

Assume a single-phase circuit as shown in Figure 5.15(a), and let the line impedance to the fault point be (4 + j40) Ω, while the fault resistance is 10 Ω. Let the current to the fault in the line in question be 400∠ − 85° amps, while the current contribution to the fault from the remote end is 600∠ − 90° amps. Then, the apparent impedance seen by the relay, as given by equation (5.17), is

$$Z_a = (4 + j40) + 10\left(1 + \frac{600\angle -90^\circ}{400\angle -85^\circ}\right) = 28.94 + j38.69\ \Omega$$

If the receiving end current contribution is in phase with the sending end current, the error in $Z_a$ will be in the real part only. That is not the case here, and hence the reactance also is in error.

The system assumed here is single phase, but even if it was a three phase system and a three phase fault occurred then,
impedance seen by relay Rab may be simplified as before:
$(E_a - E_b)/(I_a - I_b)$
$= (E_1 - a^2E_1) / (I_1 - a^2I_1)$
$= E_1 (1 - a^2) / I_1 (1 - a^2)$
$= E_1/I_1$
$= E_a/I_a$

## 5.5 Distance relay types

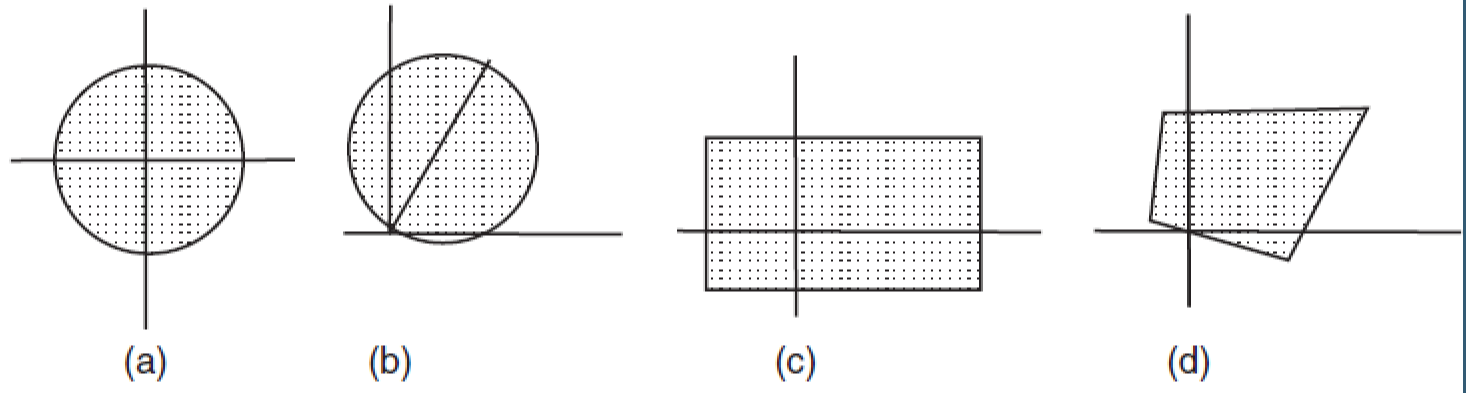



**Figure 5.16** Types of impedance relay characteristics

Four general relay types are recognized according to the shapes of their operating zones: (1) impedance relays, (2) admittance or mho relays, (3) reactance relays and (4) quadrilateral relays.

$$\frac{E_a - E_b}{I_a - I_b} = \frac{E_b - E_c}{I_b - I_c} = \frac{E_c - E_a}{I_c - I_a} = Z_{1f}$$

$$\frac{E_a}{I'_a} = Z_{1f}$$