Power System Protection

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Chapter 1 Introduction to Power Protection Systems

1.1 INTRODUCTION

Power system protection is a philosophy of system reliability with maximum safety protection and other aspects related to protection coordination. It is a science of monitoring power systems, detecting faults, initiating an operation to isolate faulted parts, and ultimately tripping the circuit breaker.

The aims of power system protection are to:

i. Minimize dangerous effects on the workers and establish techniques and procedures due to the abnormal current in the power system.
ii. Avoid damage to power system components involved in failure and human injury prevention.
iii. Limit the service duration interruption whenever equipment fails, adverse natural events occur, or human error occurs on any portion of the system.

1.2 PHILOSOPHY OF POWER SYSTEM PROTECTION

If short circuits are allowed to persist on a power system for an extended period, many or all of the following undesirable effects are likely to occur:

i. Reduced stability of the power system.
ii. Damage to the equipment that is in the vicinity of the fault due to heavy current, unbalanced current, or low voltage.
iii. Explosions that may occur in equipment with hazards.
iv. Disruptions in the entire power system service area by the action of cascaded protective systems in cascading.

The frequency of the faults incidence on different items and fault statistics with reference to power system elements in a power system is given in Table 1.1.

Table 1.1

Typical short-circuit type distribution

Type	**Rate of occurrence (%)**
Single-phase ground	70-80
Phase-phase ground	10-17
Phase-phase	8-10
Three-phase	2-3

Fault statistics with reference to power system elements

Power system element	**Probability of faults (%)**
Overhead lines	50
Underground cables	9
Transformers	10
Generators	7
Switchgear	12
CT, PT relays, control equipment, etc.	12

Causes of short-circuit faults are as follows:

i. Insulation failure due to lightning.
ii. Birds and animals bridging insulators.
iii. Dig-ups for underground cables.
iv. Collapsing poles.
v. Breaking of conductors.
vi. Effect of a vehicle collision.
vii. Wind-borne debris.
viii. Incorrect operation by personnel.

1.3 EFFECTS OF FAULTS

The effect of the fault on the power system includes the following:

i. Huge currents can flow through parts of the power network.
ii. These huge currents can only flow for a very short time (within 10 ms to 3 s); otherwise, equipment and generators would be damaged.
iii. Arcs, sparking, and the heating effect of short-circuit currents.
iv. Significant mechanical forces can be caused by short-circuit currents, which can potentially damage equipment.
v. Fault currents can escape from the network conductors and flow through paths that could create a hazard to people or livestock.

Fault occurrence can be minimized and controlled by:

1. Adequate insulation and coordination with lightning arresters.
2. Overdesigning for mechanical strength.
3. Provision of overhead ground wires.
4. Blocking or interlocking of undesirable switching operations.
5. Regular maintenance practices.

1.4 PERFORMANCE REQUIREMENTS OF PROTECTION SYSTEM

Speed, selectivity, sensitivity, security, and reliability are the keys required for reliable operation and the safety of a power system.

The area of power engineering dealing with the design, implementation, and operation of safety devices, called "**relays**" or "**protective relays**," is power system protection. The purpose of these devices is to detect irregular conditions in the power system and take appropriate steps as quickly as possible to restore the power system to its usual operating mode.

The relays have to meet the following criteria to achieve the desired performance:

i. ***Sensitivity***: This term is sometimes used when referring to the minimum operating standard of relays or full safety schemes (current, voltage, power, etc.). When their primary operational parameters are tiny, relays or security schemes are said to be vulnerable.

ii. ***Speed***: It is the relay's capacity to isolate faults as quickly as possible, mitigate harm to power system equipment, safeguard supply continuity, and prevent the loss of synchronism and consequent power system failure.

- ***iii.*** ***Stability***: It is the relay's ability to remain unaffected by incidents outside its security region, including external faults or heavy load situations.
- ***iv.*** ***Selectivity***: It is the ability to isolate only the faulted zone.
- ***v.*** ***Safety***: It is the ability to secure against improper activity.

$$\%\text{Security} = \frac{\text{No. of correct trippings}}{\text{Total no. of trippings}} \times 100 \qquad (1.1)$$

- ***vi.*** ***Discrimination***: It is between load (normal) and fault (abnormal) conditions. It should not be confused with non-damaging transient conditions. Discrimination is a relay system's ability to discriminate between internal and external faults to its intended protective zones.
- ***vii.*** ***Dependability***: A relay is dependable if it trips only when expected. Dependability is the degree of certainty that the relay will operate correctly. It can be improved by increasing the sensitivity of the relaying scheme.

$$\%\text{Dependability} = \frac{\text{No. of correct trippings}}{\text{Total no. of desired trippings}} \times 100 \qquad (1.2)$$

- ***viii.*** ***Reliability***: It is the ability not to "fail" in its function. It can be achieved by redundancy. Redundancy in protection depends on the criticality of the apparatus. Reliability can be improved by providing backup protection.

$$\% \text{ Reliability} = \frac{\text{No. of correct trips}}{\text{No. of desired trips} + \text{No. of incorrect trips}} \times 100 \qquad (1.3)$$

The number of the desired tripping can be greater than or equal to the correct tripping.

Example 1.1 An overcurrent relay was monitored and had an observed performance over one year. It was found that the relay operated 15 times, out of which 13 were correct trips. If the relay failed to issue a trip decision on 4 occasions, compute the relay’s dependability, security, and reliability.

Solution

Number of correct trips =13
Number of desired trips = 13 + 4 =17

Dependability = Number of correct trips / Number of desired trips
= 13 / 7 = 76.47%
Security = Number of correct trips / Total number of trips
= 13 /15 = 86%
Reliability = Number of correct trips / (Number of desired trips + number of incorrect trips)
= 13 / (17 + 2) = 68.42%

1.5 BASIC PROTECTION SCHEME COMPONENTS

The primary protective equipment components are shown in Figure 1.1.

i. PR – Protection relay.
ii. CB – Circuit breaker.
iii. Equip protected item.
iv. CT – Current transformer.
v. VT – Voltage transformer.
vi. DC Aux – DC auxiliary supply.
vii. HMI – Human–machine interface.
viii. PCL communications link.
ix. Tr CB – Trip coil.

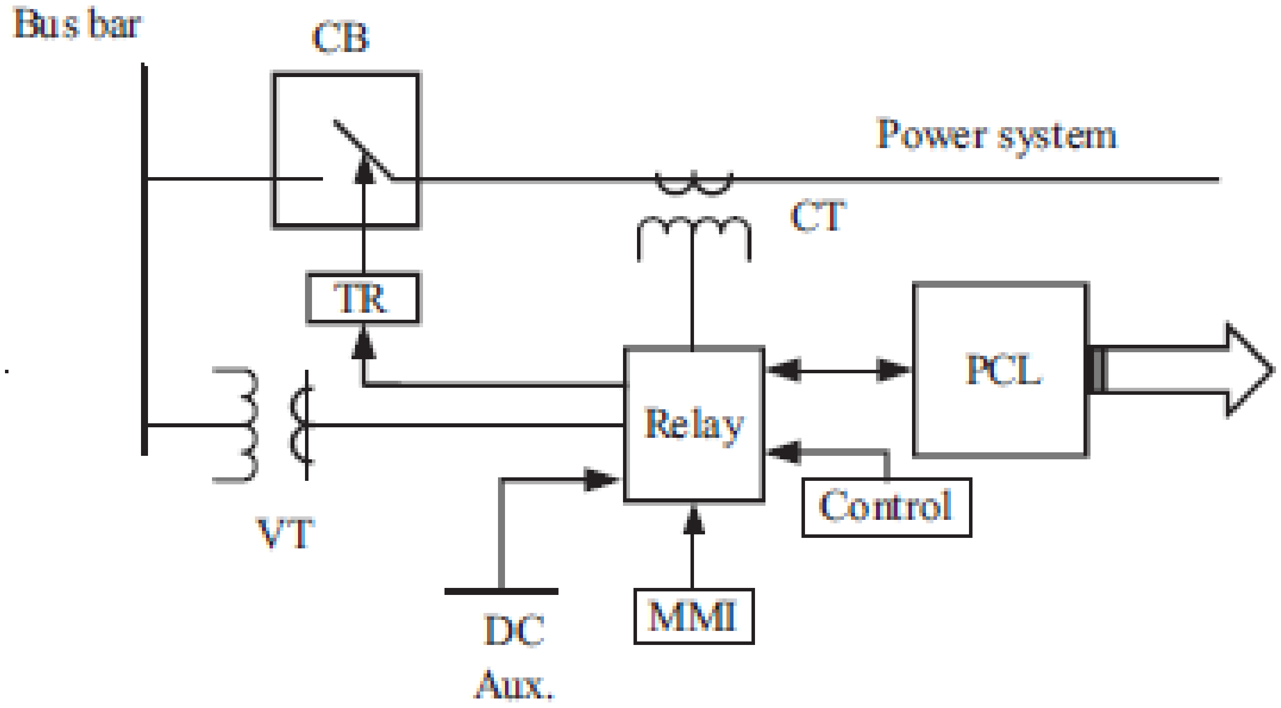

FIGURE 1.1 The basic arrangement of a protection scheme.

1.6 PROTECTIVE RELAY

It is a device that receives a signal from the power system and determines whether a “normal” or “abnormal” (measuring function) condition exists and initiates relay signal circuit breakers to disconnect the equipment that may be affected (switching or signaling function) if an irregular condition is present. Signal “relays” from the system activate the circuit breaker.

The aim of the protective relaying systems is only to isolate the defective power system portion. Relaying devices are divided into two groups:

1. Equipment for primary relaying.
2. Backup relaying units.

The first line of defense for protecting the devices is the primary relay. Backup safety relaying only works when (they are slow in action) the primary relaying system fails.

1.7 TRANSDUCERS

There are:

i. Current transformer (CT).
ii. Voltage transformer (VT) or potential transformer (PT).
iii. Linear coupler.

CTs and VTs are used.

i. To reduce the currents and voltages to a safe, adequate low value for measurements and protection use.
ii. To insulate the relay circuit from the primary power circuit.
iii. To permit the use of standardized current and voltage ratings for relays.

1.7.1 Current transformer

Current transformers are connected in series (primaries) with the protective circuit. Because the primary current is large, the primary windings usually have very few turns and a large conductor diameter. Figure 1.2 shows the CT connection to the power system.

The nominal current rating of the CT secondaries is usually 1 or 5 A (e.g., 50:5, 250:1, 1,200:5).

The main parts of a current transformer are:

- Iron core.
- Secondary winding.
- Primary conductor.
- External insulation.

Some current transformers do not have a primary conductor. In those cases, the primary is the line or bus itself. The core and secondary winding are sometimes directly installed in the circuit breakers or transformers' bushing. These CTs are called "bushing CTs."

Some current transformers may have a primary that consists of several turns. Typically, the primary number of turns is 1. The total load connected to the CT terminal is called "burden."

Figure 1.3 shows an equivalent circuit of CT, an exact circuit, and an approximate circuit.

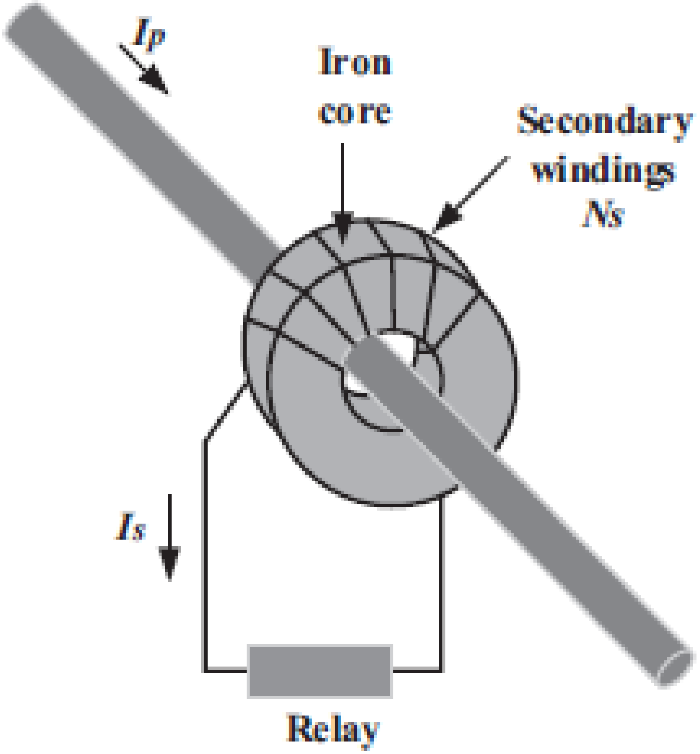

FIGURE 1.2 CT connection in the system.

1.7.1.1 IEC Standard Accuracy Classes

The IEC (International Electrotechnical Commission) specifications for the current transformer is 15 VA Class10 P 20, where 15 VA is the continuous VA; 10 represents the accuracy class (max 10% error); P represents protection; and 20 represents the accuracy limit current factor (number of times the rated primary current).
Table 1.2 shows standard current transformer ratios, and Table 1.3 shows CT accuracy class.

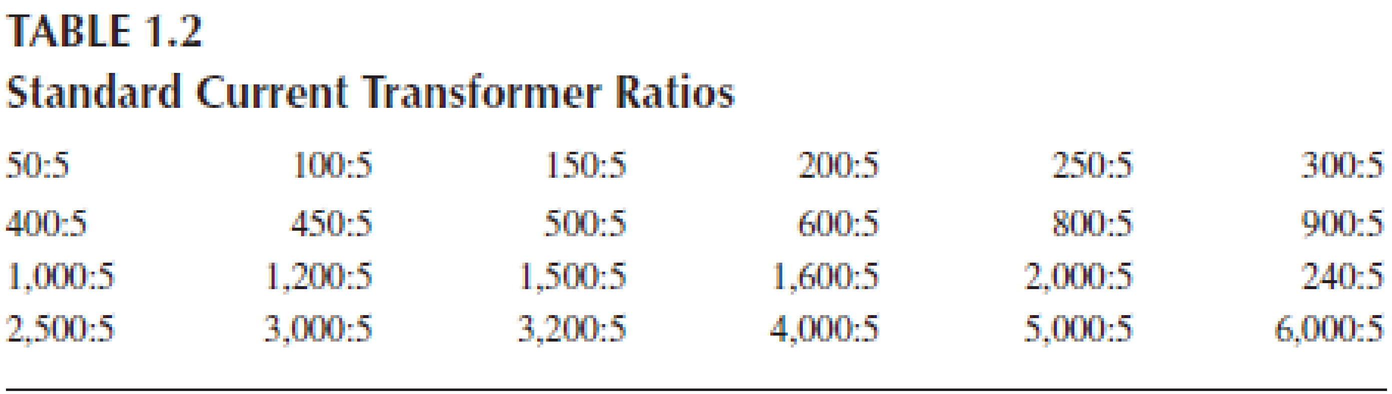

TABLE 1.2
Standard Current Transformer Ratios

50:5	100:5	150:5	200:5	250:5	300:5
400:5	450:5	500:5	600:5	800:5	900:5
1,000:5	1,200:5	1,500:5	1,600:5	2,000:5	240:5
2,500:5	3,000:5	3,200:5	4,000:5	5,000:5	6,000:5

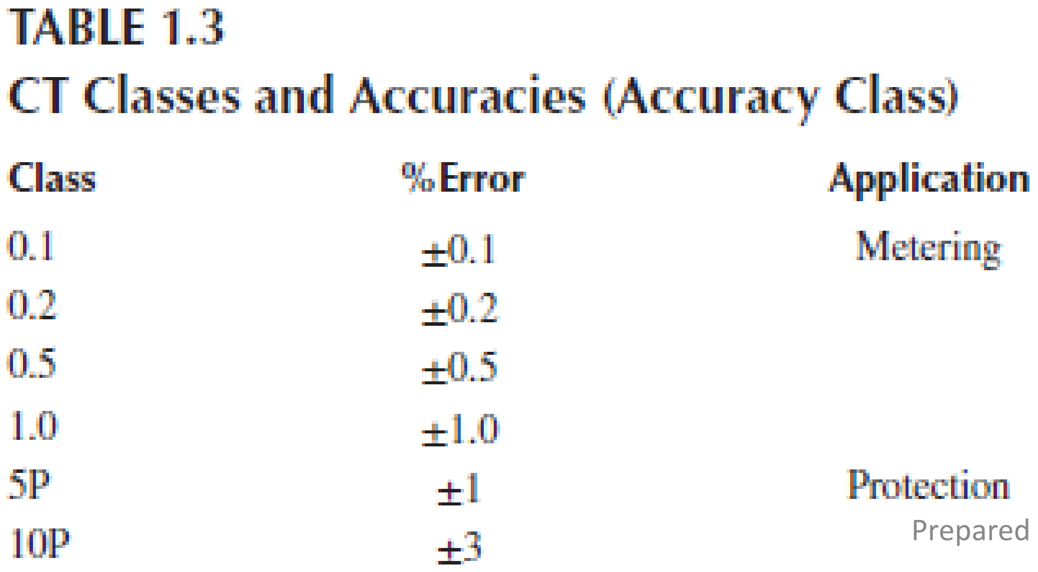

TABLE 1.3
CT Classes and Accuracies (Accuracy Class)

Class	%Error	Application
0.1	±0.1	Metering
0.2	±0.2	
0.5	±0.5	
1.0	±1.0	
5P	±1	Protection
10P	±3	

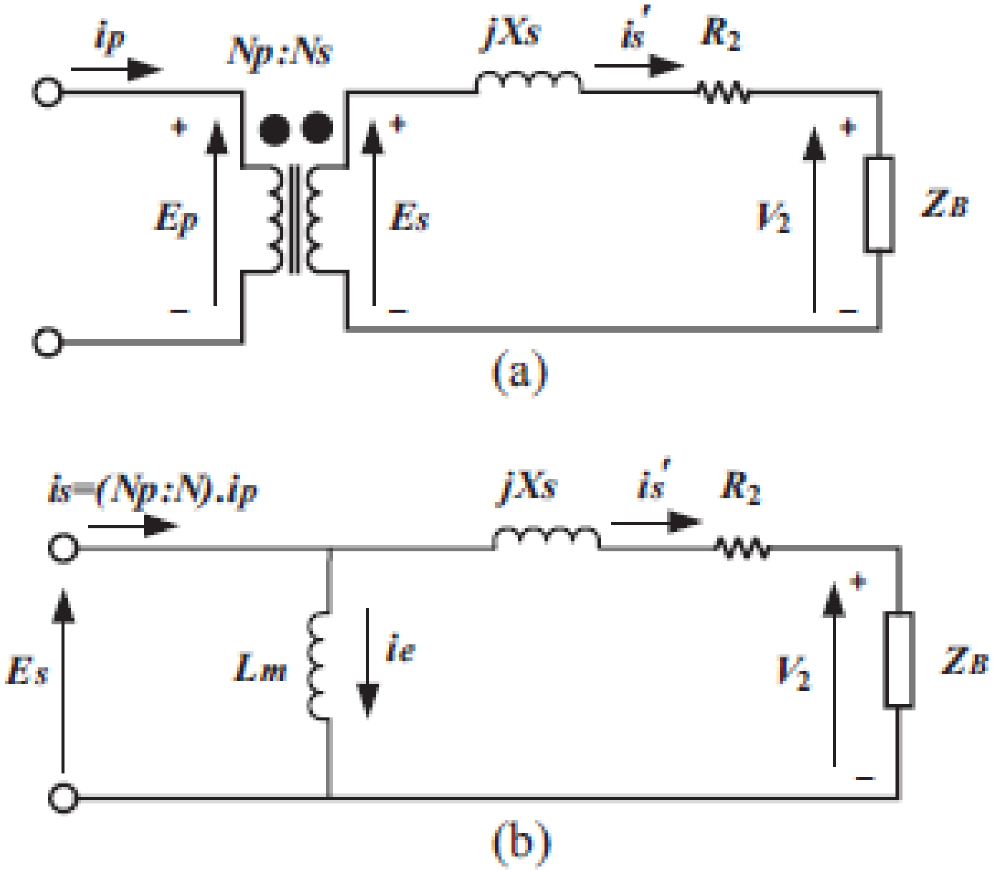

FIGURE 1.3 Equivalent circuit of CT.
(a) Exact circuit. (b) Approximate circuit.

1.7.2 Voltage transformer

These provide a voltage that is much lower than the system voltage, the nominal secondary voltage being 115 V (line–line), or 66.4 V (line to neutral) in one standard and 120 V (line–line) or 69.4 V (line to neutral) in another. There are two VT types, conventional electromagnetic and capacitor for high- voltage levels (132 kV and above). Table 1.4 shows the standard VT ratios.

TABLE 1.4 Standard VT Ratios

1:1	2:1	2.5:1	4:1	20:1	25:1	40:1	60:1	200:1
300:1	400:1	500:1	600:1	800:1	1,000:1	2,000:1	3,000:1	4,500:1

There are two main types of voltage transformers:

1. **Magnetic voltage transformers** (ordinary two-winding types – used for LV and MV).

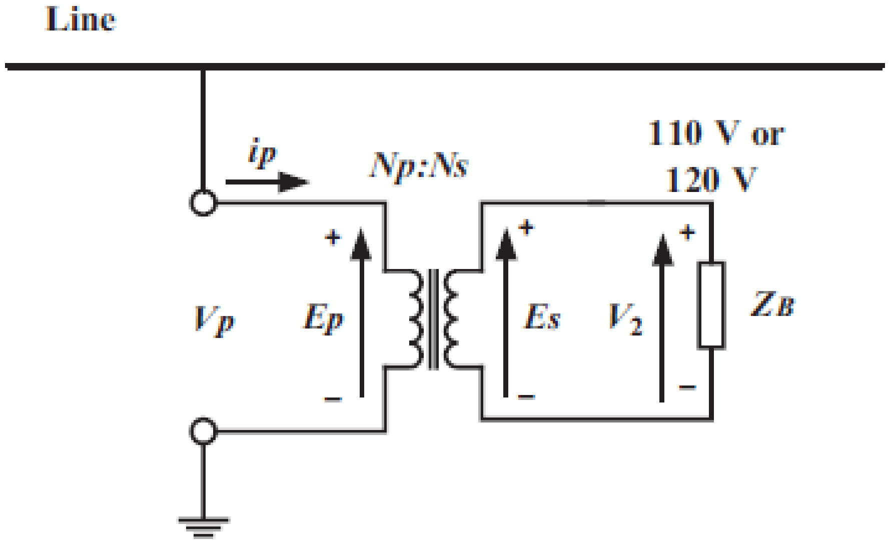

FIGURE 1.4 VT connection to the system.

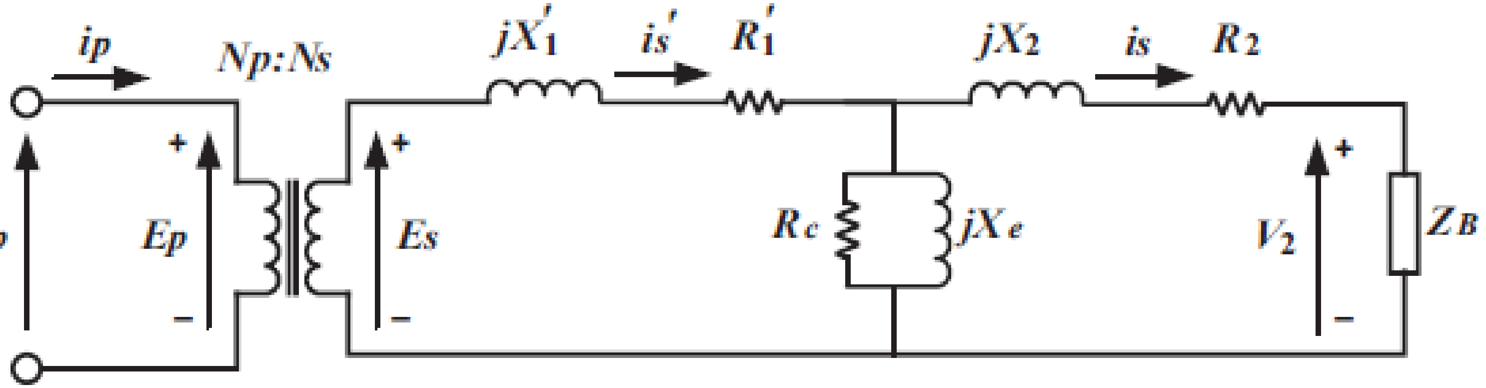

FIGURE 1.5 VT equivalent circuit referred to the secondary side.

2. **Capacitive voltage transformers (CVT)** are used for high and extra-high voltages.

Figure 1.6 shows capacitive voltage transformers, which are classified into two types:

i. Coupling-capacitor voltage transformer.
ii. Capacitor – bushing voltage transformer.

$$\mathrm{VT}_{\mathrm{error}} = \frac{nV_s - V_p}{V_p} \times 100\% \qquad (1.4)$$

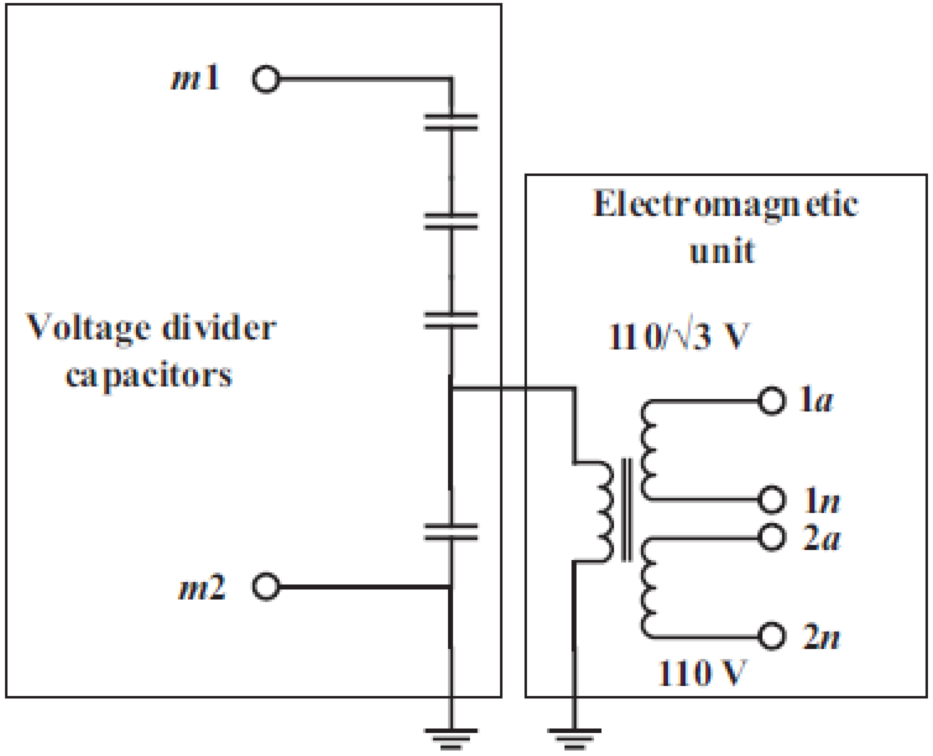

FIGURE 1.6 Capacitive voltage transformers.

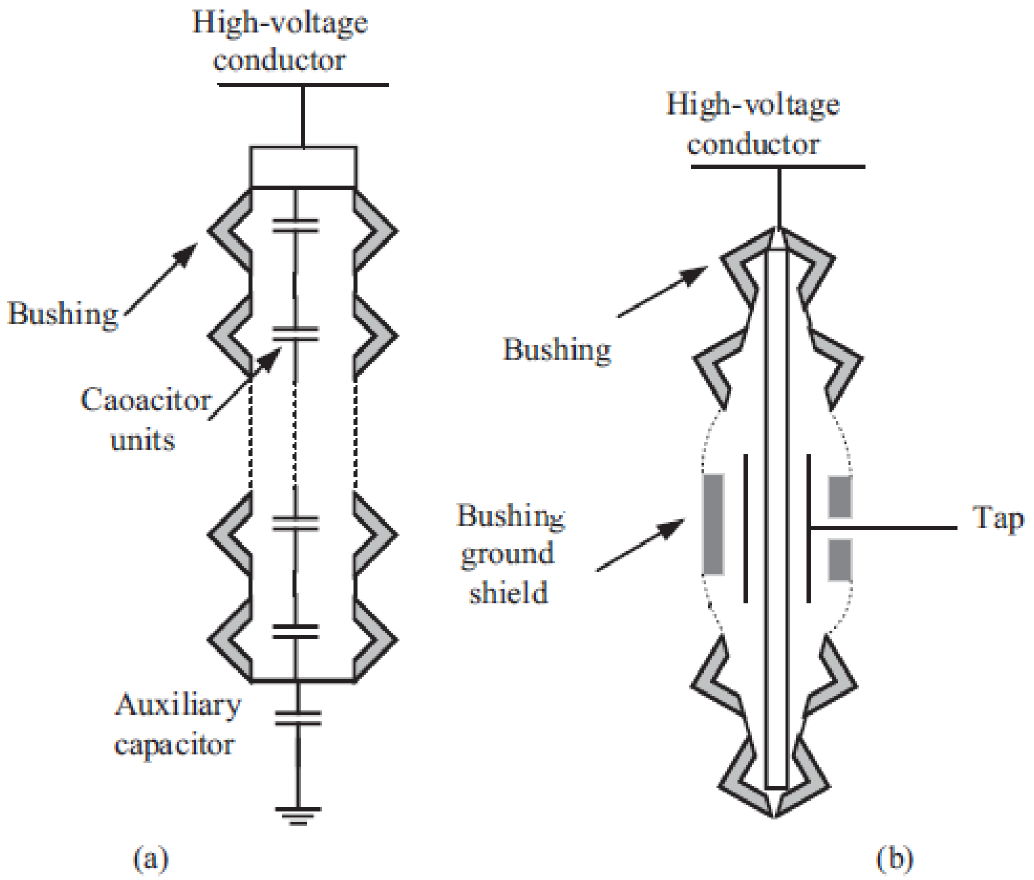

FIGURE 1.7 Capacitor voltage transformers: (a) coupling-capacitor voltage divider. (b) Capacitance-bushing voltage divider.

Table 1.5 gives the voltage transformer error limits.
There are three types of VT connections, as shown in Figure 1.8.

i. Open delta connection.
ii. Delta–star connection.
iii. Star–star connection.

CTs and VTs have ratio and phase angle errors to certain degrees. Errors are more pronounced in CTs under transient conditions and core saturation. The load on CTs and VTs is commonly known as their burden.

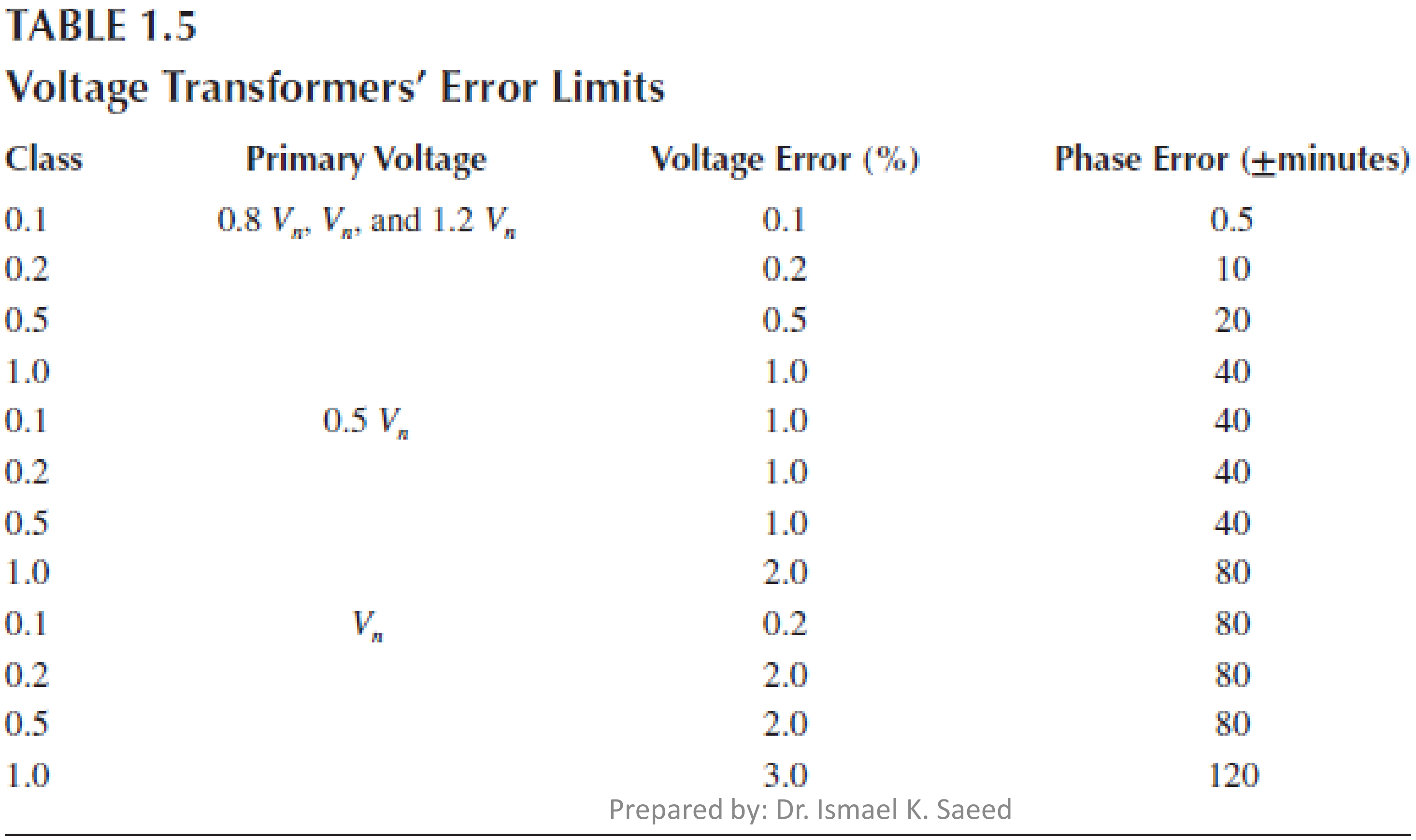

TABLE 1.5
Voltage Transformers' Error Limits

Class	Primary Voltage	Voltage Error (%)	Phase Error (±minutes)
0.1	$0.8\ V_n$, V_n, and $1.2\ V_n$	0.1	0.5
0.2		0.2	10
0.5		0.5	20
1.0		1.0	40
0.1	$0.5\ V_n$	1.0	40
0.2		1.0	40
0.5		1.0	40
1.0		2.0	80
0.1	V_n	0.2	80
0.2		2.0	80
0.5		2.0	80
1.0		3.0	120

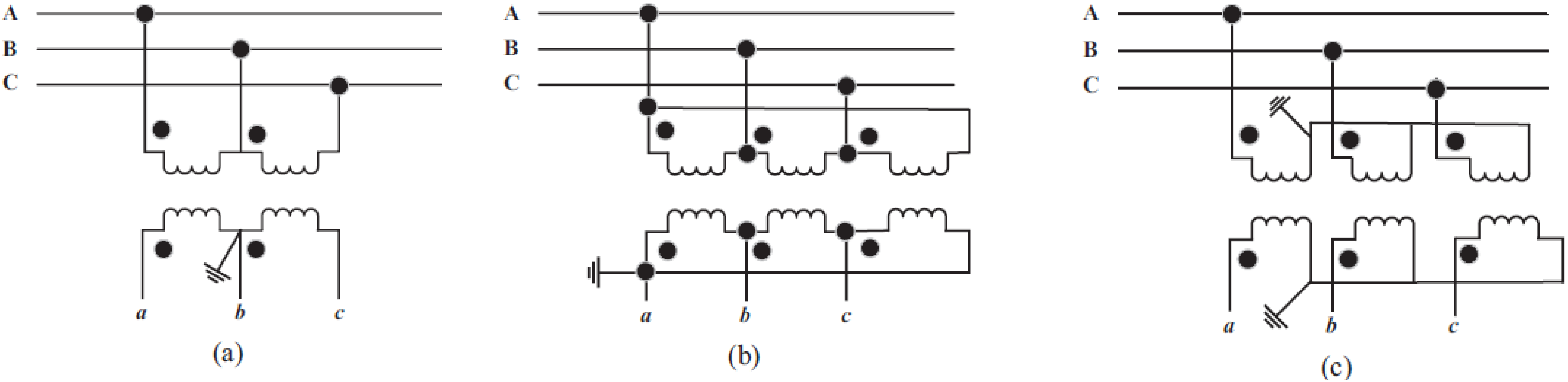

FIGURE 1.8 Different types of VT connections. (a) Open delta connection, (b) delta–star connection, and (c) star–star connection.

Example 1.2 The delta VT connection is shown in Figure 1.9, suppose $V_{AB} = 230\angle 0^o$ kV, $V_{BC} = 230\angle -120^o$ kV, $V_{CA} = 230\angle 120^o$ kV, the VT ratio is 110 kV/120 V, calculate $v_{ab}, v_{bc}, and\ v_{ca}$. If the dot mark is moved to b, recalculate the above voltage.

Solution

$$\text{VT ratio} = \frac{110{,}000}{120} = 916.6$$

$$\vec{v}_{ab} = \frac{1}{916.6}(230\angle 0^\circ \text{ kV}) = 250.92\angle 0^\circ \text{ V}$$

$$\vec{v}_{bc} = \frac{1}{916.6}(230\angle -120^\circ \text{ kV}) = 250.92\angle -120^\circ \text{ V}$$

$$\vec{v}_{ca} = -(\vec{v}_{ab} + \vec{v}_{bc}) = 250.92\angle 120^\circ \text{ V}$$

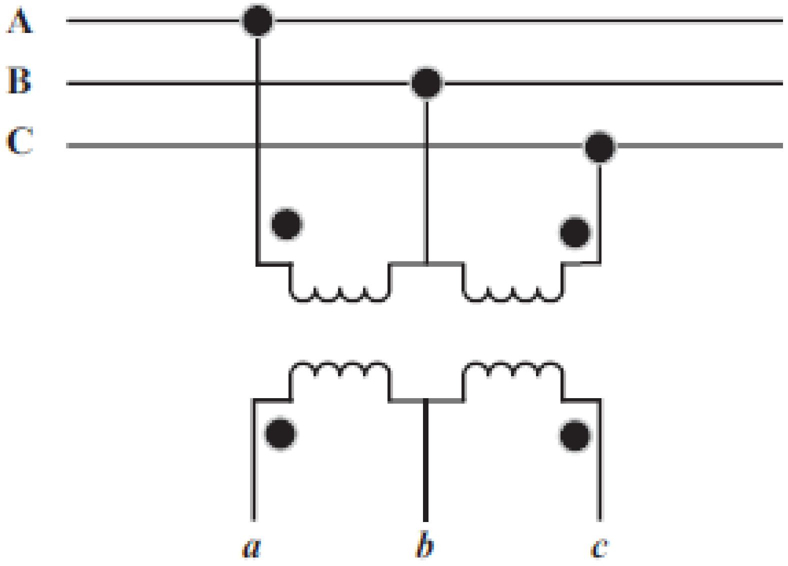

FIGURE 1.9 Configuration of Example 1.2.

If the dot mark moved to *b* (Figure 1.10),

$$\vec{v}_{ab} = \frac{1}{916.6}(230\angle 0^\circ \text{ kV}) = 250.92\angle 0^\circ \text{ V}$$

$$\vec{v}_{bc} = -\frac{1}{916.6}(230\angle -120^\circ \text{ kV}) = 250.92\angle 60^\circ \text{ V}$$

$$\vec{v}_{ca} = -(\vec{v}_{ab} + \vec{v}_{bc}) = 434.6\angle -150^\circ \text{ V}$$

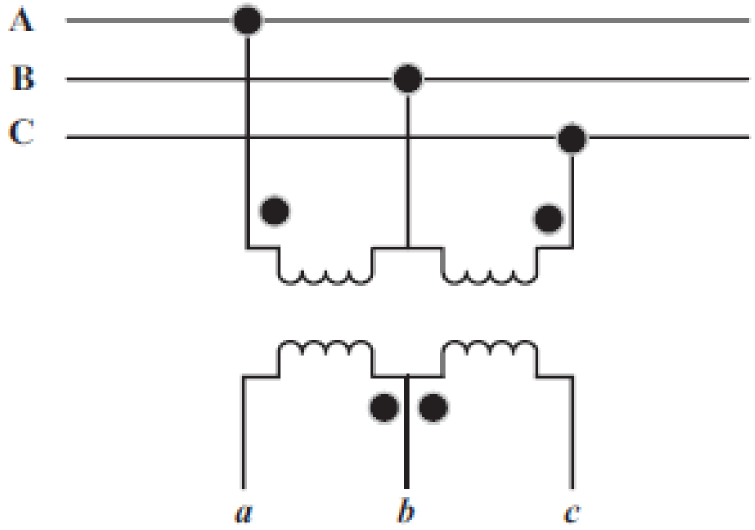

FIGURE 1.10 Another sequence connection diagram of Example 1.2.

1.8 RELAY CONNECTION TO THE PRIMARY SYSTEM

Suppose the relay is connected to the power system via a current and voltage trans-former, as shown in Figure 1.11.

$$V_{\text{line}} = V_{\text{relay}} \times K_{\text{VT}} \tag{1.5}$$

$$I_{\text{line}} = I_{\text{relay}} \times K_{\text{CT}} \tag{1.6}$$

K_{VT} = Voltage transformer ratio.
K_{CT} = Current transformer ratio.

The operating impedance of the line is

$$Z_{\text{line}} = \frac{V_{\text{line}}}{I_{\text{line}}} = \frac{V_{\text{relay}}}{I_{\text{relay}}} \times \frac{K_{\text{VT}}}{K_{\text{CT}}} = Z_{\text{relay}} \times \frac{K_{\text{VT}}}{K_{\text{CT}}} \tag{1.7}$$

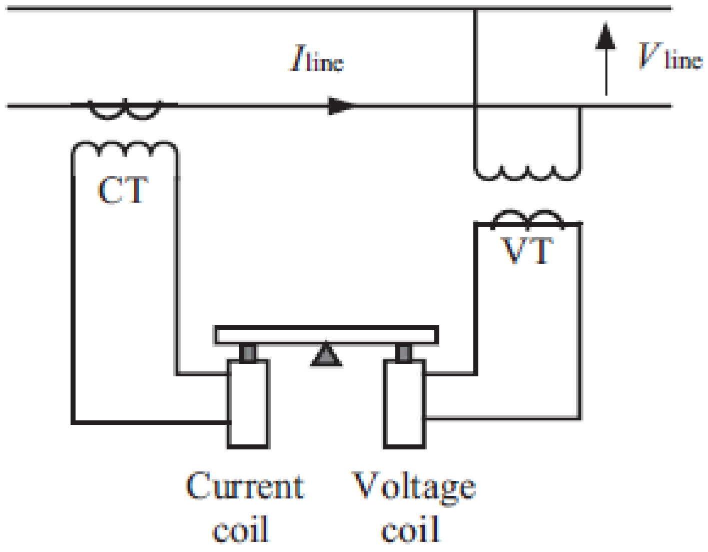

FIGURE 1.11 Relay connection to the power system.

1.9 CT ERROR

Ideally, the CT secondary is connected to a current-sensing device with zero impedance, but in practice, the secondary current divides, with most flowing through the low-impedance-sensing device and some flowing through the CT shunt excitation impedance. CT excitation impedance is kept high to minimize excitation current. The excitation impedance causes an error in the reading of the secondary current (Tables 1.6 and 1.7).

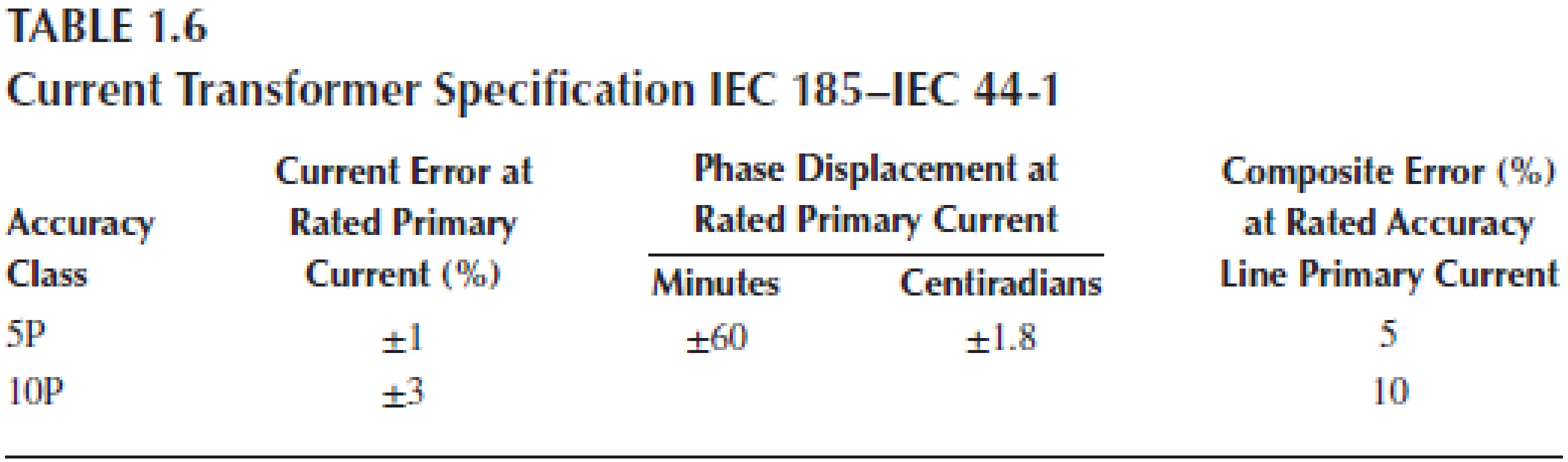

TABLE 1.6

Current Transformer Specification IEC 185–IEC 44-1

Accuracy Class	Current Error at Rated Primary Current (%)	Phase Displacement at Rated Primary Current		Composite Error (%) at Rated Accuracy Line Primary Current
		Minutes	Centiradians	
5P	±1	±60	±1.8	5
10P	±3			10

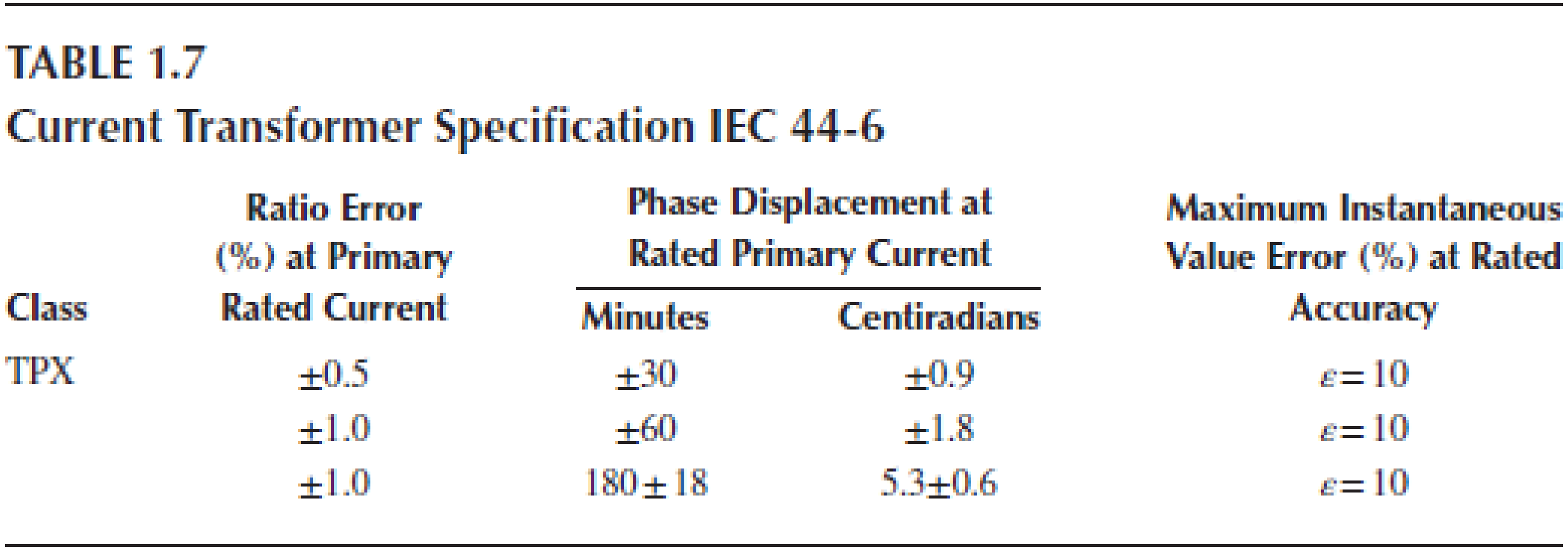

TABLE 1.7

Current Transformer Specification IEC 44-6

Class	Ratio Error (%) at Primary Rated Current	Phase Displacement at Rated Primary Current		Maximum Instantaneous Value Error (%) at Rated Accuracy
		Minutes	Centiradians	
TPX	±0.5	±30	±0.9	$\varepsilon = 10$
	±1.0	±60	±1.8	$\varepsilon = 10$
	±1.0	180 ± 18	5.3±0.6	$\varepsilon = 10$

Example 1.3 A CT has a rated ratio of 500:5 A. A secondary side impedance is $Z_2 = 0.1 + j0.5\Omega$, and the magnetizing curve is given in Figure 1.12. Compute I_2 and the CT error for the following cases:

i. $Z_L = 4.9 + j0.5\ \Omega$, $I_1 = 400$ A (load current).
ii. $Z_L = 4.9 + j0.5\ \Omega$, $I_1 = 1{,}200$ A (fault current).
iii. $Z_L = 14.9 + j1.5\ \Omega$, $I_1 = 400$ A (load current).
iv. $Z_L = 14.9 + j1.5\ \Omega$, $I_1 = 1{,}200$ A (fault current).

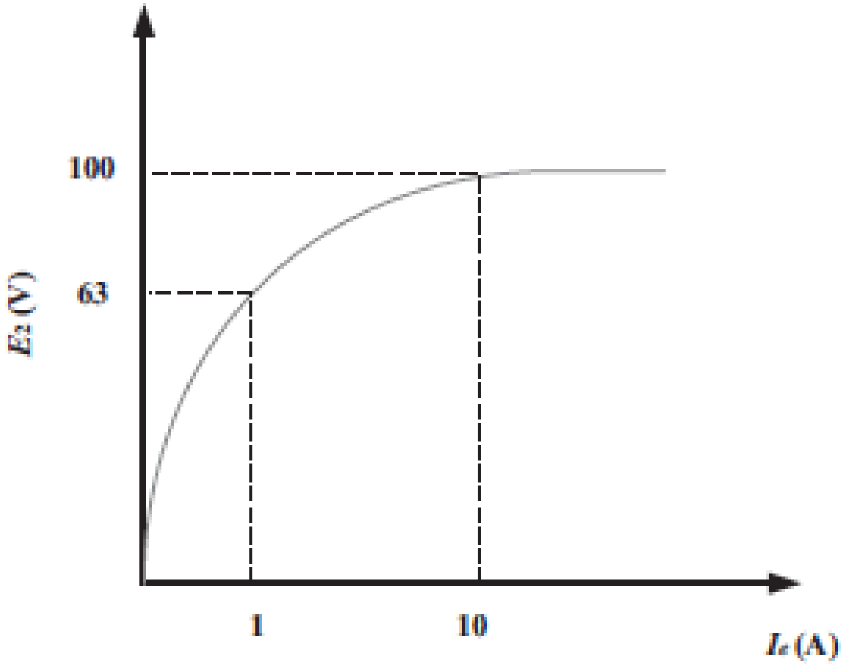

FIGURE 1.12 Magnetization curve of Example 1.3.

Solution

From the magnetizing curve, substitute the points (1, 63) and (10, 100) in Frohlich's equation:

$$E_2' = \frac{A \cdot I_e}{B + I_e}$$

$$63 = \frac{A \cdot 1}{B + 1}$$

$$100 = \frac{A \cdot 10}{B + 10}$$

Solving to get the constants *A* and *B*, where *A* = 107 and *B* = 0.698, Frohlich's equation will be

$$E_2' = \frac{107\ I_e}{0.698 + I_e}$$

i. $Z_T = Z_2 + Z_L$

$$= 4.9 + j0.5 + 0.1 + j0.5$$

$$= 5.0 + j1.0\,\Omega = 5.009\angle 11.3^\circ\,\Omega$$

$$E_2 = I_2 \cdot Z_2$$

$$= \left(\frac{5}{500} \times 400\right) \times 5.009 = 20.4\text{ V}$$

$$I_e = \frac{20.4}{\sqrt{5^2 + \left(1 + \frac{107}{0.698 + I_e}\right)^2}}$$

Using trial and error to find $I_e = 0.163\text{ A}$

From Frohlich’s equation $E_2' = \frac{107 \times 0.163}{0.698 + 0.163} = 20.3\text{ V}$

$$I_2 = \frac{E_2'}{Z_T} = \frac{20.3}{5.009} = 3.97\text{ A}$$

$$\text{CT error\%} = \frac{|4 - 3.97|}{4} \cdot 100 = 0.7\%$$

ii. For the same steps in part (i)

$$E_2 = 61.2\ \text{V}$$

$$I_e = 0.894\ \text{A}$$

$$E_2 = 60.1\ \text{V}$$

$$I_2 = 11.78\ \text{A}$$

$$\text{CT error}\ \% = 1.8\%$$

iii. CT error = 3.5%

iv. CT error = 45.1%

1.10 PROTECTIVE ZONES

A complete power system is divided into “zones,” associated, for example, with an alternator, transformer, busbar section, or a feeder end; each zone has one or more coordinated protective systems.

All network elements must be covered by at least one zone or more in the power systems. The more important elements must be included in at least two zones, where the zones must overlap to prevent any element from being unprotected. The overlap must be finite but small to minimize the likelihood of a fault inside this region. A relay location usually defines the zone boundary.

1.10.1 Backup protection

If the primary protection fails to operate, the backup protection will operate to remove the faulty part from the system. The primary and the backup are independent (relay, breaker, CT, VT). The backup relay is slower than the primary relay, but sometimes backup protection opens more circuit breakers than necessary to clear the fault. The backup protection provides primary protection when the usual primary apparatus is out of service. There are two types of backup protection depending on the method of installation:

i. *Local backup*: Clears fault in the same station where the failure has occurred (Figure 1.13).

ii. *Remote backup*: Clears fault on station away from where the failure has occurred (Figure 1.14).

1.10.2 Selectivity and zones of protection selectivity

It is defined in terms of regions of a power system (zones of protection) for which a given relay is responsible.

The relay will be considered **secure** if it responds only to faults within its zone of protection

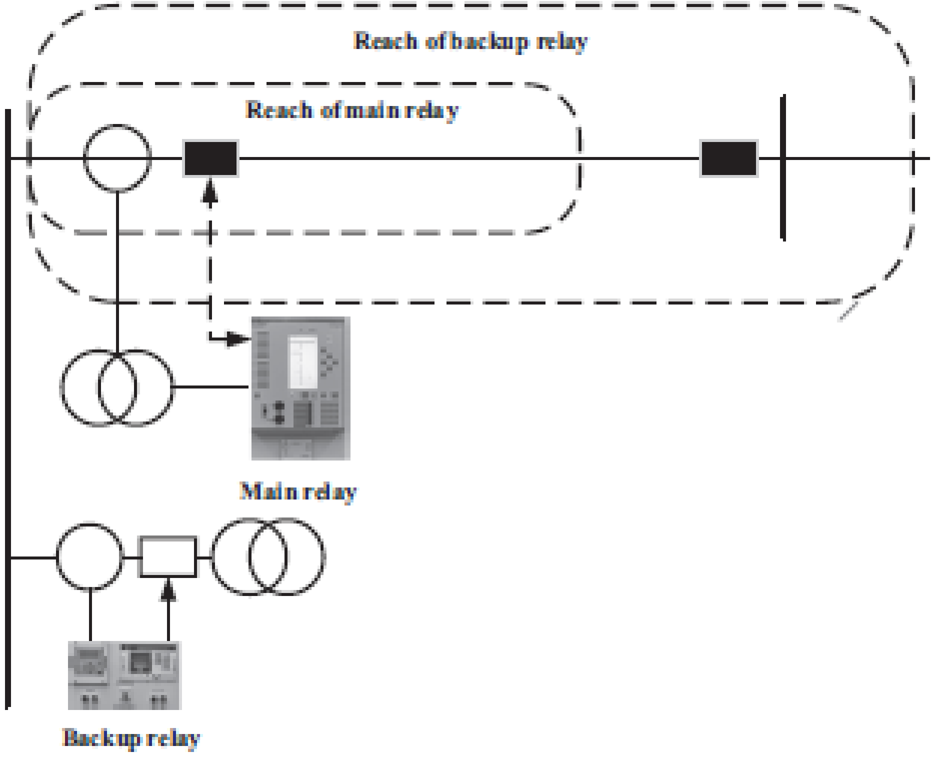

FIGURE 1.13 Local backup protection at different locations.

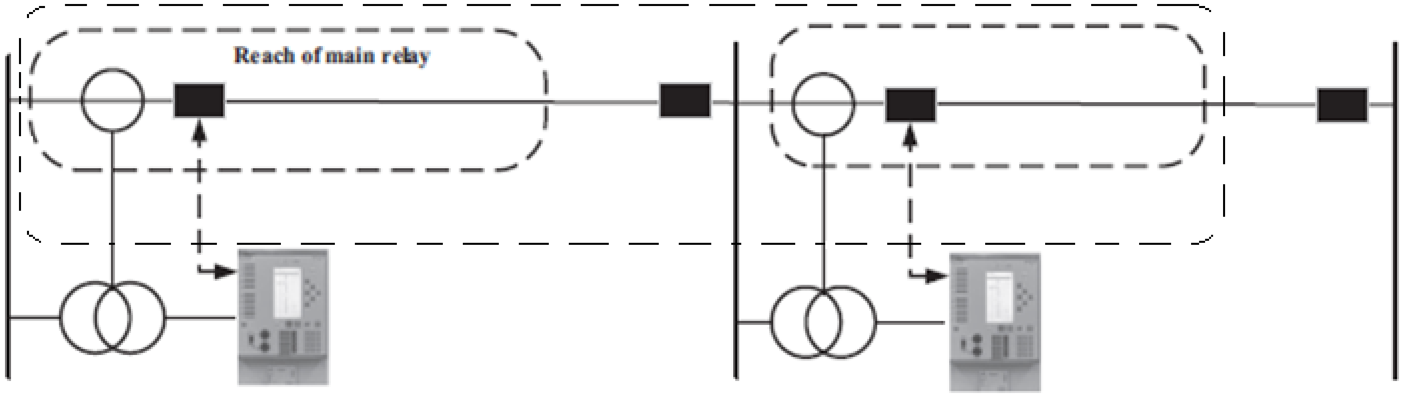

FIGURE 1.14 Remote backup protection.

Example 1.5 Consider the following simple power system, and discuss the local and remote backup protection for two fault locations in Figure 1.15.

CASE 1: LOCAL BACKUP

i. *For fault at F1*: Suppose that breaker 15 operates and breaker 14 fails to work. Therefore, breakers 11 and 13 must work as *local backup* protection.

ii. ii. *For fault at F2*: Suppose that breaker 9 operates and breaker 8 fails to operate. Therefore, breakers 3 and 6 must operate as *local backup* protection.

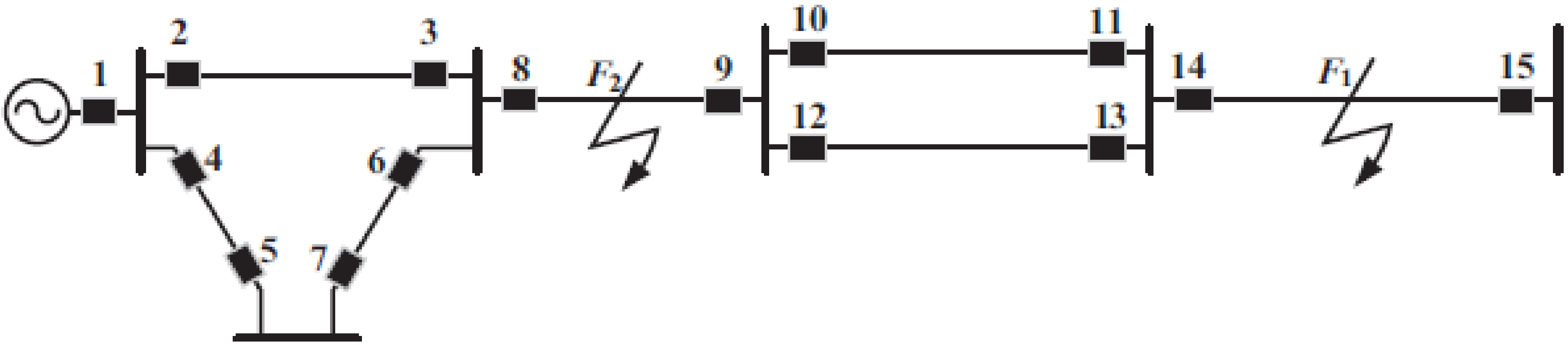

FIGURE 1.15 The power system of Example 1.5.

CASE 2: REMOTE BACKUP

i. *For fault at F1*: Suppose that breaker 15 operates and breaker 14 fails to operate. Therefore, breakers 10 and 12 must operate as *remote backup* protection.

ii. *For fault at F2*: Suppose that breaker 9 operates and breaker 8 fails to operate. Therefore, breakers 2 and 7 must operate as remote backup protection.

Example 1.6 Consider the power system shown in Figure 1.16.

i. Mark the suitable zones.

ii. Modify the protective system.

iii. Mark that all circuit breakers will operate when faults *P*1 and *P*2 occur, as shown in parts (i) and (ii).

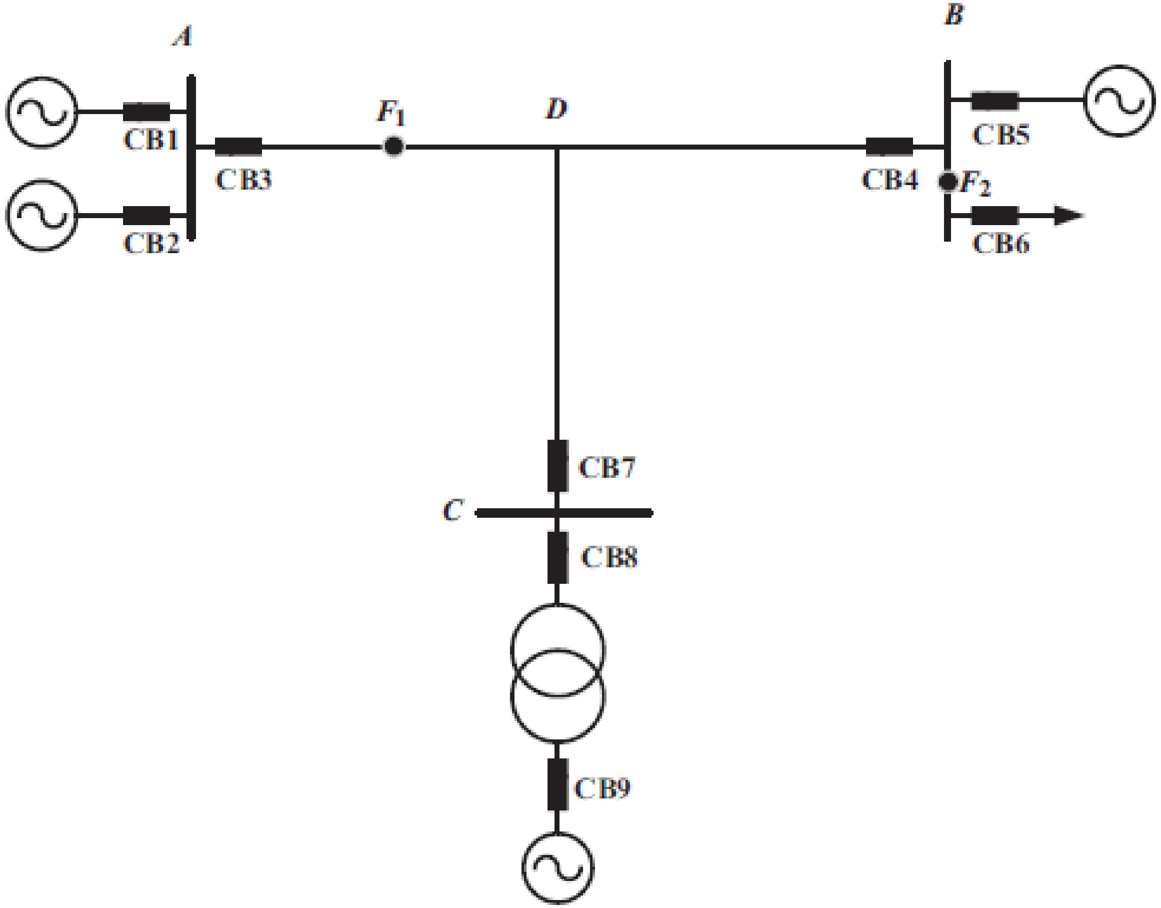

FIGURE 1.16 The power system of Example 1.6.

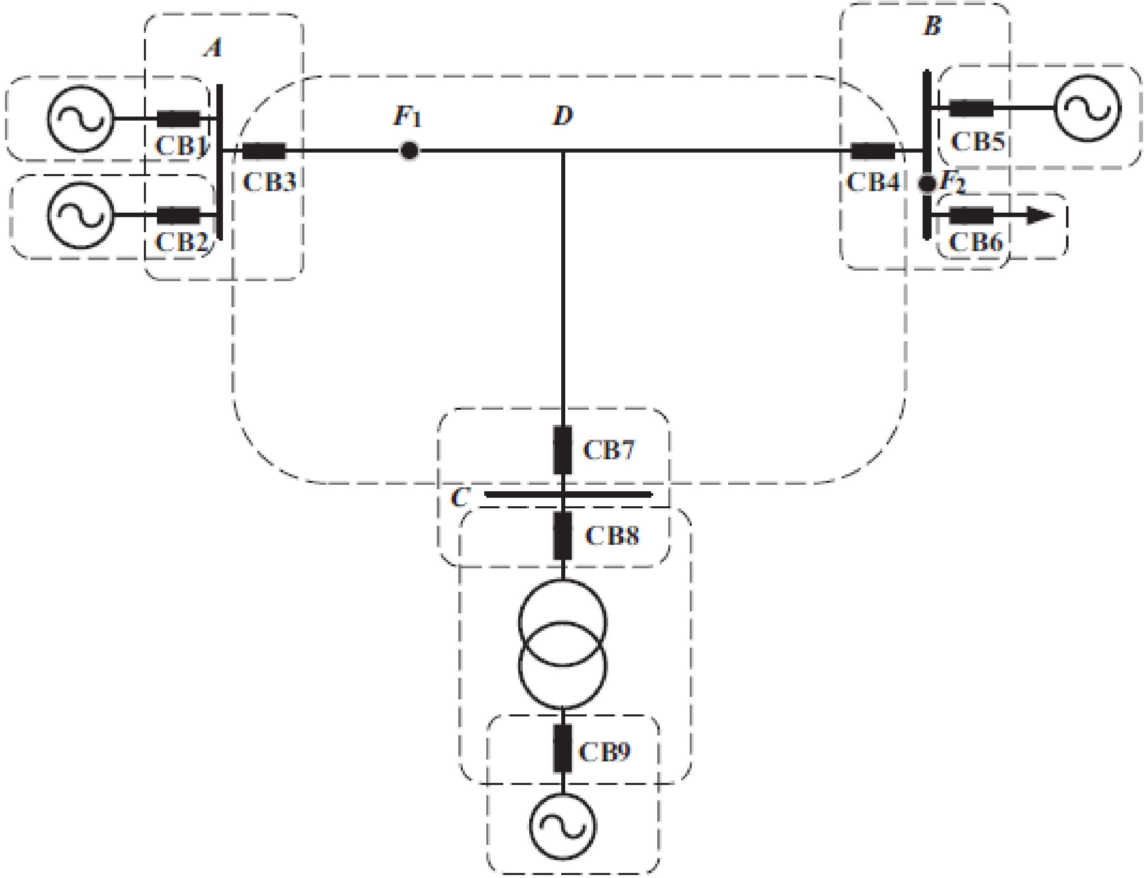

FIGURE 1.17 Protection zones for the power system of Example 1.6.

Solution

i. Figure 1.17 illustrates the distribution of the protective zone on the power system.
ii. To modify the system in Figure 1.17, add three circuit breakers at node D (CBs 10, 11, and 12), as shown in Figure 1.18.
iii. For part (i), if the fault occurs at point F1, circuit breakers 3, 4, and 7 will operate, and for a fault at F2, circuit breakers 4, 5, and 6 will operate.

For part (ii), if the fault occurs at point F1, circuit breakers 3 and 10 will operate, and for the fault at F2, circuit breakers 4, 5, and 6 will operate.

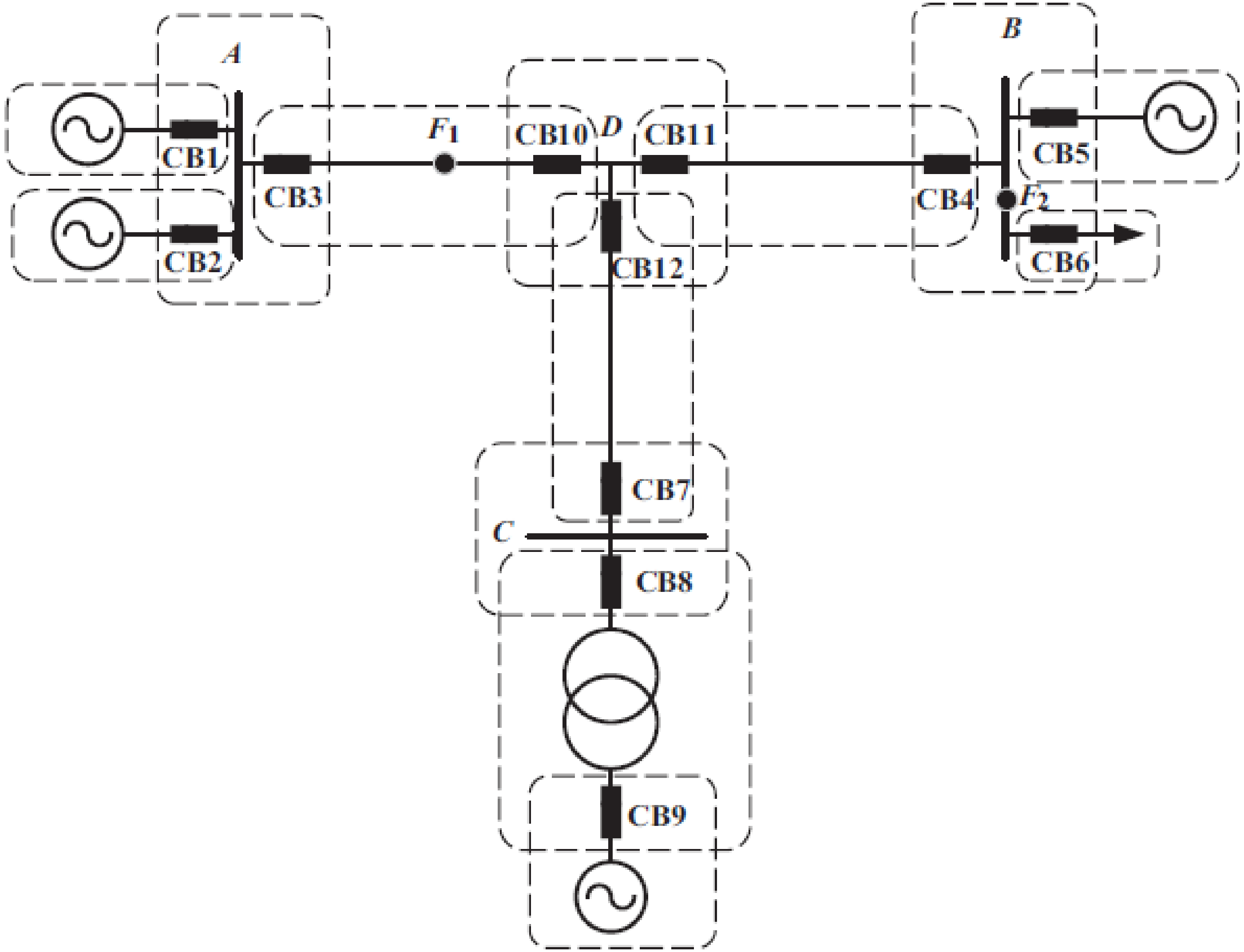

FIGURE 1.18 Modify the power system of Example 1.6.

1.11 *R–X* DIAGRAM

A relay and a system's characteristics can be graphically represented in only two variables (*R* and *X* or |*Z*| and *θ*) rather than three (*V*, *I*, and *θ*). The *R–X* diagram or *Z*-plane, or simply the complex plane. The complex variable *Z* is determined by dividing the RMS voltage by the RMS current. The resulting *Z* can be expressed in rectangular, polar form as

$$Z = R + jX = |Z|e^{j\theta} \qquad (1.8)$$

In addition to the plot of the operating characteristics of a given relay, the system condition affecting the operation of this relay can be superimposed on the same *R–X* diagram so that the response of the relay can be determined. The system characteristics must be within the relay characteristics' operation region to achieve this relay operation. Note that the superimposed system and relay characteristics have to be in terms of the plane quantities and the same scale. These can be both in p.u., where Ohm is used. Both have to be on either a primary or a secondary basis, using

$$\text{Secondary } \Omega'_s = \text{Primary } \Omega'_s \times \left(\frac{\text{CT ratio}}{\text{VT ratio}}\right) \qquad (1.9)$$

For example, in the short transmission line shown in Figure 1.19.

$$V_s = I \cdot Z_L + V_R \qquad (1.10)$$

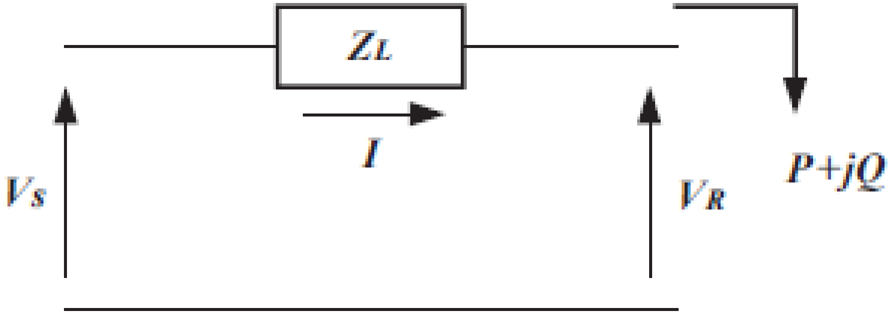

FIGURE 1.19 Short transmission line.

and

$$Z_s = \frac{V_s}{I} \qquad (1.11)$$

$$Z_R = \frac{V_R}{I} \qquad (1.12)$$

also

$$Z_s = Z_L + Z_R \qquad (1.13)$$

The receive end load impedance can also be expressed as

$$Z_R = R_R + jX_R \qquad (1.14)$$

where

$$R_R = \frac{|V|^2 P}{P^2 + Q^2} \qquad (1.15)$$

and

$$X_R = \frac{|V|^2 Q}{P^2 + Q^2} \qquad (1.16)$$

Example 1.7 Assume that a short transmission line has the receiving end load apparent power S_R and voltage $|V_R|$ of 2.5 + *j*0.9 and 1.0 p.u., respectively. If the line Z_L = 0.1 + *j*0.25 p.u., determine

i. Receive end impedance Z_R.
ii. Send-end impedance Z_S.
iii. Draw the *R*–*X* diagram.
iv. The power angle δ.

Solution

i. The real part of load impedance is:

$$R_R = \frac{|V|^2 P}{P^2 + Q^2}$$

$$= \frac{|1.0|^2 (2.5)}{2.5^2 + 0.9^2} = 0.3541 \text{ p.u.}$$

The imaginary part of load impedance is:

$$X_R = \frac{|V|^2 Q}{P^2 + Q^2} = \frac{|1.0|^2 (0.9)}{2.5^2 + 0.9^2} = 0.1275 \text{ p.u.}$$

The load impedance is:

$$Z_R = 0.3541 + j0.1275 \text{ p.u.} = 0.3764\angle 19.8^\circ \text{ p.u.}$$

ii. The send-end impedance is:

$$Z_s = Z_L + Z_R = 0.1 + j0.25 + 0.3541 + j0.1275$$

$$= 0.4541 + j0.3775 \text{ p.u.} = 0.5905\angle 39.7^\circ \text{ p.u.}$$

iii. The *R*–*X* diagram (Figure 1.20)

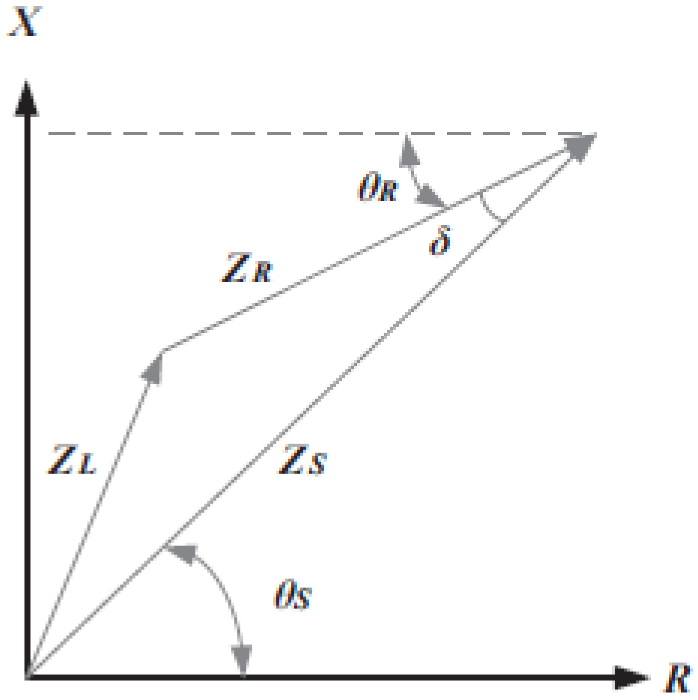

FIGURE 1.20 The *R*–*X* diagram of Example 1.7.

iv. The power angle is:

$$\delta = \theta_s - \theta_R = 39.7^\circ - 19.8^\circ = 19.9^\circ$$

Example

A CT with bar primary has 300 turns on the secondary winding. The burden connected on the secondary windings is an ammeter of resistance 1.5Ω and a reactance of 0.5Ω, while the secondary winding resistance is of 0.2Ω and reactance of 0.3Ω; 100 AT magnetization mmf is required for magnetizing the core and 50 AT for the core loss current component.

1. Calculate the current flowing through the primary windings and ratio errors when the ammeter connected in the secondary windings shows a reading of 5 A.
2. Determine the turn compensation in the secondary windings for reducing the ratio errors to zero under the above conditions.

Solution

Total resistance in the secondary circuit = 1.5 + 0.2 = 1.7Ω

Total reactance in the secondary circuit = 0.5 + 0.3 = 0.8Ω

Hence, the secondary circuit phase angle δ is = tan^{-1}(0.8/1.7) = 25.196°

cos δ = 0.90 and sin δ = 0.426

As there is a single turn primary winding N_p in the form of a bar and N_s = 300, the turn ratio $n = N_s/N_p$ = 300.

The magnetizing current is:

$$I_m = \frac{\text{Magnetizing mmf}}{\text{Primary turns}} = \frac{100}{1} = 100\text{A}$$

$$\text{The loss component } I_c = \frac{\text{Magnetizing mmf equivalent of iron loss}}{\text{Primary turns}} = \frac{50}{1} = 50 \text{ A}$$

The transformation ratio is given as:

$$T_R = n + \frac{(I_m \sin\delta + I_e \cos\delta)}{I_s} = 300 + \frac{(100 \times 0.426 + 50 \times 0.90)}{5} = 317.52$$

Primary current = actual transformation ratio × secondary current

$$I_p = 317.52 \times 5 = 1587.6 \text{ A}$$

The value of transformation ratio is greater than the nominal ratio hence the ratio errors can be eliminated by reducing the number of secondary winding turns and hence by reducing the turn ratio.

Nominal ratio (N_R) = 300

The transformation ratio is:

$$T_R = n + \frac{(I_m \sin\delta + I_e \cos\delta)}{I_s}$$

For eliminating the ratio errors:

$$T_R = N_R$$

$$300 = n + \frac{(100 \times 0.426 + 50 \times 0.90)}{5} n + 17.52$$

$$n = 282.5$$

Hence the turns on secondary windings are:

$$N_s = n\,N_P = 282.5 \times 1 = 282.5$$

So, the required reduction in secondary winding turns is:

$$= 300 - 282.5 = 17.5 \approx 17$$

Example

A bar type CT has 300 turns on the secondary side. The secondary side impedance is (3 + *j*1.5)Ω. Determine the values of the ratio and phase angle errors when the secondary winding draws 3 A current having magnetizing mmf at 80 AT and the iron loss is 1 watt.

Solution

As the CT has bar primary, hence $N_p = 1$. $N_s = 300$. Hence, turn ratio $n = N_s/N_p = 300$.

Total burden impedance on the secondary side:

$$Z_s = \sqrt{(3^2) + (1.5^2)} = 3.354\ \Omega$$

Secondary circuit power factor = cos δ = 3/3.354 = 0.89 and sin δ = 1.5/3.354 = 0.44

Secondary induced e.m.f. $E_s = I_s Z_s = 3 \times 3.354 = 10.062$ V

Primary induced voltage $E_p = E_s/n = 10.062/300 = 0.03354$ V

Core-loss component of current I_c = Iron loss/E_p = 1/0.03354 = 29.8 A

Magnetizing current I_m = mmf/N_p = 80/1 = 80 A.

The transformation ratio is:

$$T_R = n + \frac{(I_m \sin\delta + I_e \cos\delta)}{I_s}$$

$$T_R = 300 + \frac{(80 \times 0.44 + 29.8 \times 0.89)}{3} = 335.654$$

$$\text{Percentage error} = \frac{N_R - T_R}{T_R} \times 100 = 10.6\%$$

$$\text{Phase angle error is } \theta = \frac{180}{\Pi}\left[\frac{I_m \cos\delta - I_e \sin\delta}{nI_s}\right]$$

$$\theta = \frac{180}{\Pi}\left[\frac{80 \times 0.89 - 29.8 \times 0.44}{300 \times 3}\right] = 3.40^\circ$$

Example The equivalent circuit parameters of a VT with turn ratio n = 1000/100 are: primary resistance (Ω_p) = 90.4Ω, secondary resistance (Ω_s) = 0.66Ω, primary reactance (X_p) = 60.3Ω, total equivalent reactance (X_{pr}) = 100Ω, no-load current (I_0) = 0.02 A at 0.4 power factor. Determine

(1) The no-load phase angle error

(2) The burden in VA at unity power factor at which there will be zero phase angle error.

Solution

Given parameters:

(a) n = 1000/100, (b) Ω_p = 90.4Ω, (c) Ω_s = 0.66Ω, (d) X_p = 60.3Ω, (e) X_{pr} = 100Ω, (f) I_0 = 0.02 A, (g) $\cos\alpha$ = 0.4.

1. The power factor at no-load $\cos\alpha = 0.4$, so we can calculate

$$\sin\alpha = \sqrt{(1)^2 - (0.4)^2} = 0.917.$$

Also, the phase angle error in VT is given by the following equation

$$\theta = \frac{\frac{I_s}{n}\left(X_{pr}\cos\Delta - R_p\sin\Delta\right) + I_cX_p - I_m\Omega_p}{nV_s} \quad rad$$

At no-load condition, the secondary current $I_s = 0$; hence,

$$\theta = \frac{I_cX_p - I_m\Omega_p}{nV_s} \quad rad$$

The values of *Ic* and *Im* can be calculated as:

$$I_c = I_0 \cos\alpha = 0.02 \times 0.4 = 0.08 \text{ A}$$

$$I_m = I_0 \sin\alpha = 0.02 \times 0.917 = 0.01348 \text{ A}$$

Substituting the values of various parameters obtained in the above steps and calculating the value of phase angle error we get:

$$\theta \approx \frac{0.008 \times 60.3 - 0.01834 \times 90.4}{10 \times 100} \approx -0.06735^\circ$$

The no-load phase angle error is $\vartheta \approx -0.06735^\circ$

2. We know that, at unity power factor, cos Δ = 1 and sin Δ = 0; hence,

$$\theta = \frac{\frac{I_s}{n}\left(X_{pr}\right) + I_c X_p - I_m \Omega_p}{n V_s} \ rad$$

For zero phase angle error, we put $\vartheta = 0^\circ$ and the above equation reduces to:

$$\frac{I_s}{n}\left(X_{pr}\right) + I_c X_p - I_m \Omega_p = 0$$

$$I_s = \frac{n}{X_{pr}} (I_m \Omega_p - I_c X_p)$$

$$I_s = \frac{10}{100} (0.01834 * 90.4 - 0.008 * 60.3) = 0.11755\text{A}$$

Hence, burden = $V_S * I_S$ = 100 × 0.11755 = 11.755 VA.