ARINTE 2a

Section 8.7

Circuit Breaker and Fuse Selection

The computer programs SYMMETRICAL SHORT CIRCUITS (Section 8.6) and SHORT CIRCUITS (Section 9.6) may be utilized in power-system design to select, set, and coordinate protective equipment such as circuit breakers, fuses, relays, and instrument transformers. In this section we discuss basic principles of circuit breaker and fuse selection.

ac Circuit Breakers

A *circuit breaker* is a mechanical switch capable of interrupting fault currents and of reclosing. When circuit-breaker contacts separate while carrying current, an arc forms. The breaker is designed to extinguish the arc by elongating and cooling it. The fact that ac arc current naturally passes through zero twice during its 60-Hz cycle aids the arc extinction process.

Circuit breakers are classified as *power* circuit breakers when they are intended for service in ac circuits above 1500 V, and *low-voltage* circuit breakers in ac circuits up to 1500 V. There are different types of circuit breakers depending on the medium—air, oil, SF_6 gas, or vacuum—in which the arc is elongated. Also, the arc can be elongated either by a magnetic force or by a blast of air.

Some circuit breakers are equipped with a high-speed automatic reclosing capability. Since most faults are temporary and self-clearing, reclosing is based on the idea that if a circuit is deenergized for a short time, it is likely that whatever caused the fault has disintegrated and the ionized arc in the fault has dissipated.

When reclosing breakers are employed in EHV systems, standard practice is to reclose only once, approximately 15 to 50 cycles (depending on operating voltage) after the breaker interrupts the fault. If the fault persists and the EHV breaker recloses into it, the breaker reinterrupts the fault current and then "locks out," requiring operator resetting. Multiple-shot reclosing in EHV systems is not standard practice because transient stability (Chapter 12) may be compromised. However, for distribution systems (2.4–46 kV) where customer outages are of concern, standard reclosers are equipped for two or more reclosures.

For low-voltage applications, molded case circuit breakers with dual trip capability are available. There is a magnetic instantaneous trip for large fault currents above a specified threshold, and a thermal trip with time delay for smaller fault currents.

Modern circuit-breaker standards are based on symmetrical interrupting current. It is usually necessary to calculate only symmetrical fault current at a system location, and then select a breaker with a symmetrical interrupting capability equal to or above the calculated current. The breaker has the additional capability to interrupt the asymmetrical (or total) fault current if the dc offset is not too large.

Recall from Section 8.1 that the maximum asymmetry factor $K(\tau = 0)$ is $\sqrt{3}$, which occurs at fault inception ($\tau = 0$). After fault inception, the dc fault current decays exponentially with time constant $T = (L/R) = (X/\omega R)$, and the asymmetry factor decreases. Power circuit breakers with a 2-cycle rated interruption time are designed for an asymmetrical interrupting capability up to 1.4 times their symmetrical interrupting capability, whereas slower circuit breakers have a lower asymmetrical interrupting capability.

A simplified method for breaker selection is called the "E/X simplified method" [1,7]. The maximum symmetrical short-circuit current at the system location in question is calculated from the prefault voltage and system reactance characteristics, using, for example, computer programs similar to those described in Sections 8.6 and 9.6. Resistances, shunt admittances, nonrotating impedance loads, and prefault load currents are neglected. Then, if the X/R ratio at the system location is less than 15, a breaker with a symmetrical interrupting capability equal to or above the calculated current at the given operating voltage is satisfactory. However, if X/R is greater than 15, the dc offset may not have decayed to a sufficiently low value. In this case, a method for correcting the calculated fault current to account for dc and ac time constants as well as breaker speed can be used [10]. If X/R is unknown, the calculated fault current should not be greater than 80% of the breaker interrupting capability.

When selecting circuit breakers for generators, two cycle breakers are employed in practice, and the subtransient fault current is calculated; therefore, subtransient machine reactances X_d'' are used in fault calculations. For synchronous motors, subtransient reactances X_d'' or transient reactances X_d' are used, depending on breaker speed. Also, induction motors can momentarily contribute to fault current. Large induction motors are usually modeled as sources in series with X_d'' or X_d', depending on breaker speed. Smaller induction motors (below 50 hp) are often neglected entirely.

Table 8.10 shows a schedule of preferred ratings for outdoor power circuit breakers. Some of the more important ratings shown are described next.

Voltage ratings

Rated maximum voltage: Designated the maximum rms line-to-line operating voltage. The breaker should be used in systems with an operating voltage less than or equal to this rating.

Rated low frequency withstand voltage: The maximum 60-Hz rms line-to-line voltage that the circuit breaker can withstand without insulation damage.

Rated impulse withstand voltage: The maximum crest voltage of a voltage pulse with standard rise and delay times that the breaker insulation can withstand.

Rated voltage range factor K: The range of voltage for which the symmetrical interrupting capability times the operating voltage is constant.

Current ratings

Rated continuous current: The maximum 60-Hz rms current that the breaker can carry continuously while it is in the closed position without overheating.

Rated short-circuit current: The maximum rms symmetrical current that the breaker can safely interrupt at rated maximum voltage.

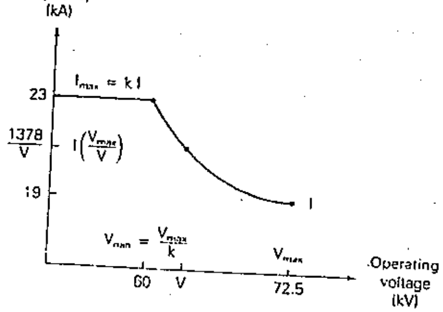
Rated momentary current: The maximum rms asymmetrical current that the breaker can withstand while in the closed position without damage. Rated momentary current for standard breakers is 1.6 times the symmetrical interrupting capability.

Rated interrupting time: The time in cycles on a 60-Hz basis from the instant the trip coil is energized to the instant the fault current is cleared.

Rated interrupting MVA: For a three-phase circuit breaker, this is $\sqrt{3}$ times the rated maximum voltage in kV times the rated short-circuit current in kA. It is more common to work with current and voltage ratings than with MVA rating.

As an example, the symmetrical interrupting capability of the 69-kV class breaker listed in Table 8.10 is plotted versus operating voltage in Figure 8.12. As shown, the symmetrical interrupting capability increases from its rated short-circuit current $I = 19$ kA at rated maximum voltage $V_{max} = 72.5$ kV up to $I_{max} = KI = (1.21)(19) = 23$ kA at an operating voltage $V_{min} = V_{max}/K = 72.5/1.21 = 60$ kV. At operating voltages V between V_{min} and V_{max}, the symmetrical interrupting capability is $I \times V_{max}/V = 1378/V$ kA. At operating voltages below V_{min}, the symmetrical interrupting capability remains at $I_{max} = 23$ kA.

Figure 8.12 Symmetrical interrupting capability of a 69-kV class breaker



Breakers of the 115-kV class and higher have a voltage range factor K = 1.0; that is, their symmetrical interrupting current capability remains constant.

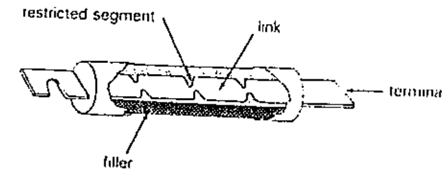
Example 8.9 The calculated symmetrical fault current is 17 kA at a three-phase bus where the operating voltage is 64 kV. The X/R ratio at the bus is unknown. Select a circuit breaker from Table 8.10 for this bus.

Solution The 69-kV-class breaker has a symmetrical interrupting capability $I\left(\frac{V_{max}}{V}\right) = 19\left(\frac{72.5}{64}\right) = 21.5$ kA at the operating voltage V = 64 kV. The calculated symmetrical fault current, 17 kA, is less than 80% of this capability (less than $0.80 \times 21.5 = 17.2$ kA), which is a requirement when X/R is unknown. Therefore, we select the 69-kV-class breaker from Table 8.10. ◁

Fuses

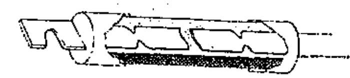
Figure 8.13(a) shows a cutaway view of a fuse, which is one of the simplest overcurrent devices. The fuse consists of a metal "fusible" link or links encapsulated in a tube, packed in filler material, and connected to contact terminals. Silver is a typical link metal, and sand is a typical filler material.

Figure 8.13 Typical fuse



(a) Cutaway view

(b) The link melts and an arc is established under sustained overload current



(c) The "open" link after clearing the overload current.

IDENTIFICATION		RATED VALUES									RELATED REQUIRED CAPABILITIES		
		VOLTAGE		INSULATION LEVEL		CURRENT					CURRENT VALUES		
				RATED WITHSTAND TEST VOLTAGE							MAX SYMMETRICAL INTERRUPTING CAPABILITY	3 SECOND SHORT-TIME CURRENT CARRYING CAPABILITY	CLOSING AND LATCHING CAPABILITY 1.6 K TIMES RATED SHORT-CIRCUIT CURRENT
											K TIMES RATED SHORT-CIRCUIT CURRENT		
NOMINAL VOLTAGE CLASS kV, rms	NOMINAL 3 PHASE MVA CLASS	RATED MAX VOLTAGE kV, rms	RATED VOLTAGE RANGE FACTOR K	LOW FREQUENCY kV, rms	IMPULSE kV, CREST	RATED CONTINUOUS CURRENT AT 60 Hz AMPERES, rms	RATED SHORT-CIRCUIT CURRENT (AT RATED MAX kV) kA, rms	RATED INTERRUPTING TIME CYCLES	RATED PERMISSIBLE TRIPPING DELAY SECONDS	RATED MAX VOLTAGE DIVIDED BY K kV, rms	kA, rms	kA, rms	kA, rms
COL 1	COL 2	COL 3	COL 4	COL 5	COL 6	COL 7	COL 8	COL 9	COL 10	COL 11	COL 12	COL 13	COL 14
14.4	250	15.5	2.67			600	8.9	5	2	5.8	24	24	38
14.4	500	15.5	1.29			1200	18	5	2	12	23	23	37
23	500	25.8	2.15			1200	11	5	2	12	24	24	38
34.5	1500	38	1.65			1200	22	5	2	23	36	36	58
46	1500	48.3	1.21			1200	17	5	2	40	21	21	33
69	2500	72.5	1.21			1200	19	5	2	60	23	23	37
115		121	1.0			1200	20	3	1	121	20	20	32
115		121	1.0			1600	40	3	1	121	40	40	64
115		121	1.0			2000	40	3	1	121	40	40	64
115		121	1.0			2000	63	3	1	121	63	63	101
115		121	1.0			3000	40	3	1	121	40	40	64
115		121	1.0			3000	63	3	1	121	63	63	101
138		145	1.0			1200	20	3	1	145	20	20	32
138	Not	145	1.0			1600	40	3	1	145	40	40	64
138		145	1.0			2000	40	3	1	145	40	40	64
138		145	1.0			2000	63	3	1	145	63	63	101
138		145	1.0			2000	80	3	1	145	80	80	128
138	Applica-	145	1.0			3000	40	3	1	145	40	40	64
138		145	1.0			3000	63	3	1	145	63	63	101
138		145	1.0			3000	80	3	1	145	80	80	128
161	ble	169	1.0			1200	16	3	1	169	16	16	26
161		169	1.0			1600	31.5	3	1	169	31.5	31.5	50
161		169	1.0			2000	40	3	1	169	40	40	64
161		169	1.0			2000	50	3	1	169	50	50	80
230		242	1.0			1600	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			3000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	40	3	1	242	40	40	64
230		242	1.0			3000	40	3	1	242	40	40	64
230		242	1.0			3000	63	3	1	242	63	63	101
345		362	1.0			2000	40	3	1	362	40	40	64
345		362	1.0			3000	40	3	1	362	40	40	64
500		550	1.0			2000	40	2	1	550	40	40	64
500		550	1.0			3000	40	2	1	550	40	40	64
700		765	1.0			2000	40	2	1	765	40	40	64
700		765	1.0			3000	40	2	1	765	40	40	64

Table 8.10 Preferred ratings for outdoor circuit breakers (symmetrical current basis of rating) [10]

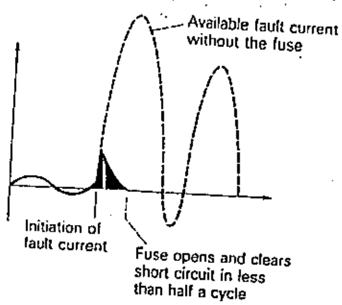
During normal operation, when the fuse is operating below its continuous current rating, the electrical resistance of the link is so low that it simply acts as a conductor. If an overload current from one to about six times its continuous current rating occurs and persists for more than a short interval of time, the temperature of the link eventually reaches a level that causes a restricted segment of the link to melt. As shown in Figure 8.13(b), a gap is then formed and an electric arc is established. As the arc causes the link metal to burn back, the gap width increases. The resistance of the arc eventually reaches such a high level that the arc cannot be sustained and it is extinguished, as in Figure 8.13(c). The current flow within the fuse is then completely cut off.

If the fuse is subjected to fault currents higher than about six times its continuous current rating, several restricted segments melt simultaneously, resulting in rapid arc suppression and fault clearing. Arc suppression is accelerated by the filler material in the fuse.

Many modern fuses are current limiting. As shown in Figure 8.14, a current-limiting fuse has such a high speed of response that it cuts off a high fault current in less than a half cycle—before it can build up to its full peak value. By limiting fault currents, these fuses permit the use of motors, transformers, conductors, and bus structures that could not otherwise withstand the destructive forces of high fault currents.

Figure 8.14

Operation of a current-limiting fuse

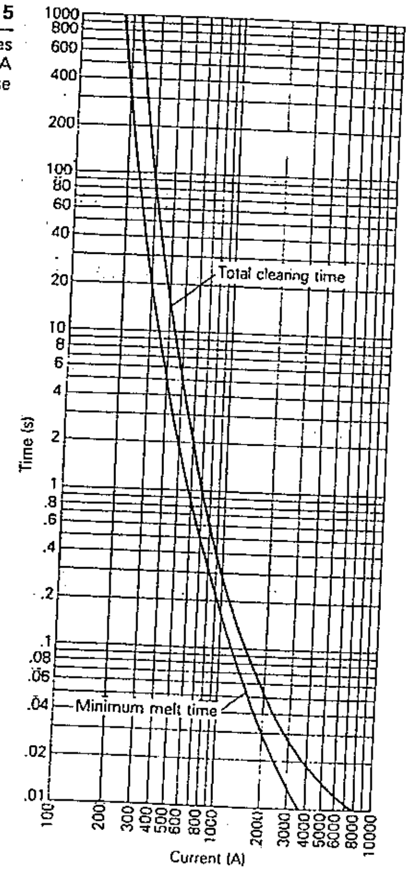


Fuse specification is normally based on the following four factors.

1. Voltage rating. This rms voltage determines the ability of a fuse to suppress the internal arc that occurs after the fuse link melts. A blown fuse should be able to withstand its voltage rating. Most low-voltage power distribution fuses have 250- or 600-V ratings. Ratings of medium voltage fuses range from 2.4 to 34.5 kV.
2. Continuous current rating. The fuse should carry this rms current indefinitely, without melting and clearing.
3. Interrupting current rating. This is the largest rms asymmetrical current that the fuse can safely interrupt. Most modern, low-voltage current-limiting fuses have a 200-kA interrupting rating. Standard interrupting ratings for medium-voltage current-limiting fuses include 65, 80, and 100 kA.
4. Time response. The melting and clearing time of a fuse depends on the magnitude of the overcurrent or fault current, and is usually specified by a "time–current" curve. Figure 8.15 shows the time–current curve of a 15.5-kV, 100-A (continuous) current-limiting fuse. As shown, the fuse link melts within 2 s and clears within 5 s for a 500-A current. For a 5-kA current, the fuse link melts in less than 0.01 s and clears within 0.015 s.

Figure 8.15

Time–current curves for a 15.5-kV, 100-A current-limiting fuse



It is usually a simple matter to coordinate fuses in a power circuit such that only the fuse closest to the fault opens the circuit. In a radial circuit, fuses with larger continuous current ratings are located closer to the source, such that the fuse closest to the fault clears before other, upstream fuses melt.

Fuses are inexpensive, fast operating, easily coordinated, and reliable, and they do not require protective relays or instrument transformers. Their chief disadvantage is that the fuse or the fuse link must be manually replaced after it melts. They are basically one-shot devices that are, for example, incapable of high-speed reclosing.

Problems

Section 8.1

8.1 In the circuit of Figure 8.1, $V = 277$ volts, $L = 2$ mH, $R = 0.4\,\Omega$, and $\omega = 2\pi 60$ rad/s. Determine (a) the rms symmetrical fault current; (b) the rms asymmetrical fault current at the instant the switch closes, assuming maximum dc offset; (c) the rms asymmetrical fault current 5 cycles after the switch closes, assuming maximum dc offset; (d) the dc offset as a function of time if the switch closes when the instantaneous source voltage is 300 volts.

8.2 Repeat Example 8.1 with $V = 4$ kV, $X = 2\,\Omega$, and $R = 1\,\Omega$.

Section 8.2

8.3 A 1000-MVA 20-kV, 60-Hz three-phase generator is connected through a 1000-MVA 20-kV Δ/345-kV Y transformer to a 345-kV circuit breaker and a 345-kV transmission line. The generator reactances are $X_d'' = 0.17$, $X_d' = 0.30$, and $X_d = 1.5$ per unit, and its time constants are $T_d'' = 0.05$, $T_d' = 1.0$, and $T_A = 0.10$ s. The transformer series reactance is 0.10 per unit; transformer losses and exciting current are neglected. A three-phase short-circuit occurs on the line side of the circuit breaker when the generator is operated at rated terminal voltage and at no-load. The breaker interrupts the fault 3 cycles after fault inception. Determine (a) the subtransient current through the breaker in per-unit and in kA rms, (b) the rms asymmetrical fault current the breaker interrupts, assuming maximum dc offset. Neglect the effect of the transformer on the time constants.

8.4 For Problem 8.3, determine (a) the instantaneous symmetrical fault current in kA in phase a of the generator as a function of time, assuming maximum dc offset occurs in this generator phase; and (b) the maximum dc offset current in kA as a function of time that can occur in any one generator phase.

Section 8.3

8.5 Recalculate the subtransient current through the breaker in Problem 8.3 if the generator is initially delivering rated MVA at 0.80 p.f. lagging and at rated terminal voltage.

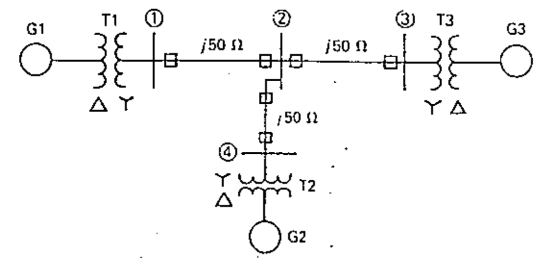
8.6 Solve Example 8.3, parts (a) and (c) without using the superposition principle. First calculate the internal machine voltages E_g'' and E_m'', using the prefault load current. Then determine the subtransient fault, generator, and motor currents directly from Figure 8.4(a). Compare your answers with those of Example 8.3.

8.7 Equipment ratings for the four-bus power system shown in Figure 8.16 are as follows:

Generator G1:	500 MVA, 13.8 kV, $X'' = 0.20$ per unit
Generator G2:	750 MVA, 18 kV, $X'' = 0.18$ per unit
Generator G3:	1000 MVA, 20 kV, $X'' = 0.17$ per unit
Transformer T1:	500 MVA, 13.8 Δ/500 Y kV, $X = 0.12$ per unit
Transformer T2:	750 MVA, 18 Δ/500 Y kV, $X = 0.10$ per unit
Transformer T3:	1000 MVA, 20 Δ/500 Y kV, $X = 0.10$ per unit
Each 500-kV line:	$X_1 = 50\,\Omega$

Figure 8.16

Problem 8.7



A three-phase short circuit occurs at bus 1, where the prefault voltage is 525 kV. Prefault load current is neglected. Draw the positive-sequence reactance diagram in per-unit on a 1000-MVA, 20-kV base in the zone of generator G3. Determine (a) the Thévenin reactance in per-unit at the fault, (b) the subtransient fault current in per-unit and in kA rms, (c) contributions to the fault current from generator G1 and from line 1-2.

Section 8.4

8.8 The bus impedance matrix for a three-bus power system is

$$Z_{bus} = j\begin{bmatrix} 0.4 & 0.1 & 0.3 \\ 0.1 & 0.8 & 0.5 \\ 0.3 & 0.5 & 1.2 \end{bmatrix} \quad \text{per unit}$$

where subtransient reactances were used to compute Z_{bus}. Prefault voltage is 1.0 per unit and prefault current is neglected. (a) Draw the bus impedance matrix equivalent circuit (rake equivalent). Identify the per-unit self and mutual impedances as well as the prefault voltage in the circuit. (b) A three-phase short circuit occurs at bus 2. Determine the subtransient fault current and the voltages at buses 1, 2, and 3 during the fault.

8.9 Determine Y_{bus} in per-unit for the circuit in Problem 8.7. Then invert Y_{bus} to obtain Z_{bus}.

Section 8.5

8.10 For the three-bus power system whose Z_{bus} is given in Problem 8.8, a new impedance $Z_b = j0.7$ per unit is added from old bus 2 to new bus 4. The new impedance element is not mutually coupled to any of the existing impedance elements. Determine the new bus impedance matrix.

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equation (9.47) [Bunch and Kaufman, 1977]. The essential step at each stage of the elimination is to choose 1×1 or 2×2 blocks for pivoting. This choice is dictated by the magnitude of the pivot which affects numerical stability of implementation.

In an important result, Steven M Serbin [Serbin, 1980] showed that if a complex matrix has Symmetric Positive Definite (spd) like characteristics, it can be exploited to expedite the solution. This characteristics corresponds to category C_1 matrices. Serbin showed that for category C_1 matrix, LDL^T decomposition can be obtained in a numerical stable manner using diagonal pivots alone. Thus, it was concluded by [Pandit et al., 2000b] that:

- conventional wisdom of solving sparse spd/ Hermitian matrices by analyze, factorize breakup can be applied for solving such complex symmetric matrices also.
- the LDL^T algorithm for sparse spd linear system solver can be used by replacing data type *float* to data type *complex*, without affecting numerical stability.

Therefore, the linear system solver of chapter 4 is used in both the short circuit analysis and FDLF programs. In fact in C_{++} , by defining data type as a variable using template, the very same implementation is used for FDLF and fault analysis program.

$$SparseMatrix < complex < float > > YBUS$$

The above construct defines a complex symmetric matrix for short circuit analysis. $SparseMatrix < float > B1$ defines a real matrix for FDLF. Then $YBUS.factorize()$ factorizes the YBUS matrix and $B1.factorize()$ factorizes the matrix $B1$. Similarly, $solver(YBUS, e_i)$ solves the equation (9.46) $solver(B_1, \Delta P)$ solves the mismatch equation in FDLF. The solution of equation (9.46) gives us the Thevenin sequence impedance and the prefault load flow Thevenin voltage source. The calculation of fault current is now reduced to the proper interconnection of sequence networks. These are summarized in appendix A. In rest of the chapter, we discuss the application of short circuit analysis.

One of the important applications of short circuit analysis is in coordination of the overcurrent relays. The next section discusses this application.

↑ NO

7. Overcurrent Relay Coordination

An overcurrent relay compares the fault current with a reference or pickup current. If the ratio of the fault current to pickup current is greater than unity (a more realistic range is 1.5-2.0), then relay issues a trip decision. Usually, inverse characteristic is used, *i.e.*, as ratio of the fault current to pickup current increases, the time of operation of relay decreases (figure 9.14). In radial systems, this feature provides a natural *discrimination* between faults on the line which is to be primarily protected by the relay and faults on the downstream lines. If the pickup current is chosen such that (1) it is less than the minimum fault current on adjacent line (down stream) and (2) more than pick up current of the adjacent (down stream) relay, then the relay will not only respond to fault on the adjacent (downstream) line but also act after the down stream relay has had it's opportunity. Thus, it can *backup* the operation of corresponding *primary* relay. Now, each primary/backup relay pair has to be coordinated so that, a backup relay responds only if primary relaying system has failed. The minimum time interval required between operation of primary and backup relay is known as Coordination Time Interval (CTI). Pickup current alone can not provide the necessary freedom to maintain the CTI. For providing this time gradation, additionally, a time multiplier setting (TMS) is also provided. By changing the TMS, the curve can be moved (scaled) up or down. For example, an IEC standard inverse curve is given by following equation.

$$t = TMS \times \left(\frac{0.14}{(I/I_s)^{0.02} - 1} \right) \tag{9.48}$$

where I_s is the pickup current. Thus, for the same pickup current, increasing the TMS setting by a factor of two will double the relay operation time.

Each relay, has to perform both the *primary* and the *backup* protection roles. This can be explained by figure 9.15, which shows a typical radial network with directional relays [Damborg and Venkata, 1984]. Use of directional relay implies that a fault can be fed from both the ends. Here, A, B, C, D are the buses or *nodes* of the system. As relay number 9 is located on line AB, near bus A, line AB is the *primary* line for relay 9, with bus B as it's *remote bus*. Bus C and bus D are it's *second remote buses*. Lines emanating from the remote bus are called *remote lines*. For faults at $F1$ and $F2$, relays 11 and 5 act as *primary* relays; with relays 9 and 6 acting as *backup* relays. For a fault at $F3$, relay 9 and 10 act as *primary* relays while relays 5 and 6 act as *backup* relays. For fault at $F4$, relay 11 backs up relay 7. Thus, relay 11 has to coordinate with relay 9 and 6 for faults at $F1$ and $F2$, while it also has to coordinate with relay 7 for fault at $F4$.

In overcurrent relay coordination application, the following information is required during relay coordination:

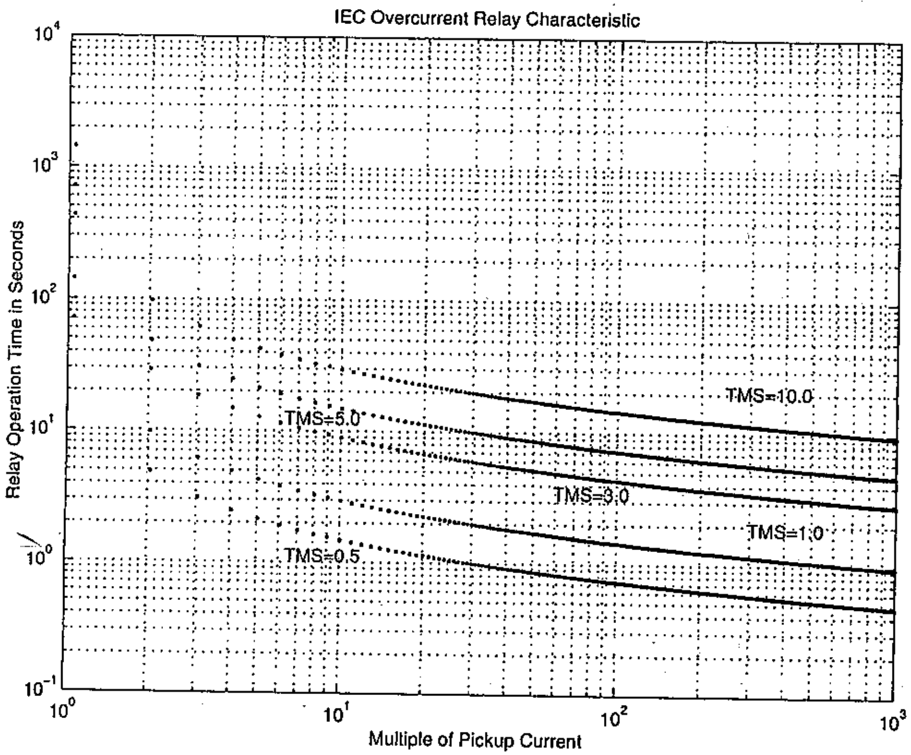

Figure 9.14. Overcurrent Relay Characteristics

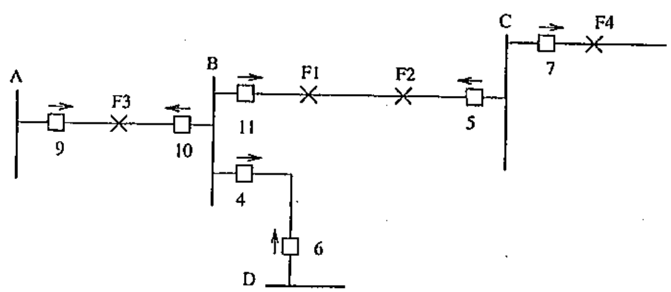

Figure 9.15. Typical Radial System with Directional Relays

1 Fault current at the faulted line for faults at both the remote bus and intermediate points at the line. This information is used to decide the pickup currents of the instantaneous and inverse time overcurrent units.

2 Currents in the adjacent lines for deciding the pickup current of backup relay as well as evaluating primary, backup coordination.

Let the fault be created at bus i and the sequence bus fault currents be given by I_f^0, I_f^1 and I_f^2 respectively. Note that a fault current I_f can be modeled as a current injection of $-I_f$ in the YBUS/ZBUS network model. Then by superposition, the post fault voltages at bus i are given by the following equations:

NO

$$V_i^{f,1} = V_i^{pref,1} - Z_{ii}^1 I_f^1 \tag{9.49}$$
$$V_i^{f,2} = 0 - Z_{ii}^2 I_f^2 \tag{9.50}$$
$$V_i^{f,0} = 0 - Z_{ii}^0 I_f^0 \tag{9.51}$$

Superscript f refers to post fault condition and $pref$ to the prefault condition. To compute the post fault node voltage at an adjacent bus j, we require transfer impedance $Z_{ji}^{0,1,2}$. These are already available from the solution of the following linear system of equations:

$$[YBUS^{012}][Z_i^{012}] = [e_i^{012}]$$

Similarly, by superposition fault voltage at bus j is given by,

$$V_j^{f,1} = V_j^{pref,1} - Z_{ji}^1 I_f^1 \tag{9.52}$$
$$V_j^{f,2} = -Z_{ji}^2 I_f^2 \tag{9.53}$$
$$V_j^{f,0} = -Z_{ji}^0 I_f^0 \tag{9.54}$$

Thus, the post fault sequence currents in branch j to i on which primary relay is installed will be given by the following equations.

$$I_{ji}^1 = \frac{V_j^{pref,1} - V_i^{pref,1} + (Z_{ii}^1 - Z_{ji}^1) I_f^1}{r_{ij}^1 + jx_{ij}^1} \tag{9.55}$$
$$I_{ji}^2 = \frac{(Z_{ii}^2 - Z_{ji}^2) I_f^2}{r_{ij}^2 + jx_{ij}^2} \tag{9.56}$$
$$I_{ji}^0 = \frac{(Z_{ii}^0 - Z_{ji}^0) I_f^0}{r_{ij}^0 + jx_{ij}^0} \tag{9.57}$$

As mentioned in section-1, it is a common practice to neglect the shunt capacitance in fault calculation. However, from a computational view point, if shunt capacitances are available then, the effect of line charging can be easily accounted for in the diagonal elements of the sequence admittance matrices. Positive sequence shunt capacitances are almost