EE 5200 - Lecture 29 **Wednesday Nov 6, 2019**

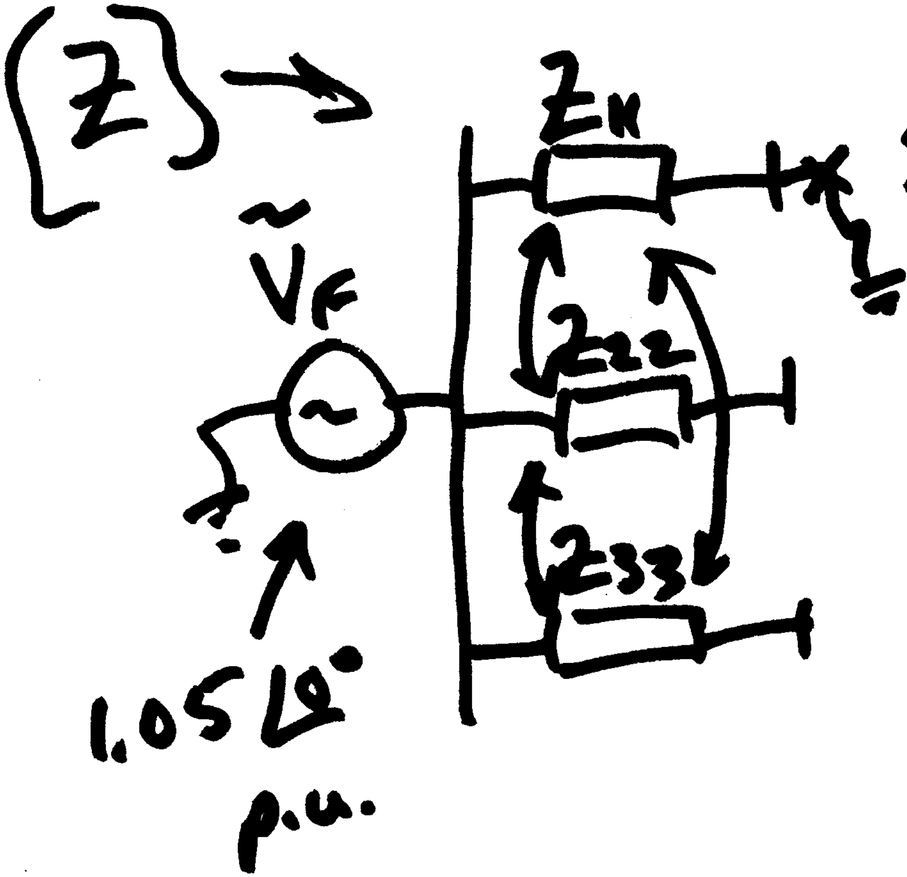
Topics for Today:

- Announcements
  - Term Project: select journal paper, outline it, begin analysis.
  - Nov 18th - Term Project: complete journal paper analysis, draft summary
  - Dec 6th - Term Project: complete journal paper .ppt presentation.
  - Software: online students - if desired, apply for ATP/ATPDraw license, verify licensing when you receive it by e-mail, and we will mail you the install CD.
  - ASPEN software - arranging to run off of MTU server via internet.
  - Office: EERC 614
  - Recommended problems & all solutions: Ch.7, 8 solns now posted.

- Chapter 7,10 - Network Equations, Basic Fault applications
  - Fault current - dc offset. Section 10.1
  - Importance of X/R ratio
  - Circuit breaker ratings
  - Three-Phase fault calcs using [Zbus]. Section 10.3
  - Fault current contributions using [Zbus]. Eqn. (10.21)
  - Admittance approach using [Ybus]

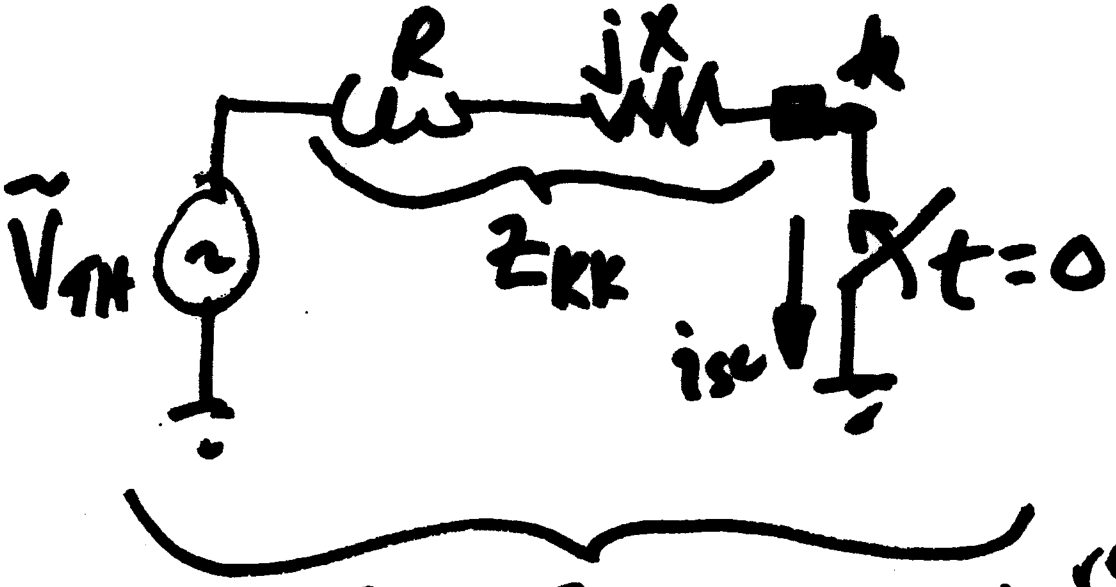
- Next - Chapter 9 - Power Flow (also known as Load Flow)

[Ybus] and/or [Zbus] for fault calcs.



$I_F = V_F / Z_{11}$

See Lecture 28 [redacted]



$$e^{-\frac{t}{\tau}} = \underbrace{e^{-\frac{tR}{L}}}$$

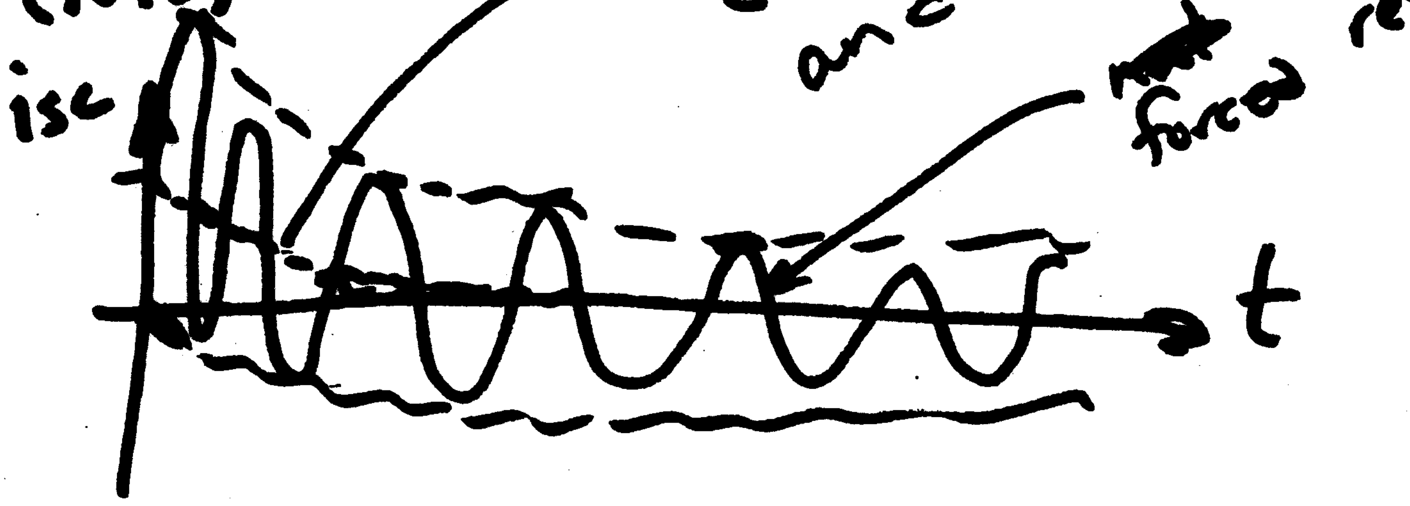
R-L <u>time const.</u>

Thev Equiv.

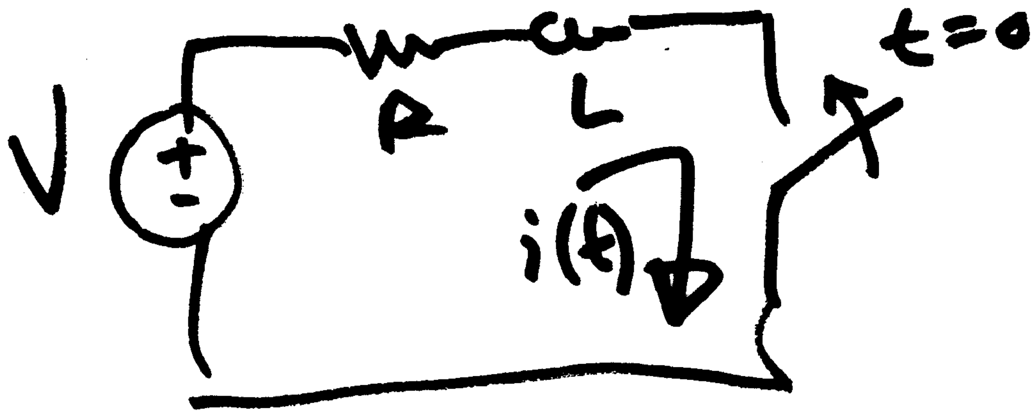
Section 10.1

Eq (10.2)

(nat'l response)
dc offset
due to X/R ratio
and inception ang.

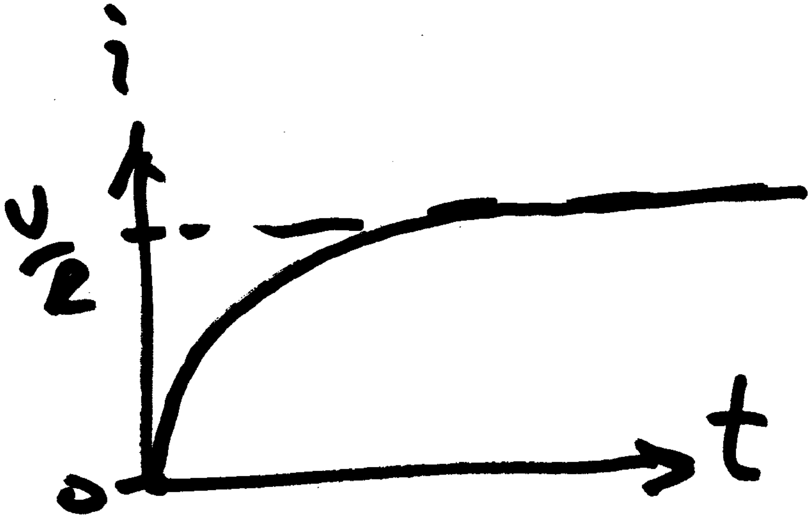


forced resp.



$$\tau = \frac{L}{R} = \boxed{\frac{X}{\omega R}}$$

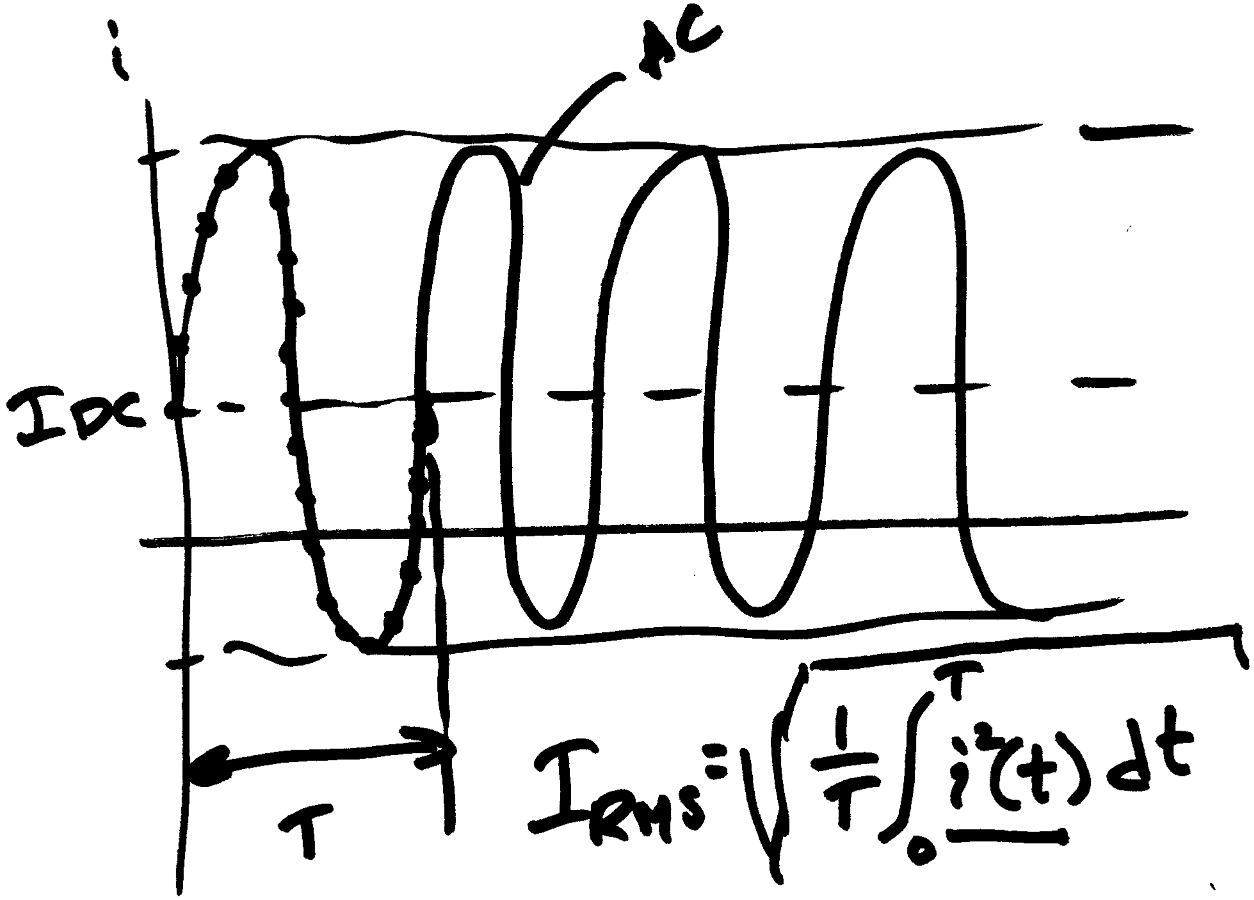
$$i(t) = \left(1 - e^{-\frac{R}{L}t}\right)\frac{V}{R}$$



$i(0) = 0$

$i(\infty) = \frac{V}{R}$

$$\boxed{\frac{X}{R} =} \frac{\omega L}{R} \Rightarrow \underbrace{\tau = \frac{X}{\omega R}}$$

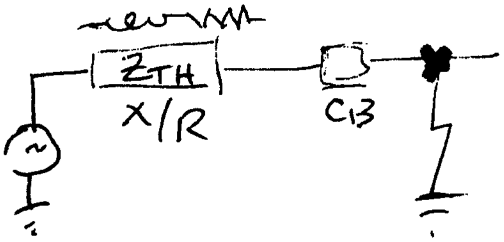


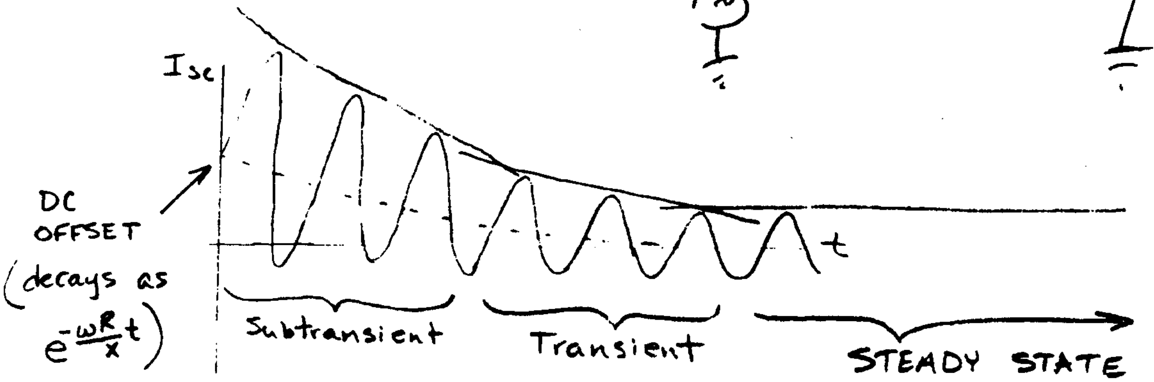
$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T \underline{i^2(t)}\,dt}$$

$$I_{\underline{RMS}} = \sqrt{I_{DC}^2 + I_{\textcircled{60}\,SYM}^2}$$

$$\cong I_{SYM} * S$$

FAULT CURRENTS





Subtransient impedence X_d'' lasts about 3 cycles.

Transient impedance X_d' lasts about 30 cycles.

DC offset due to system X/R ratio and time fault occurs. Decay of DC component is determined by X/R ratio. Larger X/R gives slower decay.

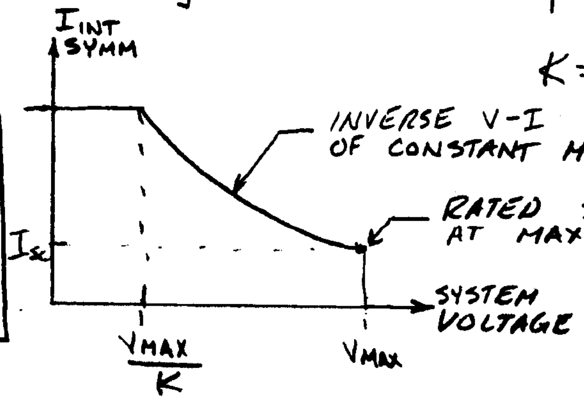
For typical system, $4 < \frac{X}{R} < 10^*$

CIRCUIT BREAKER RATINGS –

IEEE C37.04-1999
(Newer stds are in Draft form)

ANSI defines symmetrical interrupting capability

*
See ANSI C37.010
if:
$\frac{X}{R} > 6.6$ (Molded Case)
$\frac{X}{R} > 15$ (H.V. C.B's)



K = Voltage range factor (ANSI C37.0

69-KV and below.

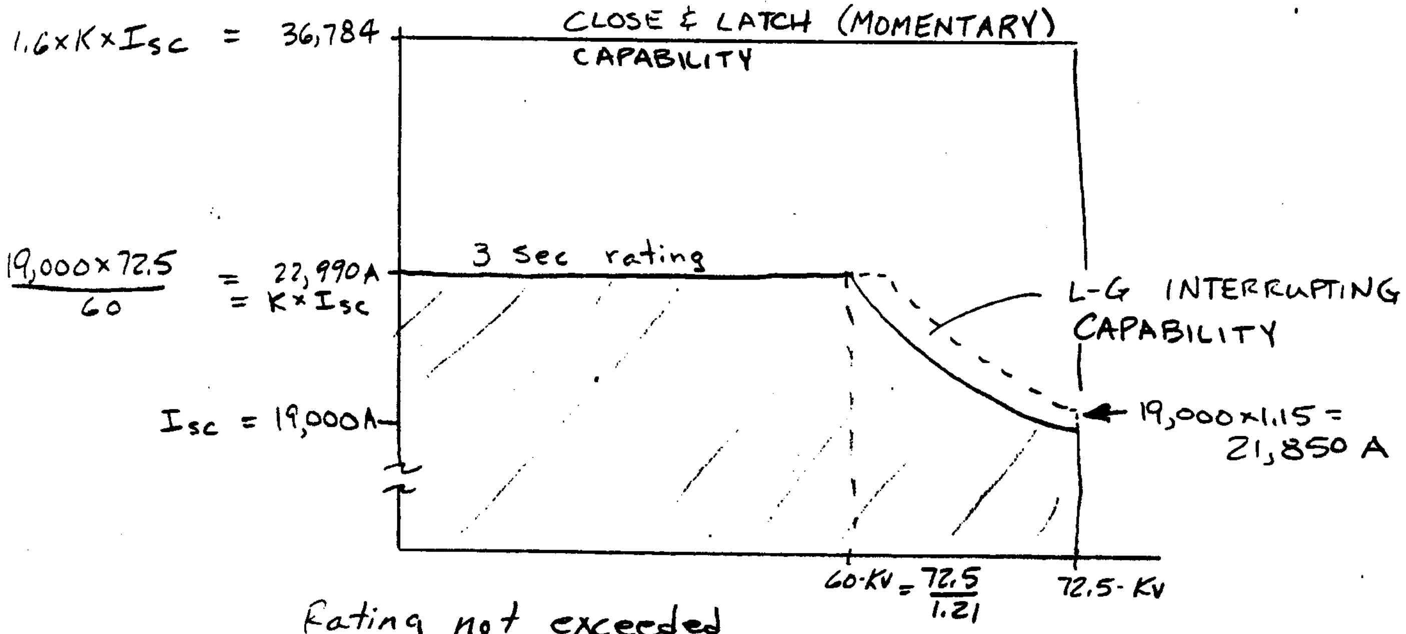
For assymmetrical 3φ or L-L
$I_{INT} = I_{SYM} \times S$

BKR SPEED	S Factor
1.0	1.4
1.5	1.3
2	1.2
3	1.1
≥4	1.0

For assymmetrical L-G
$I_{INT} = I_{SYM} \times S \times 1.15$
(Not to exceed $K \times I_{SYM}$)

EXAMPLE

CIRCUIT BREAKER: VOLTAGE CLASS: 69-KV
72.5-KV MAX
I_{CONT} = 1200 A
K = 1.21
I_{SC} = 19,000 A @ 72.5 KV
Speed = 4 cycles

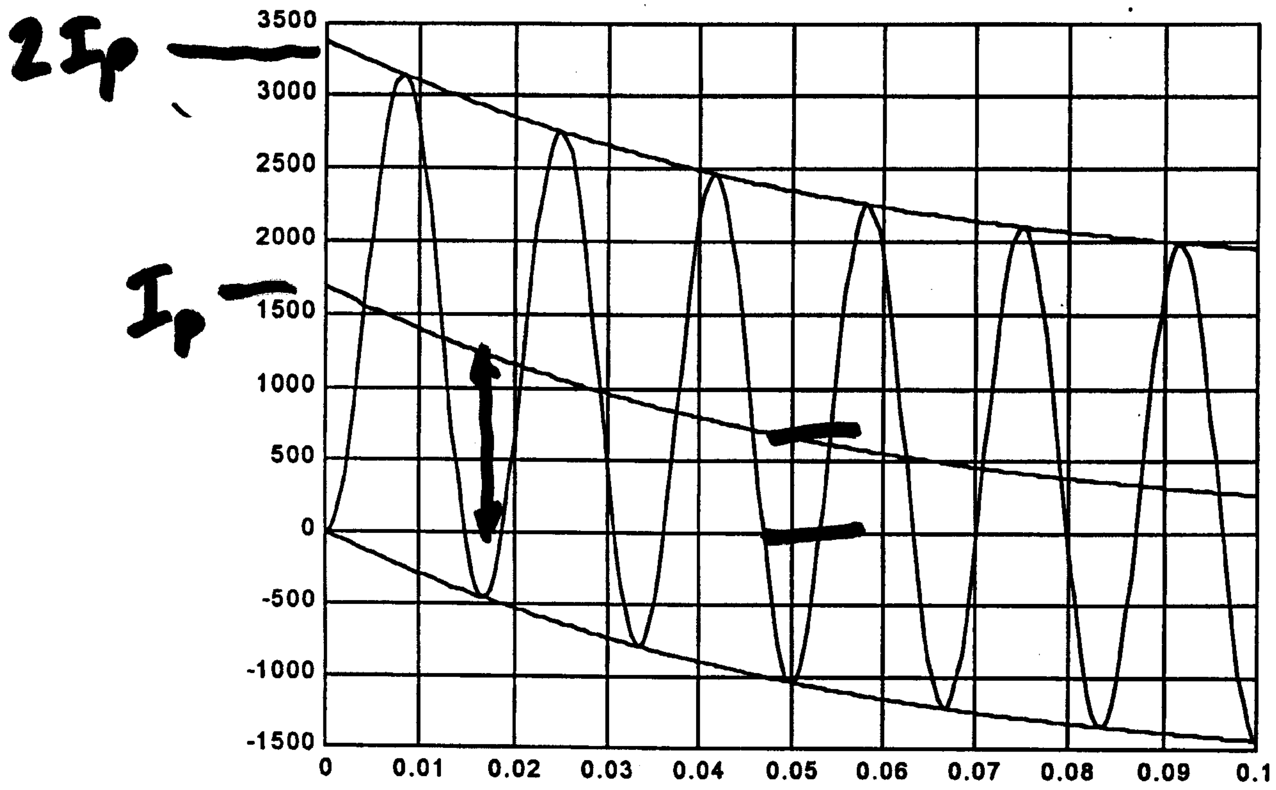


Rating not exceeded for symmetrical fault in shaded area

3Ø assymmetrical and L-L have same rating as symmetrical due to breaker speed

L-G rating is 15% higher (dotted line)

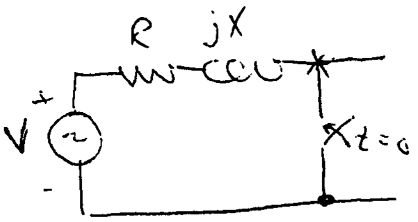
EE 582 Short-Circuit Example. (From MatLab fault.c)



Plot of fault current with worst-case dc offset. X/R = 20.

Vrms = 2400 volts
R = 0.1 ohms
X = 2.0 ohms

$\frac{X}{R} = 20$



Breaker Speed	I_{RMS} factor, Ki	Effect of dc offset on I_{PEAK}	IEEE "s" Factor
1.0	1.44	x 1.73	1.4
1.5	1.33	x 1.62	1.3
2.0	1.25	x 1.533	1.2
3.0	1.14	x 1.39	1.1
4.0	1.08	x 1.28	1.0

TABLE 7.9

Fault currents and bus voltages for Example 7.6

Fault Bus	Fault Current (per unit)	Contributions to Fault Current		
		Gen Line or TRSF	Bus-to-Bus	Current (per unit)
1	37.872			
		G 1	GRND–1	23.332
		T 1	5–1	14.544
2	23.328			
		L 1	4–2	5.608
		L 2	5–2	10.24
		L 4	4–2	7.48
3	57.756			
		G 2	GRND–3	46.668
		T 2	4–3	11.088
4	44.704			
		L 1	2–4	1.128
		L 3	5–4	9.768
		L 4	2–4	1.504
		T 2	3–4	32.308
5	36.268			
		L 2	2–5	4.268
		L 3	4–5	15.848
		T 1	1–5	16.152

$V_F = 1.05$ Fault Bus	Per-Unit Bus Voltage Magnitudes during the Fault				
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	0.0000	0.6775	0.5510	0.4921	0.3231
2	0.4451	0.0000	0.2117	0.1127	0.2133
3	0.7228	0.7114	0.0000	0.3231	0.5974
4	0.5773	0.5609	0.1109	0.0000	0.3962
5	0.2909	0.5119	0.3293	0.2442	0.0000

■

7.5

CIRCUIT BREAKER AND FUSE SELECTION

A SHORT CIRCUITS computer program 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 as *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 13) 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 7.1 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 computer programs. 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 7.10 shows a schedule of preferred ratings for outdoor power circuit breakers. We describe some of the more important ratings shown next.

Voltage ratings

Rated maximum voltage: Designates 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

TABLE 7.10

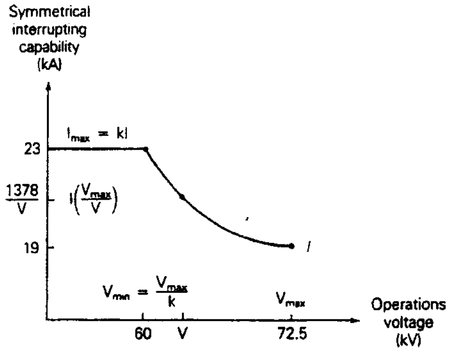
Preferred ratings for outdoor circuit breakers (symmetrical current basis of rating) [10]

		Rated Values					
Identification		Voltage		Insulation Level		Current	
				Rated Withstand Test Voltage			
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)
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
14.4	250	15.5	2.67			600	8.9
14.4	500	15.5	1.29			1200	18
23	500	25.8	2.15			1200	11
34.5	1500	38	1.65			1200	22
46	1500	48.3	1.21			1200	17
69	2500	72.5	1.21			1200	19
115		121	1.0			1200	20
115		121	1.0			1600	40
115		121	1.0			2000	40
115		121	1.0			2000	63
115		121	1.0			3000	40
115		121	1.0			3000	63
138		145	1.0			1200	20
138	Not	145	1.0			1600	40
138		145	1.0			2000	40
138		145	1.0			2000	63
138		145	1.0			2000	80
138	Applicable	145	1.0			3000	40
138		145	1.0			3000	63
138		145	1.0			3000	80
161		169	1.0			1200	16
161		169	1.0			1600	31.5
161		169	1.0			2000	40
161		169	1.0			2000	50
230		242	1.0			1600	31.5
230		242	1.0			2000	31.5
230		242	1.0			3000	31.5
230		242	1.0			2000	40
230		242	1.0			3000	40
230		242	1.0			3000	63
345		362	1.0			2000	40
345		362	1.0			3000	40
500		550	1.0			2000	40
500		550	1.0			3000	40
700		765	1.0			2000	40
700		765	1.0			3000	40

TABLE 7.10
(continued)

Rated Values		Related Required Capabilities			
			Current Values		
Rated Interrupting Time	Rated Permissible Tripping Delay	Rated Max Voltage Divided by K	Max Symmetrical Interrupting Capability	3-Second Short-Time Current Carrying Capability	Closing and Latching Capability 1.6K Times Rated Short-Circuit Current
			K Times Rated Short-Circuit Current		
(Cycles)	(Seconds)	(kV, rms)	(kA, rms)	(kA, rms)	(kA, rms)
Col 9	Col 10	Col 11	Col 12	Col 13	Col 14
5	2	5.8	24	24	38
5	2	12	23	23	37
5	2	12	24	24	38
5	2	23	36	36	58
5	2	40	21	21	33
5	2	60	23	23	37
3	1	121	20	20	32
3	1	121	40	40	64
3	1	121	40	40	64
3	1	121	63	63	101
3	1	121	40	40	64
3	1	121	63	63	101
3	1	145	20	20	32
3	1	145	40	40	64
3	1	145	40	40	64
3	1	145	63	63	101
3	1	145	80	80	128
3	1	145	40	40	64
3	1	145	63	63	101
3	1	145	80	80	128
3	1	169	16	16	26
3	1	169	31.5	31.5	50
3	1	169	40	40	64
3	1	169	50	50	80
3	1	242	31.5	31.5	50
3	1	242	31.5	31.5	50
3	1	242	31.5	31.5	50
3	1	242	40	40	64
3	1	242	40	40	64
3	1	242	63	63	101
3	1	362	40	40	64
3	1	362	40	40	64
2	1	550	40	40	64
2	1	550	40	40	64
2	1	765	40	40	64
2	1	765	40	40	64

FIGURE 7.8



Symmetrical interrupting capability of a 69-kV class breaker

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 7.10 is plotted versus operating voltage in Figure 7.8. 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.

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 7.7 Circuit breaker selection

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 7.10 for this bus.

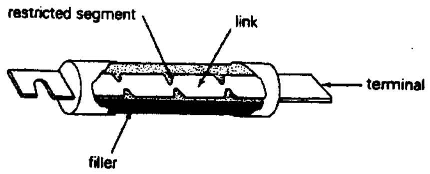
SOLUTION The 69-kV-class breaker has a symmetrical interrupting capability $I(V_{max}/V) = 19(72.5/64) = 21.5$ kA at the operating voltage $V = 64$ kV. The calculated symmetrical fault current, 17 kA, is less than 80% of this capability (less than $0.80 \times 21.5 = 17.2$ kA), which is a requirement when X/R is unknown. Therefore, we select the 69-kV-class breaker from Table 7.10. ■

FUSES

Figure 7.9(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.

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 7.9(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 7.9(c). The current flow within the fuse is then completely cut off.

FIGURE 7.9
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.

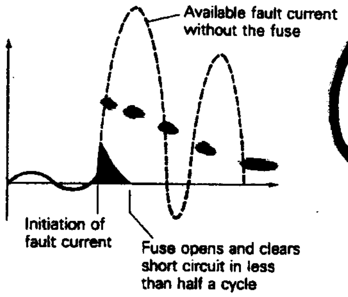
If the fuse is subjected to fault currents higher than about six times its continuous current rating, several restricted segments melt simultaneously, resulting in rapid arc suppression and fault clearing. Arc suppression is accelerated by the filler material in the fuse.

Many modern fuses are current limiting. As shown in Figure 7.10, 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.

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 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

FIGURE 7.10
Operation of a current-limiting fuse



i^2t

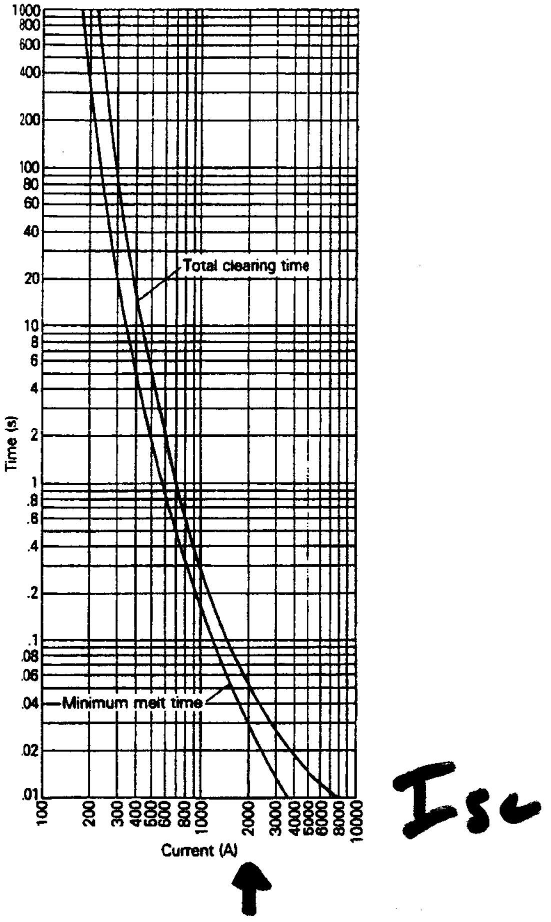
by a "time–current" curve. Figure 7.11 shows the time–current curve of a 15.5-kV, 100-A (continuous) current-limiting fuse. As shown, the fuse link melts within 2 s and clears within 5 s for a 500-A current. For a 5-kA current, the fuse link melts in less than 0.01 s and clears within 0.015 s.

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.

FIGURE 7.11

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



PROBLEMS

SECTION 7.1

7.1 In the circuit of Figure 7.1, $V = 220$ volts, $L = 3$ mH, $R = 0.5\ \Omega$, 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 244 volts.

7.2 Repeat Example 7.1 with $V = 4$ kV, $X = 3\ \Omega$, and $R = 1\ \Omega$.

7.3 In the circuit of Figure 7.1, let $R = 0.125\ \Omega$, $L = 10$ mH, and the source voltage is $e(t) = 151 \sin(377t + \alpha)$ V. Determine the current response after closing the switch for the following cases: (a) no dc offset; (b) maximum dc offset. Sketch the current waveform up to $t = 0.10$ s corresponding to case (a) and (b).

SECTION 7.2

7.4 A 1500-MVA 20-kV, 60-Hz three-phase generator is connected through a 1500-MVA 20-kV Δ/500-kV Y transformer to a 500-kV circuit breaker and a 500-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; and (b) the rms asymmetrical fault current the breaker interrupts, assuming maximum dc offset. Neglect the effect of the transformer on the time constants.

7.5 For Problem 7.4, 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.

7.6 A 300-MVA, 13.8-kV, three-phase, 60-Hz, Y-connected synchronous generator is adjusted to produce rated voltage on open circuit. A balanced three-phase fault is applied to the terminals at $t = 0$. After analyzing the raw data, the symmetrical transient current is obtained as

$$i_{ac}(t) = 10^4(1 + e^{-t/\tau_1} + 6e^{-t/\tau_2}) \quad \text{A}$$