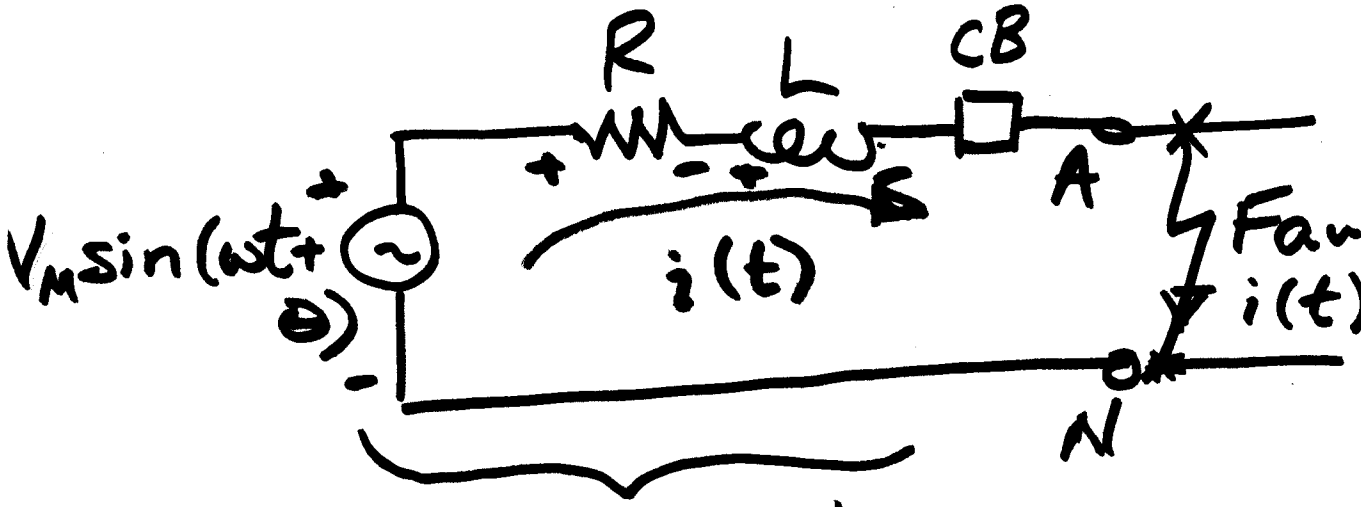
EE 5220 - Lecture 5 Wed Jan 17, 2024

Topics for Today:

- Startup
  - Web page: https://pages.mtu.edu/~bamork/ee5220/index.htm
  - Book, references, syllabus, more are on web page.
  - Software - Matlab. ATP/EMTP [License - www.emtp.org]
  - ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = min half letter grade)

- HW#2 probs 1.4, 1.5, 1.6, 1.7, 2.4 due Tues Jan 23rd.
- HW#3 probs 3.2, 3.3, 3.4, 3.6, 3.12 due Tues Jan 30th.
- Forced response of RL, RLC circuits.
- ATP Simulation pointers
- Next: Cap Bank Switching
  - Read/peruse/study Chapter 3
  - Print out Cap Bank Sw handout, bring to class!

Forced Response - RL CKts



$-\pi < \theta < \pi$

In time domain, KVL

$$R i(t) + L \frac{di(t)}{dt} = V_m \sin(\omega t + \theta)$$

$$R I(s) + L s \underline{I(s)} - L I(0) = V_M \left[\frac{\omega \cdot \cos\theta}{s^2 + \omega^2} + \frac{s \cdot \sin\theta}{s^2 + \omega^2} \right]$$

<u>Note</u>: $V_m = [\sin\omega t \cdot \cos\theta + \cos\omega t \sin\theta$

Since $I(0) = 0$

$$I(s) = \frac{V_M}{L} \frac{1}{s + R/L} \left[\frac{\omega \cos\theta}{s^2 + \omega^2} + \frac{s \cdot \sin\theta}{s^2 + \omega^2} \right]$$

USEFUL TRIGONOMETRIC IDENTITIES

$$\sin (A+B) = \sin A \cos B + \cos A \sin B$$

$$\sin (A-B) = \sin A \cos B - \cos A \sin B$$

$$\cos (A+B) = \cos A \cos B - \sin A \sin B$$

$$\cos (A-B) = \cos A \cos B + \sin A \sin B$$

$$\cos A \cos B = 1/2 \left[\cos (A-B) + \cos (A+B)\right]$$

$$\sin A \sin B = 1/2 \left[\cos (A-B) - \cos (A+B)\right]$$

$$\sin A \cos B = 1/2 \left[\sin (A+B) + \sin (A-B)\right]$$

$$\cos A \sin B = 1/2 \left[\sin (A+B) - \sin (A-B)\right]$$

$$\sin^2 A = 1/2 \, (1 - \cos 2A)$$

$$\cos^2 A = 1/2 \, (1 + \cos 2A)$$

$$\sin A \cos A = 1/2 \sin 2A$$

$$A \cos \omega t + B \sin \omega t = C \cos (\omega t - \alpha)$$

where $C = \sqrt{A^2 + B^2}$

$$\alpha = \tan^{-1} \frac{B}{A}$$

$$I(s) = \frac{A}{(s+\alpha)(s^2+\omega^2)} + \frac{B}{(s+\alpha)(s^2+\omega^2)}$$

where $A = \frac{V_M}{L}\omega\cos\theta$

$$B = \frac{V_M}{L}\sin\theta$$

$$\alpha = \frac{R}{L}$$

$$\frac{1}{(s+\alpha)(s^2+\omega^2)} = \frac{1}{(\alpha^2+\omega^2)}\left[\frac{1}{s+\alpha} - \frac{s}{s^2+\omega^2} + \frac{\alpha}{s^2+\omega^2}\right]$$

$$\mathcal{L}^{-1}\left\{\frac{1}{(s+\alpha)(s^2+\omega^2)}\right\} = \frac{1}{\alpha^2+\omega^2}\left[e^{-\alpha t} - \cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right]$$

$$\mathcal{L}^{-1}\left\{\frac{s}{(s+\alpha)(s^2+\omega^2)}\right\} = \frac{1}{\alpha^2+\omega^2}\left[-\alpha e^{-\alpha t} + \omega\sin\omega t + \alpha\cos\omega t\right]$$

$$I(t) = \frac{V_M}{L(\alpha^2+\omega^2)}\left[\omega\cos\theta\left(e^{-\alpha t} - \cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right.$$

$$\left. + \sin\theta\left(\alpha\cos\omega t + \omega\sin\omega t - \alpha e^{-\alpha t}\right)\right]$$

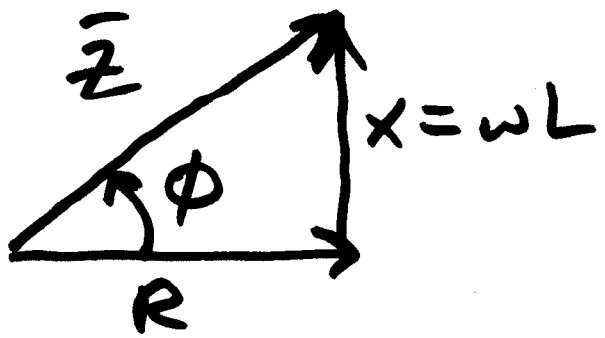
<u>Subst</u>: $\phi = \tan^{-1}\frac{\omega L}{R}$ ↑ Note: $\frac{\omega L}{R} = \frac{X}{R}$

$$I(t) = \frac{V_m}{\sqrt{R^2+\omega^2L^2}}\left[\sin(\omega t+\theta-\phi) - \sin(\theta-\phi)e^{-\alpha t}\right]$$

12!

<u>Check</u>: S-S response...

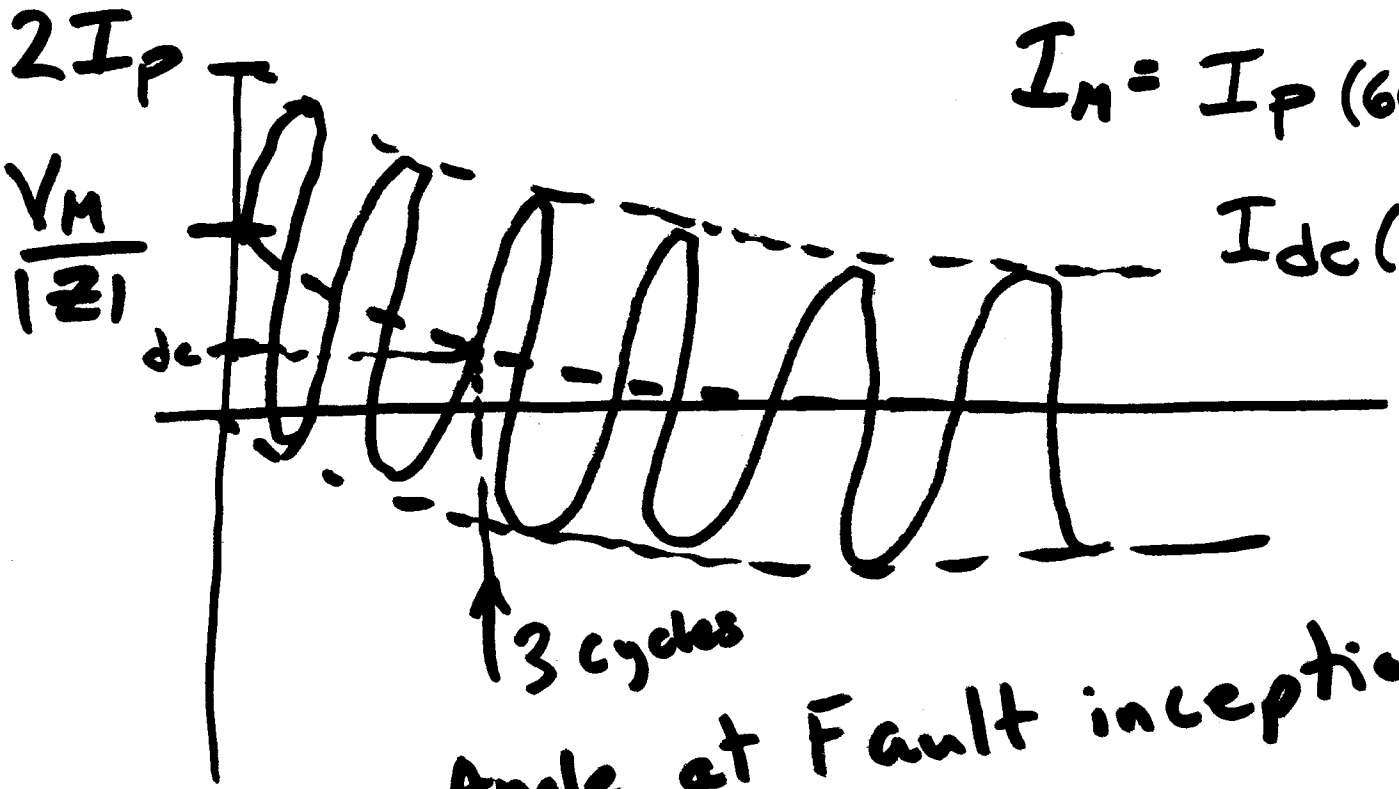
$$\tilde{I} = \frac{V_M\angle\theta}{\sqrt{2}(\bar{Z})} = \frac{V_M \quad \angle\theta-\phi}{\sqrt{2}\sqrt{R^2+X^2}}$$



$$i(t) = \frac{V_M}{|Z|}\left[\underbrace{\sin(\omega t + \theta + \phi)}_{\text{Forced Response}} - \underbrace{\sin(\theta-\phi)}_{\text{worst case when } \sin(\theta-\phi) = \pm 1}\, e^{-\frac{R}{L}t}\right]$$

Forced Response

Nat'l Response



$I_M = I_{p\,(60\,Hz)} = \frac{V_M}{|Z|}$

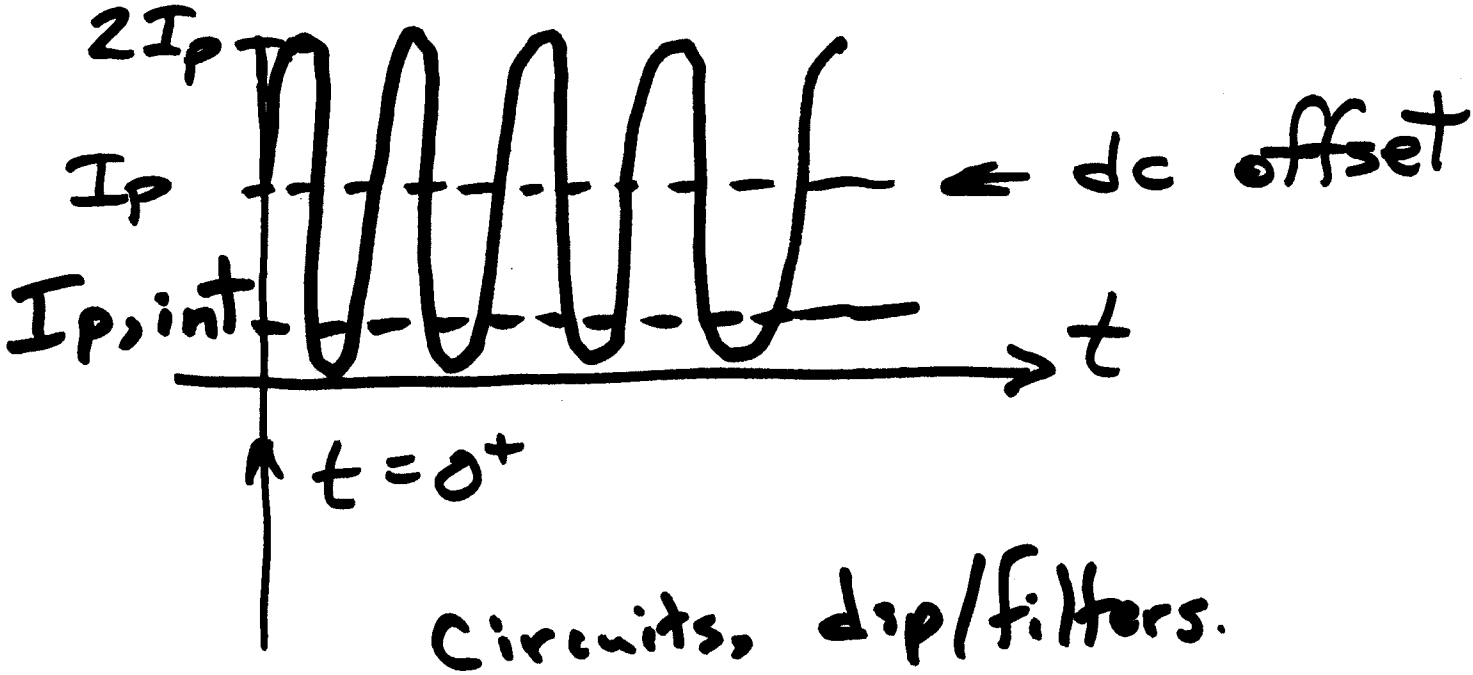
$I_{dc\,(worst)} = ?$

Angle at Fault inception?

CB Ratings -

Based on True-RMS current in a moving window.

At $t = 0^+$, I (true RMS) =



From [redacted] Circuits, dsp/filters.

$$I_{RMS} = \sqrt{I_{dc}^2 + I_1^2 + I_2^2 + \ldots \rightarrow 0}$$

↑ 60Hz

In this case

$$I_{RMS} = \sqrt{I_{dc}^2 + I_{60,RMS}^2}$$

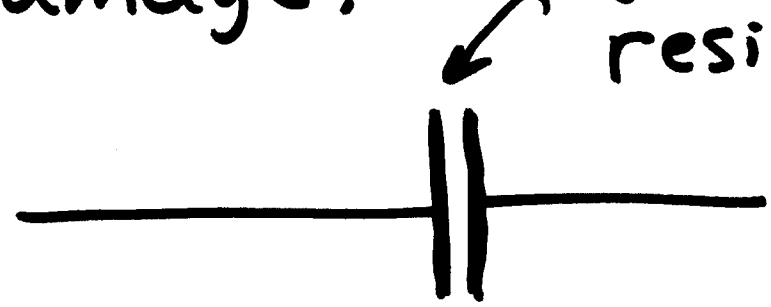
Recall

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

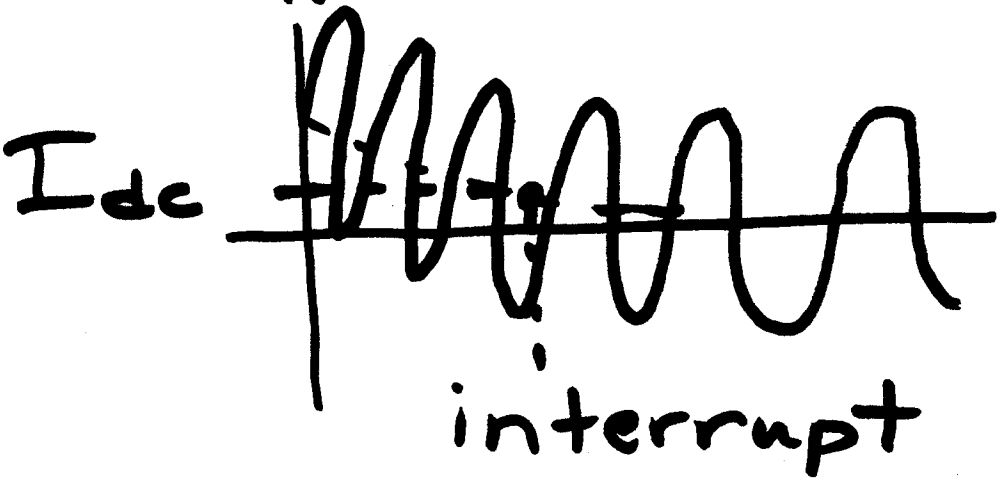
$$I_{AVG} = \frac{1}{T}\int_0^T i(t)\,dt$$

T = whole no. period

S.C. Current at $t = 0^+$ passes thru CB. Contacts must pass it w/o damage.



Upon interreption,



Max dc offset:

$$I_{dc,max} = \sqrt{2}\, I_{\underset{RMS}{60\,Hz}}$$

Rate of decay of nat'l response

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

Transient dc offset

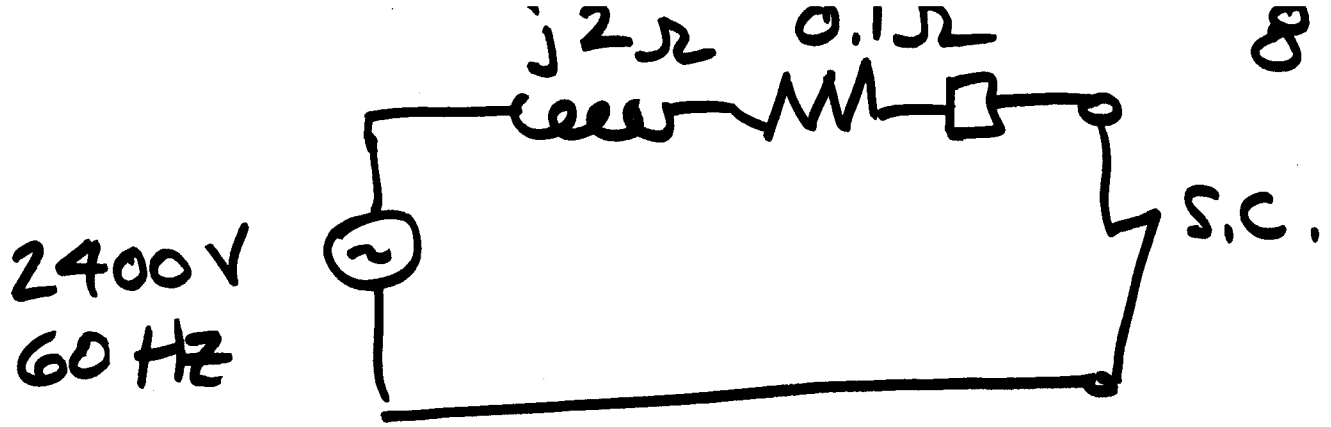
$$I_{dc}(t) = I_{dc,max}\, e^{-\frac{t}{\tau}}$$

True RMS Transient Current as a function of time,

$$I(t) = \sqrt{I^2_{\underset{RMS}{60\,Hz}} + I^2_{dc}(t)}$$

$$\tilde{I}(t) = I_{\underset{RMS}{60\,Hz}} \sqrt{1 + 2e^{-2t/\tau}}$$

Ex:



$$I_{\substack{60\,Hz \\ RMS}} = \frac{2400}{2} \cong 1200\,A\,RMS$$

Operate time: 2 cycles

$$t_{op} = 2/60 = 0.03\overline{3}\ s$$

$$\tau = \frac{X}{\omega R} = \frac{2}{377 \cdot 0.1} = \underline{0.053\,s}$$

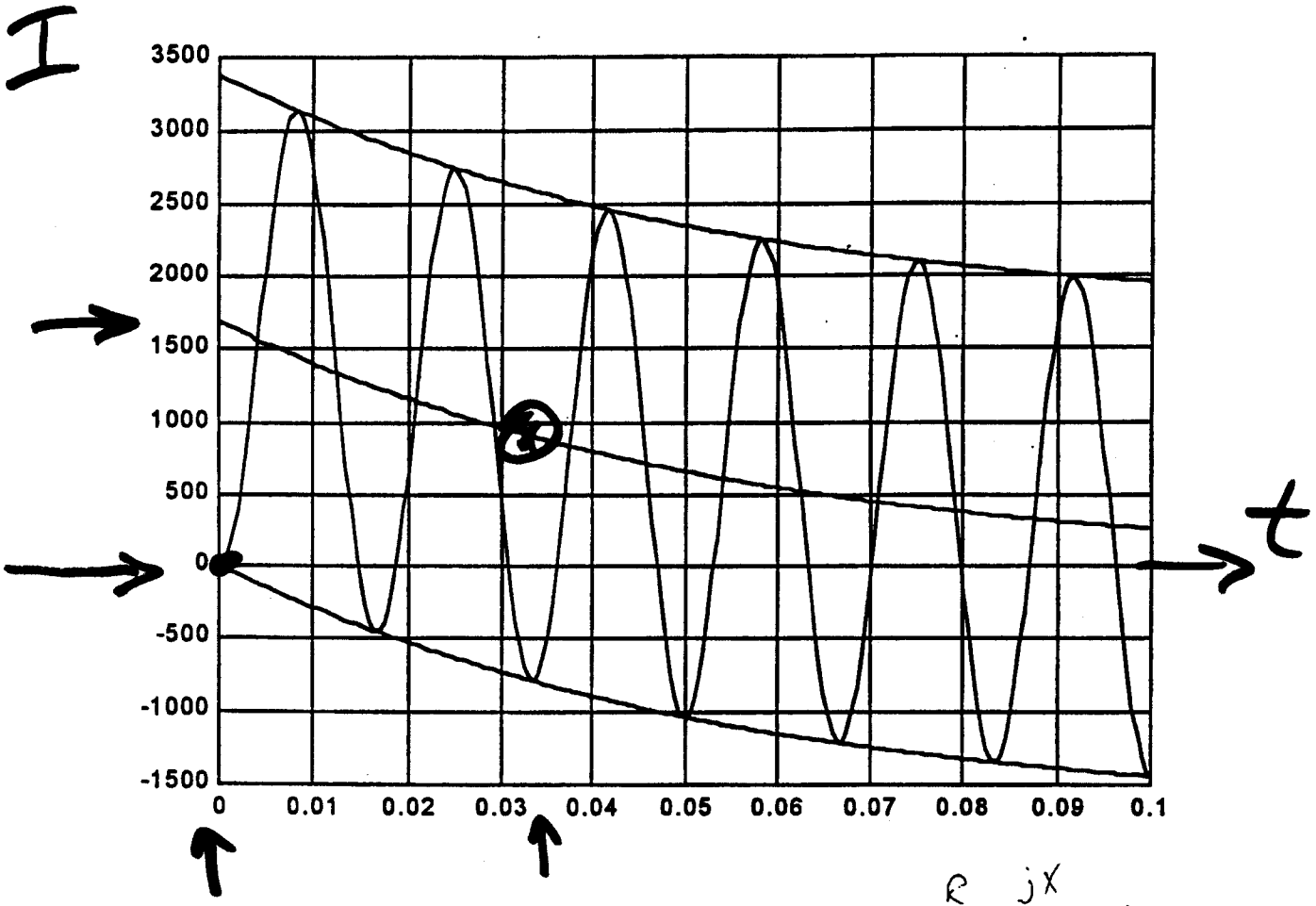
$$I(t) = 1200 \underbrace{\sqrt{1 + 2e^{-.667/.053}}}_{K_i}$$

at 2 cycles

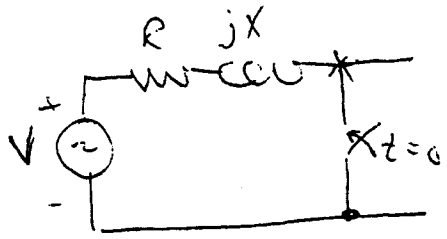
$$I(t) = (1200)(1.252) = \underline{1503\,A}$$

CB must be able to interrupt 1500 A!

[redacted] 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

Ki

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

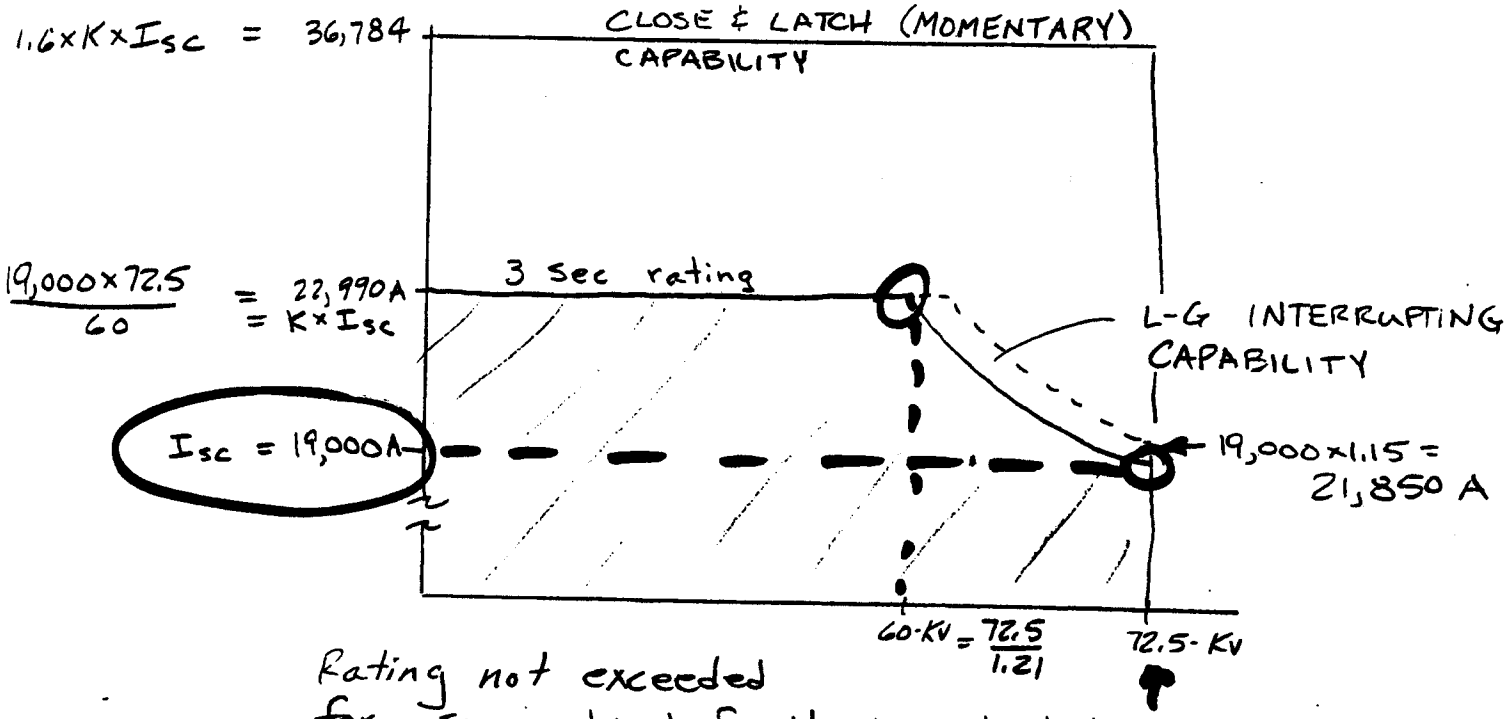
IEEE

EXAMPLE

CIRCUIT BREAKER: VOLTAGE CLASS: 69-KV
72.5-KV MAX

I_{CONT} = 1200 A
K = 1.21
I_{SC} = 19,000A @ 72.5 KV
Speed = 4 cycles

Voltage range factor

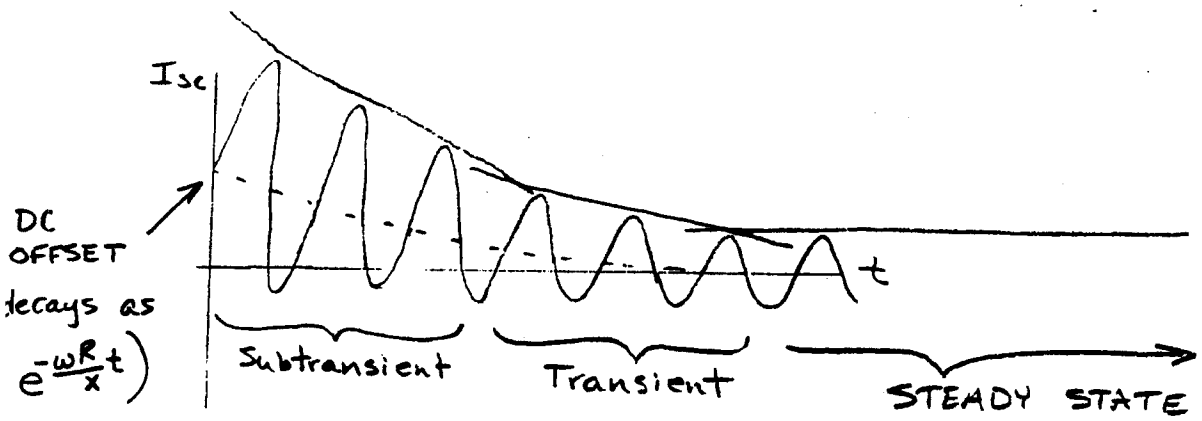


Rating not exceeded for symmetrical fault in shaded area

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

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

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 - ANSI C37.04-1979

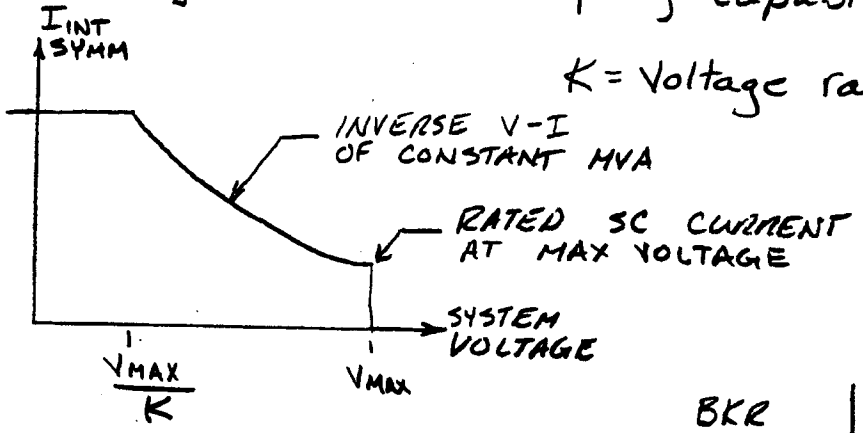
ANSI defines symmetrical interrupting capability

K

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

Ki

For assymmetrical 3Φ or L-L

$I_{INT} = I_{SYM} \times S$

For assymmetrical L-G

$I_{INT} = I_{SYM} \times S \times 1.15$

(Not to exceed $K \times I_{SYM}$)

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

From Glover & Sarma. 12

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

IDENTIFICATION		RATED VALUES					
		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	Applica-	145	1.0			3000	40
138		145	1.0			3000	63
138		145	1.0			3000	80
161	ble	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 8.10 (continued)

RATED VALUES		RELATED REQUIRED CAPABILITIES			
			CURRENT VALUES		
			MAX SYMMETRICAL INTERRUPTING CAPABILITY	3-SECOND SHORT-TIME CURRENT CARRYING CAPABILITY	CLOSING AND LATCHING CAPABILITY 1.6*K* TIMES RATED SHORT-CIRCUIT CURRENT kA, rms
RATED INTERRUPTING TIME CYCLES	RATED PERMISSIBLE TRIPPING DELAY SECONDS	RATED MAX VOLTAGE DIVIDED BY *K* kV, rms	*K* TIMES RATED SHORT-CIRCUIT CURRENT		
			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