Inrush...

For transformers:

The saturation current that can occur when transformers are first switched into service.

Why Important?

Fuse coordination work

Topics

- The B-H Curve and Remnance
- Transformers - Volts and Fluxes
- Air Core Inductance
- Peak First Half Cycle Current/Considerations
- The Transient Consideration
- Milestones - ESP 0.1 Second
- Medium Voltage Transformer Tables
- Step-Up Transformer Considerations

The B-H Curve and Remnance

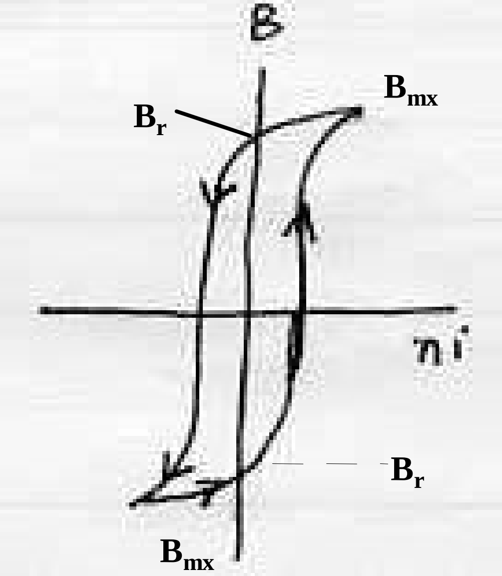


Figure 1. Magnetic Induction vs. Excitation

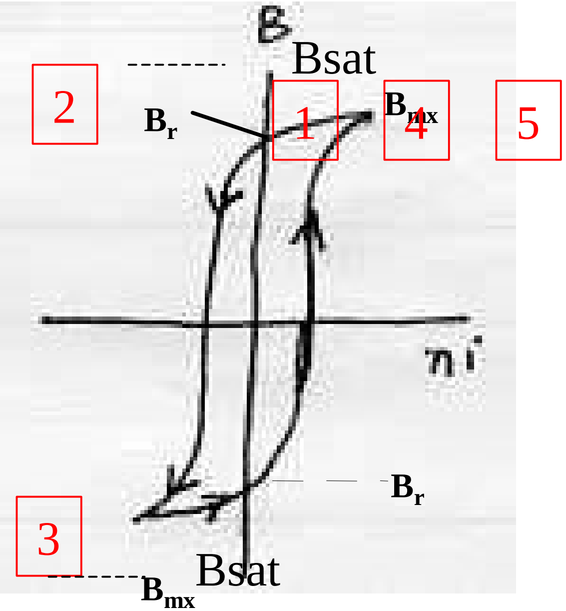
Here, Bmx = Peak operating flux density

Br = Magnetic remnance

$$Br = 10^{(-.51713 + 1.362317 \times LOG(K * Bmx))}$$

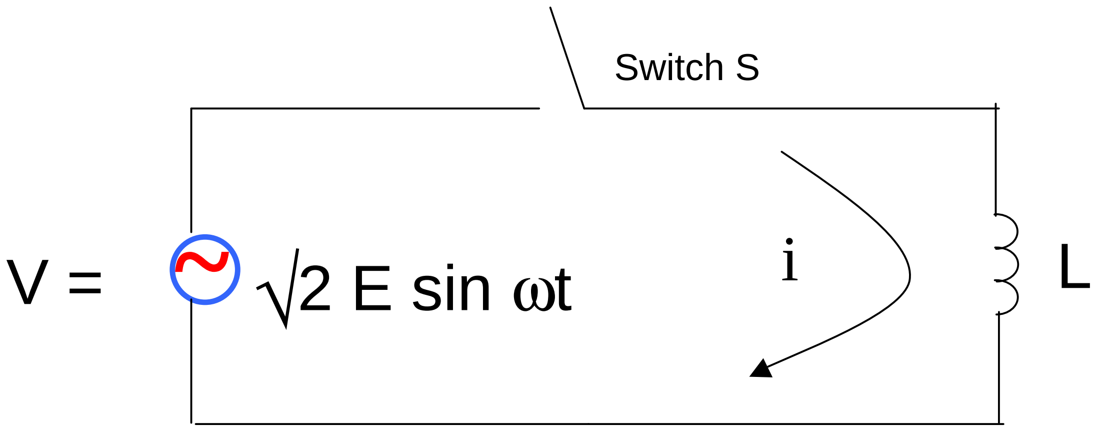
Core Steel	K	Typical B_r
Grain Oriented	1.0	**.9 B_{mx}**
Non Oriented	.6	**.7 B_{mx}**

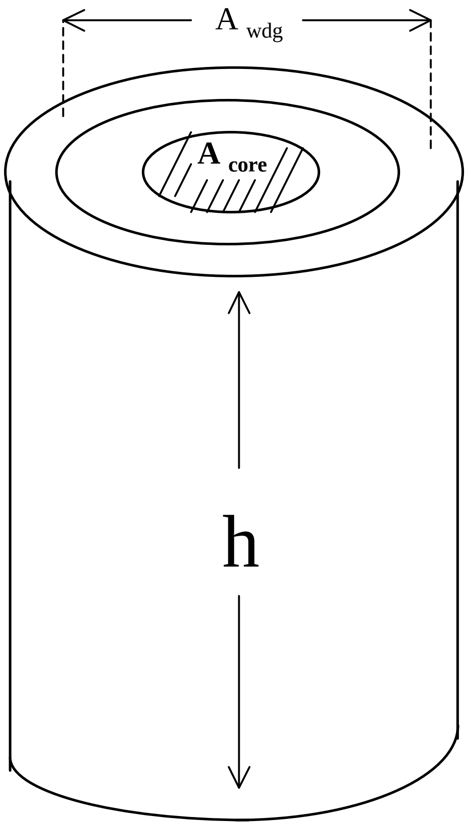
Core Saturation Produces Inrush



1	Power switched off at Bmx
2	Flux density decays to Br
3	Power switched back on
4	Flux density = 2 Bmx + Br
5	Core saturation = 2 Bmx + Br -Bsat

Inrush Current Calculation without Resistance





$$V = L\,di/dt,$$

$$\therefore \quad i = \int V/L \cdot dt$$

$$V = \sqrt{2}\,E \sin \omega t$$

$$\text{Hence, } i_{pk} = -\frac{\sqrt{2}\,E \cos \omega t}{L\omega}\Bigg|_{\omega t = 0^\circ}^{\omega t = 180^\circ}$$

Peak Inrush

$$i_{pk} = K\left(\frac{A_{core}}{A_{winding}}\right)\left(\frac{h}{n}\right)(2B_{mx} + B_{rem} - B_{sat})$$

The Transient Consideration with Resistance

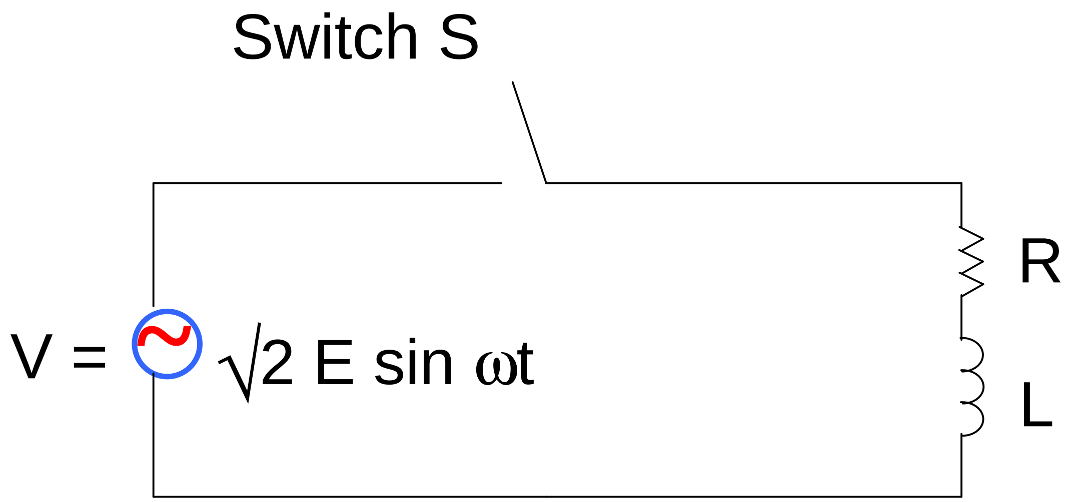
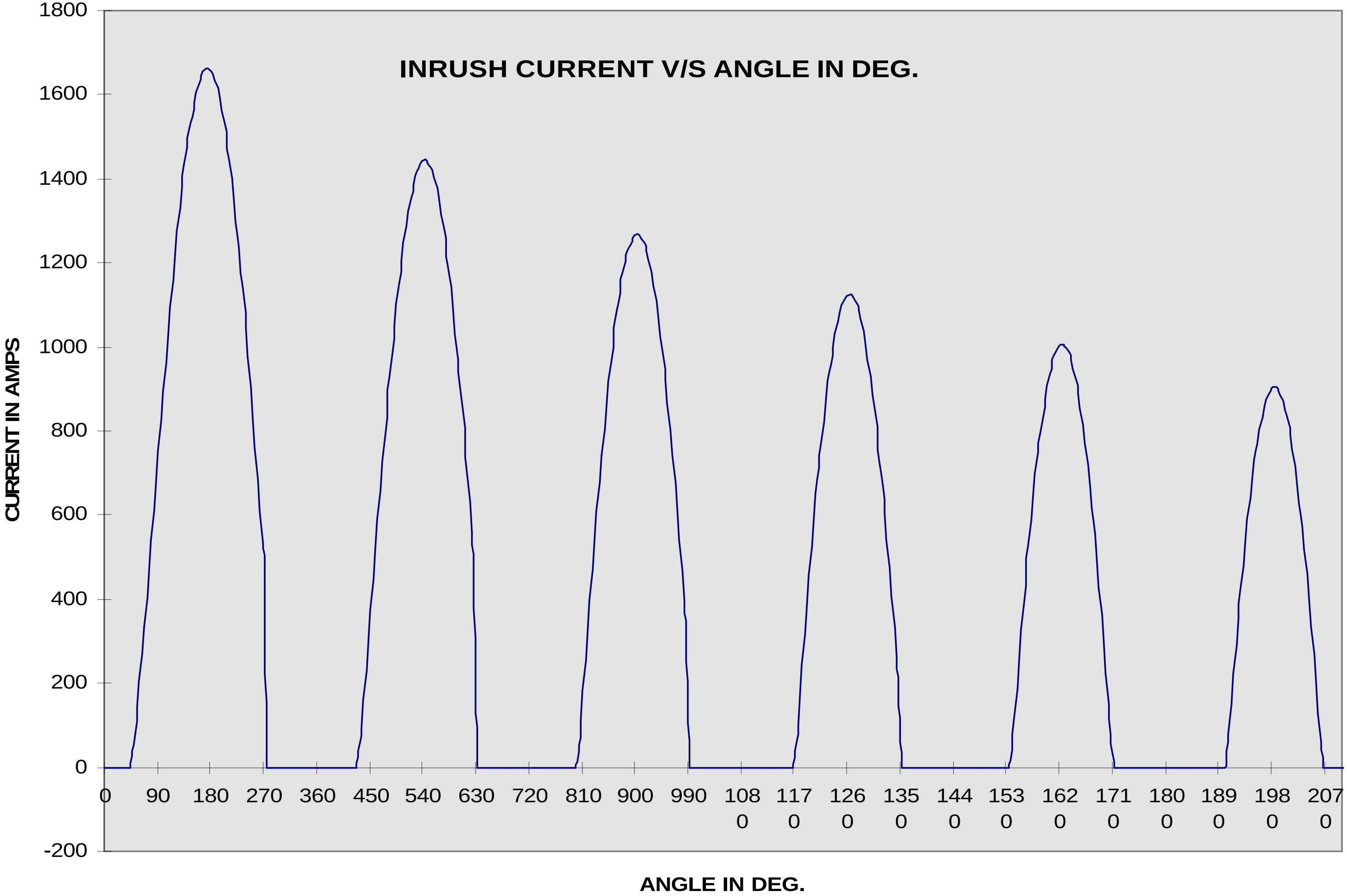


Fig. 2 Schematic diagram of transformer with saturated core

E = rms value at exciting voltage
R = transformer winding resistance, core effects, and external resistance
L = air core inductance of transformer winding plus external inductance

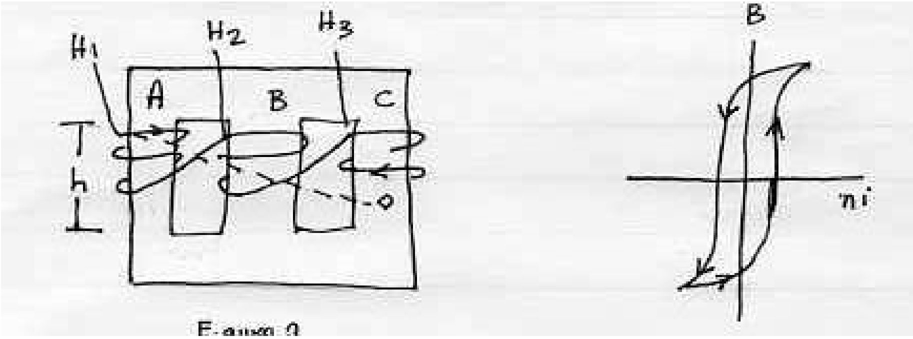
$$\text{With } V = \sqrt{2}\, E \sin \omega t = L \frac{di}{dt} + Ri$$

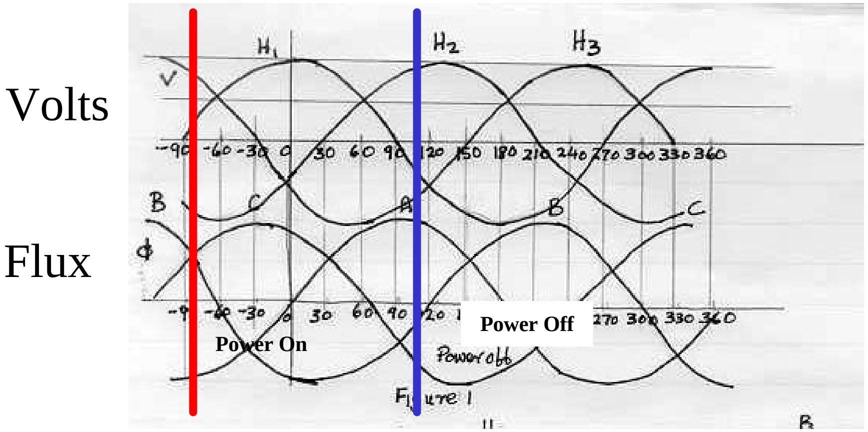
$$i = Ke^{\frac{-Rt}{L}} * \frac{\sqrt{2}\, E \sin (\omega l - \Phi)}{\sqrt{(R^2 + \omega^2 L^2)}}$$



Damping/Decay Increases with Resistance

Transformers - Volts and Fluxes





A is the worst phase!

1. If power is turned off at 90°, A is left at peak positive remnance, B at -50%, and C at -50%.

2. When power is switched on again at 0°, Phase A gets full inrush positive i.e. (Br + 2 Bmx) or (~ 2.9 x Bmx), Phase B gets (-.5 Br - 1.5 Bmx) or in absolute terms (~2.0 Bmx - 1.2 Bmx), Phase C gets (-.5 Br + .5 Bm). Hence line current into Terminal H1 is drawn by Phase A only, but Phase B also saturates, hence the return path for flux is via air permeability.

3. When Phase B or Phase C are so switched the adjacent phase does not saturate when power is returned.

Maximum Line Current
The “A” Phase H2 Terminal

$$I_{H2} = I_{H2 - H1} + I_{H2 - H3}$$

or

$$I_{H2} = I_A + I_B$$

or

$$I_{H2} \sim 1.256 * I_A$$

Line current exceeds phase current because (2) phases saturate

Critical Values for Fuse/Relay Coordination

Currents

First Half Cycle Crest Current

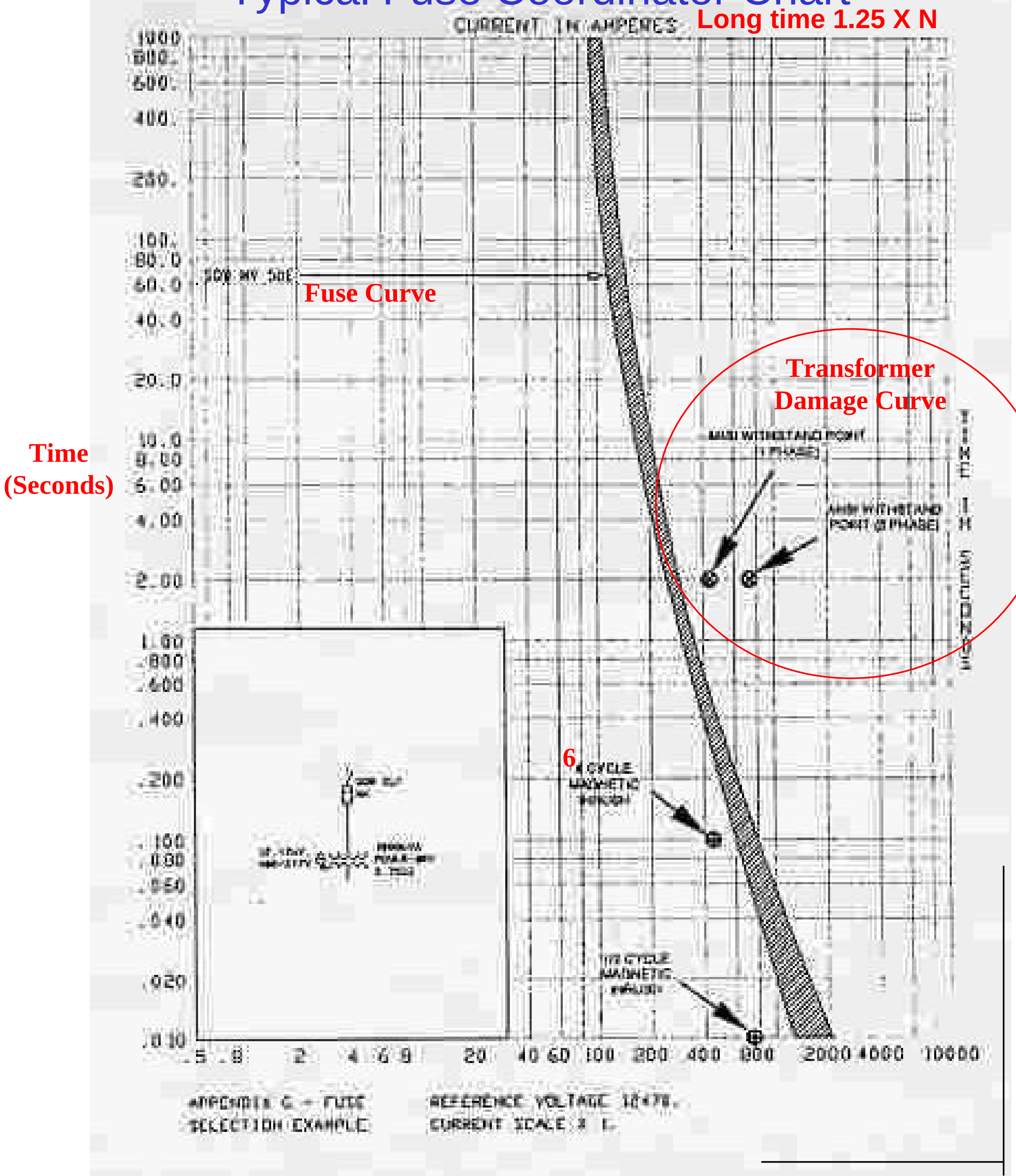
First Half Cycle RMS Equivalent Current

One-Tenth Second RMS Equivalent Current

Temperatures

+20°C and -40°C

Typical Fuse Coordinator Chart



Transformer Connections

Step-Down

Delta Connected Primary

Grounded Y Primary

Step-Up

Delta Connected Primary

Grounded Y Primary

Approximate Relationships for Inrush with no external impedance

Step-Down	**Peak Inrush Current**	
Delta Connected Primary	100%	19-25 x N
Grounded Y Primary	140%	30-35 x N
Step-Up	**Peak Inrush Current**	
Delta Connected Primary	170%	30-45 x N
Grounded Y Primary	250%	50-60 x N

Types of Transformers Studied

- Power Cast
- Uni Cast
- Power Dry
- Liquid Filled

RMS Equivalent Currents (XN) with no external impedance

Part I High Voltage Delta Connected Winding or Wye Winding to 3-Wire Source

Transformer Type	Peak Inrush (XN)		1st Half Cycle		1st Cycle		0.1 Seconds	
	20C	-40C	20C	-40C	20C	-40C	20C	-40C
Power Cast 80 Rise>1000kVA	23.9	24.1	16.9	17.1	13.4	13.6	9.6	10.0
34.5kV-200kV BIL-Cu	28.4	28.7	20.1	20.3	15.7	15.9	11.1	11.6
Power Cast 80 Rise< 750 kVA	25.4	25.8	18.0	18.3	14.4	14.6	10.3	11.1
Uni-Cast 100 Rise>1000kVA	23.0	23.3	16.3	16.4	13.0	13.2	9.2	9.6
Uni-Cast 100 Rise< 750 kVA	24.5	25.0	17.4	17.6	14.0	14.2	10.5	10.7
Pwr Dry 15KV 80 Rise>1000kVA	22.3	22.6	15.7	16.0	12.6	12.8	8.7	9.1
Pwr Dry 15KV150 Rise>1000kVA	19.1	19.4	13.5	13.8	10.8	11.0	7.0	7.4
Pwr Dry 95BIL150 Rise>1000kVA	18.3	18.6	13.0	13.2	10.3	10.5	7.1	7.5
Pwr Dry 5KV 150 Rise>1000kVA	22.4	22.8	15.8	16.1	12.5	12.8	7.9	8.5
Pwr Dry 15kV 80 Rise< 750 kVA	23.8	24.3	16.8	17.2	13.6	13.8	9.0	10.2
Pwr Dry 15kV150 Rise< 750 kVA	21.5	22.1	15.2	15.6	12.0	12.4	7.7	8.4
Pwr Dry 95BIL150 Rise< 750 kVA	19.7	20.1	13.9	14.2	10.8	11.1	7.2	7.9
Pwr Dry 5KV 150 Rise<750kVA	18.7	19.3	13.2	13.7	10.4	10.8	6.2	6.9
Liquid-Filled 65 Rise>1000kVA	18.2	18.5	12.8	13.1	10.3	10.6	6.9	7.4
High BIL-CU- low winding loss	18.6	18.9	13.2	13.3	10.7	10.8	7.7	8.1
Liquid-Filled 65 Rise< 750 kVA	23.3	23.8	16.5	16.8	13.2	13.5	9.0	9.7

RMS Equivalent Currents (XN) with No External Impedance

Part II High Voltage Grounded Wye Winding Connected to 4-Wire Source

Transformer Type	Peak Inrush (XN)		1st Half Cycle		1st Cycle		0.1 Seconds	
	20C	**-40C**	**20C**	**-40C**	**20C**	**-40C**	**20C**	**-40C**
Power Cast 80 Rise>1000kVA	32.9	33.3	23.3	23.5	18.5	18.8	13.2	13.8
34.5kV-200kV BIL-Cu	39.2	39.6	27.7	28.0	21.7	22.0	15.3	16.0
Power Cast 80 Rise< 750 kVA	35.1	35.6	24.8	25.2	19.8	20.2	14.2	15.3
Uni-Cast 100 Rise>1000kVA	31.7	32.1	22.4	22.7	17.9	18.2	12.6	13.3
Uni-Cast 100 Rise< 750 kVA	33.9	34.4	23.9	24.4	19.2	19.6	13.8	14.8
Pwr Dry 15kV 80 Rise>1000kVA	30.7	31.1	21.7	22.0	17.4	17.7	11.9	12.6
Pwr Dry 15kV150 Rise>1000kVA	26.4	26.8	18.6	19.0	14.9	15.2	9.6	10.3
Pwr Dry 95BIL150Rise>1000kVA	25.3	25.7	17.9	18.1	14.2	14.4	9.7	10.3
Pwr Dry 5KV 150 Rise>1000kVA	30.9	31.5	21.8	22.3	17.3	17.7	10.9	11.7
Pwr Dry 15kV 80 Rise< 750 kVA	32.9	33.4	23.2	23.7	18.7	19.1	13.0	14.1
Pwr Dry 15kV150 Rise< 750 kVA	29.7	30.4	21.0	21.5	16.6	17.1	10.6	11.6
Pwr Dry 95BIL150 Rise< 750 kVA	27.1	27.7	19.1	19.6	14.9	15.3	10.0	10.9
Pwr Dry 5KV 150 Rise<750kVA	25.8	26.6	18.3	18.8	14.3	14.9	8.5	9.5
Liquid-Filled 65 Rise>1000kVA	25.0	25.5	17.7	18.0	14.3	14.6	9.5	10.1
High BIL-CU- low winding loss	27.1	27.5	19.2	19.5	15.4	15.6	10.4	11.0
Liquid-Filled 65 Rise< 750 kVA	32.2	32.8	22.7	23.2	18.2	18.6	12.4	13.4

Part III   Low Voltage Grounded Wye Winding Connected to 4-Wire Source with No External Impedance

	RMS Equivalent Currents (XN)							
	20C	**-40C**	**20C**	**-40C**	**20C**	**-40C**	**20C**	**-40C**
Transformer Type	**Peak Inrush (XN)**		**1st Half Cycle**		**1st Cycle**		**0.1 Seconds**	
Power Cast 80 Rise>1000kVA	53.1	53.9	37.6	38.1	29.6	30.2	18.9	20.0
34.5kV-200kV BIL-Cu	68.3	68.9	48.3	48.7	37.6	38.1	25.4	26.3
Power Cast 80 Rise< 750 kVA	58.1	59.4	41.1	42.0	32.4	33.4	20.5	22.5
Uni-Cast 100 Rise>1000kVA	47.2	48.2	33.4	34.1	26.3	26.7	16.0	17.1
Uni-Cast 100 Rise>1000kVA	52.2	53.7	36.9	38.0	29.1	29.9	17.6	19.6
Power Dry 80 Rise>1000kVA	62.6	63.2	44.2	44.7	35.2	35.7	22.5	23.4
Power Dry 80 Rise< 750 kVA	67.6	68.7	47.7	48.6	38.0	38.9	24.1	25.9
Liquid-Filled 65 Rise>1000kVA	40.6	41.5	28.7	29.3	22.9	23.5	14.0	15.0
High BIL CU Primary, CU LV	44.6	45.5	31.5	32.2	25.0	25.6	14.8	15.9
Liquid-Filled 65 Rise< 750 kVA	55.6	56.8	39.3	40.2	31.3	32.1	20.3	22.0

Part IV Low Voltage Delta Connected Winding or Wye Winding Connected to 3-Wire Source with No External Impedance

			RMS Equivalent Currents (XN)					
Transformer Type	**Peak Inrush (XN)**		**1st Half Cycle**		**1st Cycle**		**0.1 Seconds**	
	20C	**-40C**	**20C**	**-40C**	**20C**	**-40C**	**20C**	**-40C**
Power Cast 80 Rise>1000kVA	38.6	39.2	27.3	27.7	21.5	21.9	13.7	14.5
34.5kV-200kV BIL-Cu	49.5	50.0	35.0	35.3	27.3	27.6	18.4	19.1.
Power Cast 80 Rise< 750 kVA	42.1	43.1	29.8	30.5	23.5	24.2	14.9	16.3
Uni-Cast 100 Rise>1000kVA	34.3	35.0	24.6	25.2	19.1	19.4	11.6	12.4
Uni-Cast 100 Rise< 750 kVA	37.8	38.9	27.1	28.0	21.1	21.7	12.8	14.2
Power Dry 80 Rise>1000kVA	45.5	45.9	32.1	32.5	25.6	26.0	16.3	17.0
Power Dry 80 Rise< 750 kVA	49.0	46.8	34.6	35.3	27.6	28.3	18.5	19.8
Liquid-Filled 65 Rise>1000kVA	29.6	30.3	20.9	21.3	16.7	17.1	10.2	10.9
High BIL CU Primary, CU LV	32.3	33.0	22.8	23.3	18.1	18.6	10.8	11.5
Liquid-Filled 65 Rise< 750 kVA	40.4	41.2	28.5	29.1	22.7	23.3	14.7	16.0

Inrush vs. Transformer Type With No External Impedance

Transformer Type	Temperature Rise	Peak Inrush
Power Cast	80	130%
Uni Cast	100	110%
Power Dry	80	120%
	150	100%
Liquid Filled	65	100%

Factors Influencing Inrush

Factor	Cause
Flux Density	Saturation
Volts per Turn	Air Core Reactance
kVA Size	Varies as $kVA^{-.25}$
Voltage Class	Impact on Volts/Turn
Winding Resistance/Core Loss Or External Resistance	Damping
Conductor	CU worse than AL

Acknowledgements

Transient Computer Program by

Jayant Patwardhan

Fusing Considerations by

Ermal Curd

Animation and Sound by

Vanessa Purefoy