Transformer Protection

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Power Transformer Protection

1. Protection Philosophies
2. Overvoltage Protection
3. Overcurrent and Thermal Protection
    a. Transformer Damage Curve
    b. Fuse Protection
    c. Overcurrent Relay Protection
    d. Differential Protection
    e. Thermal Protection
    f. Gas Pressure
4. Monitoring and On-Line Diagnostics

Power Transformer Protection

Transformer Protection Philosophies

1. Reasons to provide transformer protection
    a. Detect and Isolate Faulty Equipment
    b. Maintain System Stability
    c. Limit Damage
    d. Minimize Fire Risk
    e. Minimize Risk to Personnel

2. Factors Affecting Transformer Protection
    a. Cost of Repair
    b. Cost of Down Time
    c. Affects on the Rest of the System
    d. Potential to Damage Adjacent Equipment
    e. Length of Time to Repair or Replace

Transformer Protection Philosophies

3. Basic Tenets of Protection
    a. Speed
    b. Sensitivity
    c. Reliability
    d. Security

4. Applicable Standards
    a. C57.12.00 – IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
    b. C57.12.80 – IEEE Standard Terminology for Power and Distribution Transformers
    c. C57.109 - IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration
    d. C37.91 – IEEE Guide for Protecting Power Transformers
    e. C62.22 – IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

Transformer Overvoltage Protection

Types of Over Voltages

1. Temporary
   a. Power Frequency
   b. Relatively Long Duration (seconds to hours)
   c. Attributable to Ground Faults, Load Rejection, Low Frequency Resonance

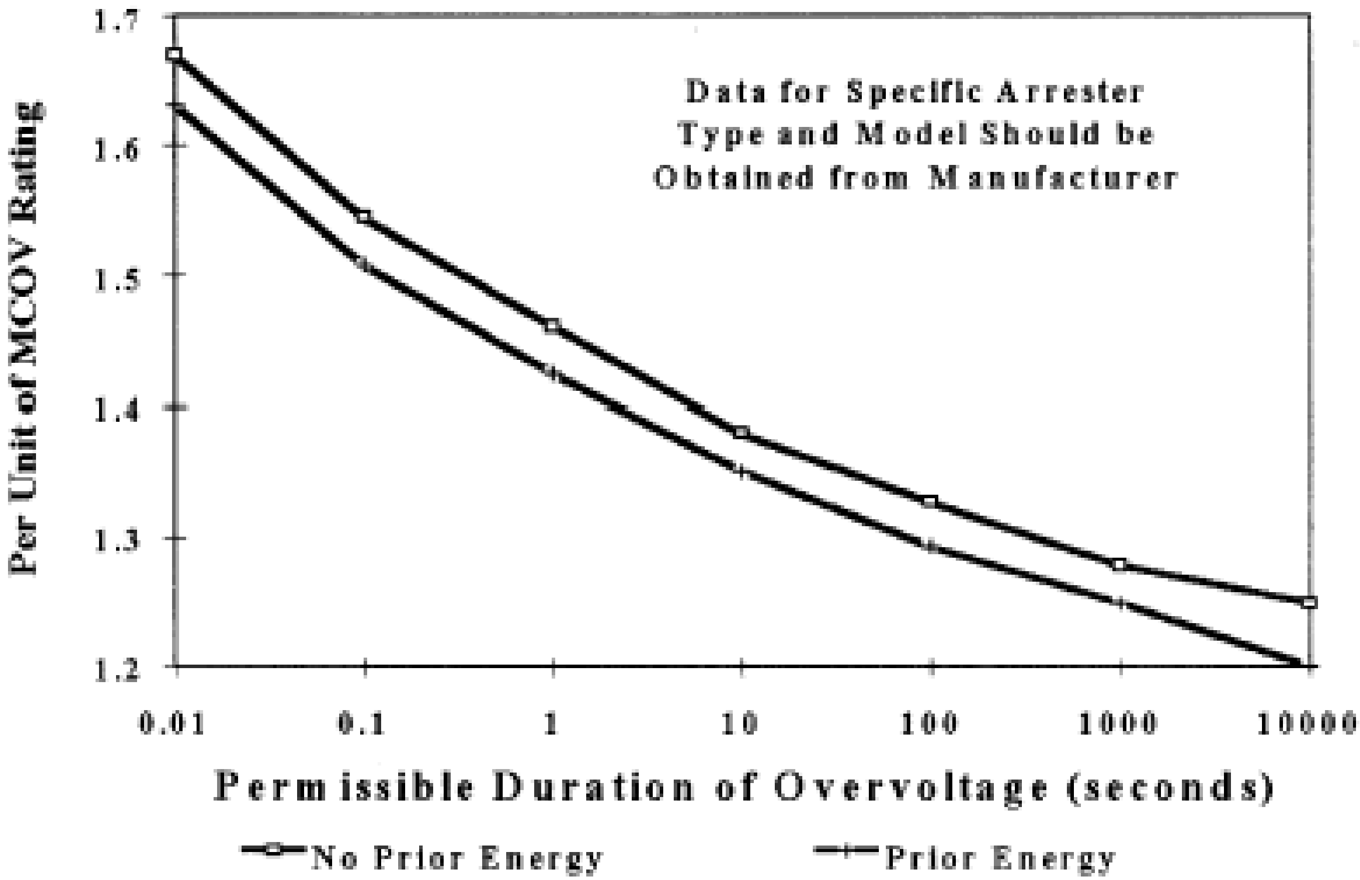
2. Transient
   a. Fast Rate of Rise
   b. Short Duration (microseconds to milliseconds)
   c. Attributable to Lightning, Switching, Flashover and Restrike Phenomena

Transformer Overvoltage Protection

Considerations for Overvoltage Protection

Temporary Overvoltage Levels and Duration
Equipment BIL
System Grounding

Transformer Overcurrent Protection



Transformer Overvoltage Protection

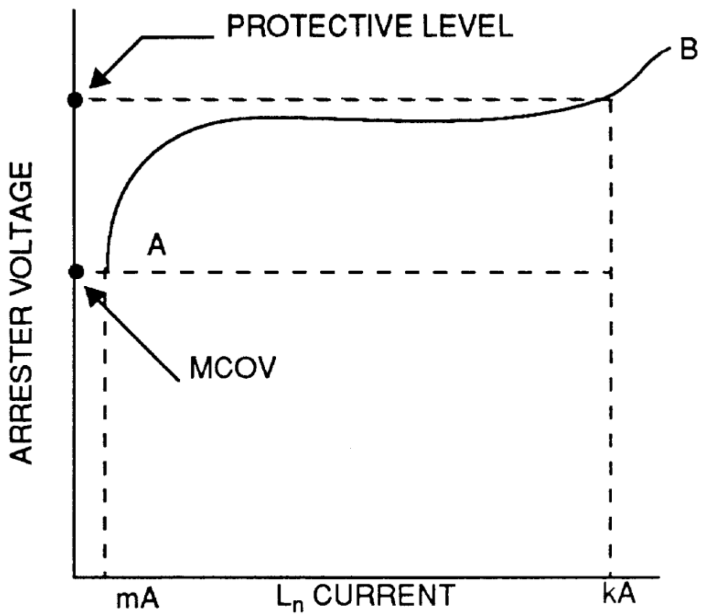
Equipment Overvoltage Withstand Ratings

Table 8 – High-voltage winding insulation levels of three-phase transformers

High-Voltage Ratings (V)	Basic Impulse Insulation Level (kV)	
	Distribution Transformers	Power Transformers
2 400	45	60
4 160	60	75
4 800	60	75
6 900	75	95
7 200	75	95
12 000	95	110
13 200	95	110
13 800	95	110
23 000	125	150
34 500	150	200
46 000	–	250
69 000	–	350
115 000	–	450
138 000	–	550
161 000	–	650
230 000	–	750

Transformer Overvoltage Protection

Gapless Metal Oxide Arrester Characteristics



(b)

Table 2a Polymer Station Arrester Characteristics									
				8/20 µs Maximum Discharge Voltage - kVcrest					
Rated Voltage kVrms	MCOV kVrms	0.5 µsec 10 kA Max IR-kVcrest	Switching Surge Maximum IR-kVcrest[1]	1.5 kA	3 kA	5 kA	10 kA	20 kA	40 kA
3	2.55	8.4	6.0	6.4	6.7	7.1	7.6	8.4	9.6
6	5.10	16.7	11.9	12.8	13.5	14.1	15.2	16.8	19.1
9	7.65	25.0	17.8	19.2	20.2	21.1	22.7	25.1	28.3
10	8.40	27.8	19.8	21.4	22.5	23.5	25.3	28.0	31.8
12	10.2	33.3	23.7	25.6	26.9	28.1	30.3	33.5	38.1
15	12.7	41.7	29.7	32.0	33.7	35.2	37.9	42.0	47.6
18	15.3	50.1	35.6	38.4	40.4	42.3	45.5	50.0	57.2
21	17.0	56.3	40.1	43.2	45.5	47.6	51.2	56.7	64.4
24	19.5	63.9	45.5	49.1	51.6	54.0	58.1	64.3	73.0
27	22.0	72.9	51.9	56.0	58.9	61.6	66.3	73.4	83.3
30	24.4	80.4	57.2	61.7	64.9	67.9	73.1	80.9	91.9
36	29.0	95.9	68.3	73.6	77.4	81.0	87.2	96.5	109.6
39	31.5	104.2	74.2	80.0	84.1	88.0	94.7	104.8	119.0
45	36.5	120.9	86.1	92.8	97.6	102.1	109.9	121.7	138.1
48	39.0	128.7	91.6	98.8	103.9	108.7	117.0	129.5	147.1
54	42.0	144.4	102.8	110.9	116.6	122.0	131.3	145.3	165.0
60	48.0	163.5	116.4	125.5	132.0	138.0	148.6	164.5	186.8
66	53.0	179.9	128.0	138.1	145.2	151.8	163.5	181.0	205.5
72	57.0	191.8	136.6	147.3	154.9	162.0	174.4	193.1	219.2
90	70.0	241.8	172.1	185.6	195.2	204.2	219.8	243.3	276.3
96	76.0	257.4	183.2	197.6	207.8	217.4	234.0	259.0	294.1
108	84.0	288.9	205.6	221.8	233.2	244.0	262.6	290.7	330.1
120	98.0	326.9	241.3	251.0	263.9	276.1	297.2	329.0	373.6
132	106.0	362.7	267.7	278.5	292.8	306.3	329.7	365.0	414.4
144	115.0	386.1	285.0	296.5	311.7	326.1	351.0	388.6	441.2

Transformer Overvoltage Protection

GENERAL ELECTRIC

TRANSFORMER

NO. CLASS OA/FA/FOA THREE PHASE 60 HERTZ

CAUTION! INSTRUCTION BOOK INSIDE BOX
BEFORE INSTALLING OR OPERATING READ INSTRUCTIONS

VOLTAGE RATING 115000-13800Y/7970
KVA RATING 33000 CONTINUOUS 65 C RISE SELF COOLED
KVA RATING 44000 CONTINUOUS 65 C RISE FORCED AIR
KVA RATING 55000 CONTINUOUS 65 C RISE FORCED OIL-AIR

P.O. NO. 497801

IMPEDANCE VOLTS % 115000-13800Y VOLTS AT 33000KVA

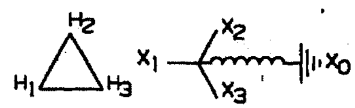
HV WINDING CONNECTION				
VOLTS	TAP CHANGER POS	AMP AT 33000 KVA	AMP AT 44000 KVA	AMP AT 55000 KVA
120000	1	159	213	265
117500	2	162	216	270
115000	3	166	221	275
112500	4	169	225	282
110000	5	173	231	289

FOR STEP DOWN OPERATION

LV WINDING CONNECTION			
VOLTS	AMP 33000 KVA	AMP 44000 KVA	AMP 55000 KVA
13800	1380	1840	2300

ITEM	BIL -KV
H_1 H_2 H_3	450
X_0 X_1 X_2 X_3	110

ALL WINDINGS COPPER



VECTOR DIAGRAM

APPROXIMATE WEIGHTS IN POUNDS

TOTAL	165100
UNTANKING	86200
TANK AND FITTINGS	33300
MAIN TANK TYPE II OIL 6120 GAL	45600

LIQUID LEVEL CHANGES 1.1 INCH PER 10 C CHANGE IN LIQUID TEMPERATURE.
LIQUID LEVEL BELOW TOP SURFACE OF THE HIGHEST POINT OF MANHOLE FLANGE AT 25 C IS 12.1 INCHES.
MAXIMUM OPERATING PRESSURE OF LIQUID PRESERVATION SYSTEM 7.5 POUNDS POSITIVE TO 5.0 POUNDS NEGATIVE.
TANK SUITABLE FOR 14.7 POUNDS VACUUM FILLING.
CT-A IS FOR USE WITH WINDING TEMPERATURE EQUIPMENT.
CT'S 1,2,3,5,6,7,9,10,11 ARE 1200/5 AMP.
(ACC CLASS 10C800).
CT'S 21,22,23 ARE 3000/5 AMP. (METERING ACC. 0.3B1.8).
CT'S 25,26,27,29,30,31 ARE 3000/5 AMP.

DATE OF MANUFACTURE ______

SOUND LEVEL GUARANTEED
OA : 61 DB
FA : 65 DB
FOA : 66 DB

Transformer Overvoltage Protection

Transformer Primary Rated Line to Ground Voltage:

$$\frac{115kV}{\sqrt{3}} = 66.4kV$$

Transformer Secondary Rated Line to Ground Voltage:

$$\frac{13.8kV}{\sqrt{3}} = 7.97kV$$

However – Note that the secondary neutral is reactor grounded

Transformer Overvoltage Protection

Table 1 Typical Arrester Ratings for System Voltages					
	Arrester Rating (kV)			Arrester Rating (kV)	
Nominal Sytem L-L Voltage (kV)	Grounded Neutral Circuits	High Impedance Grounded, Ungrounded, or Temporarily Ungrounded	Nominal System L-L Voltage (kV)	Grounded Neutral Circuits	High Impedance Grounded, Ungrounded, or Temporarily Ungrounded
2.4	2.7	3.0	69	54	--
				60	--
4.16	3.0	--		--	66
	4.5	4.5		--	72
		5.1	115	90	--
4.8	4.5	--		90	--
	5.1	5.1		108	108
	--	6.0		--	120
			138	108	--
6.9	6.0	--		120	--
	--	7.5		--	132
	--	8.5		--	144
12.47	9.0	--	161	120	--
	10	--		132	--
	--	12		144	144
	--	15		--	168
13.2,13.8	10	--	230	172	--
	12	--		180	--
	--	15		192	--
	--	18		--	228
23, 24.94	18	--		--	240
	21	--	345	258	--
	24	24		264	--
	--	27		276	--
34.5	27	--		288	288
	30	--		294	294
	--	36		300	300
	--	39		312	312
46	39	--	400	300	--
	--	48		312	--
				336	--
				360	--

Transformer Overvoltage Protection

Table 2a Polymer Station Arrester Characteristics

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6	5.10	16.7	11.9	12.8	13.5	14.1	15.2	16.8	19.1
9	7.65	25.0	17.8	19.2	20.2	21.1	22.7	25.1	28.3
10	8.40	27.8	19.8	21.4	22.5	23.5	25.3	28.0	31.8
12	10.2	33.3	23.7	25.6	26.9	28.1	30.3	33.5	38.1
15	12.7	41.7	29.7	32.0	33.7	35.2	37.9	42.0	47.6
18	15.3	50.1	35.6	38.4	40.4	42.3	45.5	50.0	57.2
21	17.0	56.3	40.1	43.2	45.5	47.6	51.2	56.7	64.4
24	19.5	63.9	45.5	49.1	51.6	54.0	58.1	64.3	73.0
27	22.0	72.9	51.9	56.0	58.9	61.6	66.3	73.4	83.3
30	24.4	80.4	57.2	61.7	64.9	67.9	73.1	80.9	91.9
36	29.0	95.9	68.3	73.6	77.4	81.0	87.2	96.5	109.6
39	31.5	104.2	74.2	80.0	84.1	88.0	94.7	104.8	119.0
45	36.5	120.9	86.1	92.8	97.6	102.1	109.9	121.7	138.1
48	39.0	128.7	91.6	98.8	103.9	108.7	117.0	129.5	147.1
54	42.0	144.4	102.8	110.9	116.6	122.0	131.3	145.3	165.0
60	48.0	163.5	116.4	125.5	132.0	138.0	148.6	164.5	186.8
66	53.0	179.9	128.0	138.1	145.2	151.8	163.5	181.0	205.5
72	57.0	191.8	136.6	147.3	154.9	162.0	174.4	193.1	219.2
90	70.0	241.8	172.1	185.6	195.2	204.2	219.8	243.3	276.3
96	76.0	257.4	183.2	197.6	207.8	217.4	234.0	259.0	294.1
108	84.0	288.9	205.6	221.8	233.2	244.0	262.6	290.7	330.1
120	98.0	326.9	241.3	251.0	263.9	276.1	297.2	329.0	373.6
132	106.0	362.7	267.7	278.5	292.8	306.3	329.7	365.0	414.4
144	115.0	386.1	285.0	296.5	311.7	326.1	351.0	388.6	441.2

Transformer Overcurrent Protection

Protect Transformer from Overloads

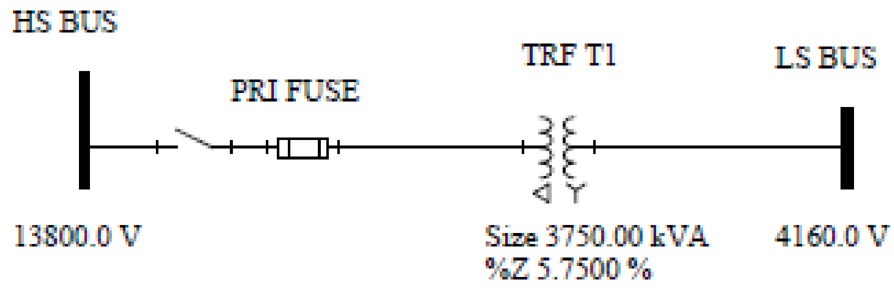
C57.91 - IEEE Guide for Loading Mineral-Oil-Immersed Transformers

Protect Transformer from Internal Faults

Protect Transformer from Through Faults

C57.109 - IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration

Transformer Overcurrent Protection



Transformer Overcurrent Protection

- Rated Current

  Rated kVA and Voltage plus adjustments from C57.91

- Inrush Current

  12x Rated Current for 0.1 sec

- Short Circuit Currents

  From system fault study, available SCC on Primary, Sec based on Trf. Z

- Transformer Damage Curve

  Calculated per C57.109

Transformer Overcurrent Protection

Rated Transformer Primary Current:

$$\frac{3750000}{\sqrt{3}*13800} = 157A$$

Rated Transformer Secondary Current:

$$\frac{3750000}{\sqrt{3}*4160} = 520A$$

Transformer Inrush Current:

$$157*12 = 1884A$$

Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Table 1—Transformer categories

Category	Single phase (kVA)	Three phase (kVA)
I*	5 to 500	15 to 500
II	501 to 1667	501 to 5000
III	1668 to 10 000	5001 to 30 000
IV	Above 10 000	Above 30 000

*Category I shall include distribution transformers manufactured in accordance with IEEE Std C57.12.20-1988 up through 500 kVA, single phase or three phase. In addition, autotransformers of 500 equivalent two-winding kilovoltamperes or less, which are manufactured as distribution transformers in accordance with IEEE Std C57.12.20-1988, shall be included in Category I, even though their nameplate kVA may exceed 500.

NOTE—All kilovoltampere ratings are minimum nameplate kVA for the principal windings.

Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Table 2—Transformer short-time thermal load capability

Time	Times rated current
2 s	25.0
10 s	11.3
30 s	6.3
60 s	4.75
5 min	3.0
30 min	2.0

$$i^2 t = 1250$$

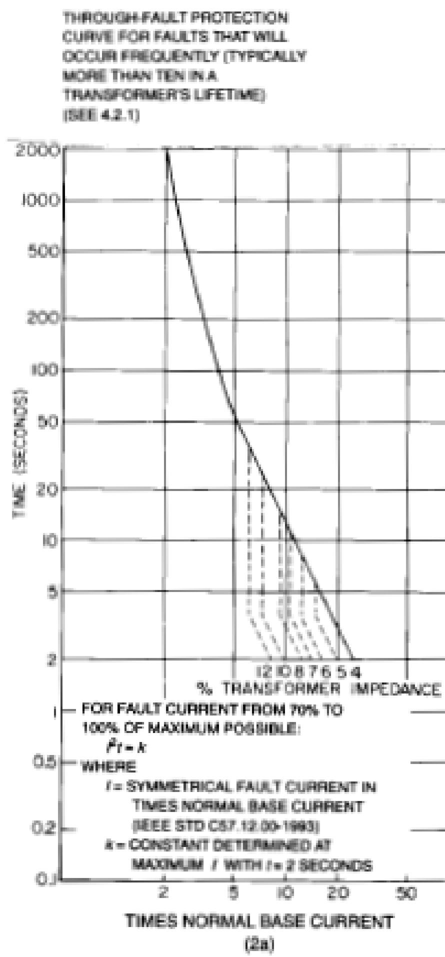
Transformer Overcurrent Protection

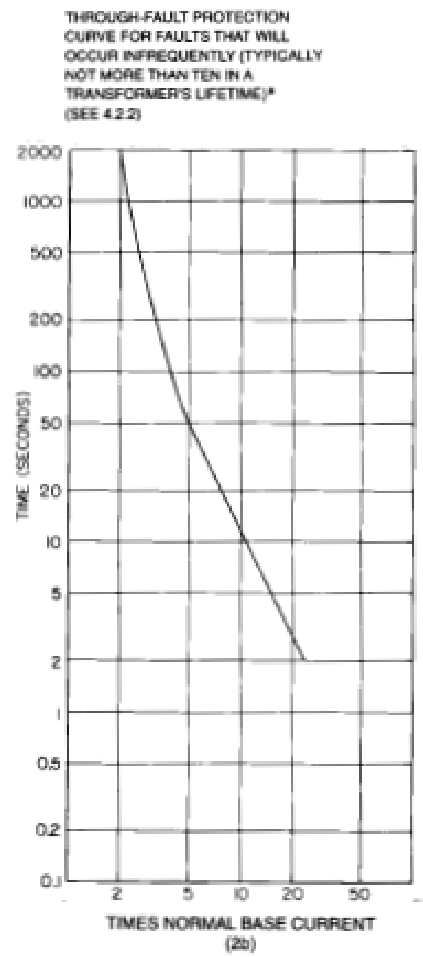
Transformer Damage Curve – C57.109

Figure 2—Category II transformers
501 to 1667 kVA single-phase
501 to 5000 kVA three-phase

$$i^2 t = K$$

$$K = \frac{2}{Z_T^{\ 2}}$$





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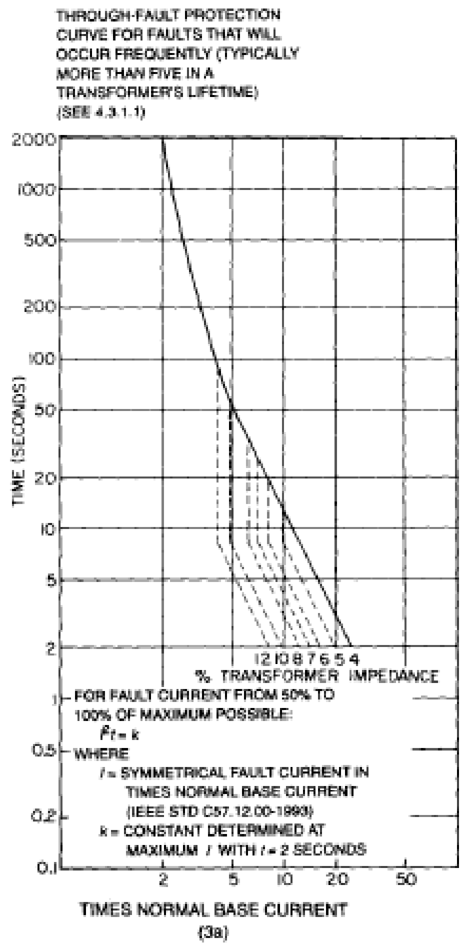
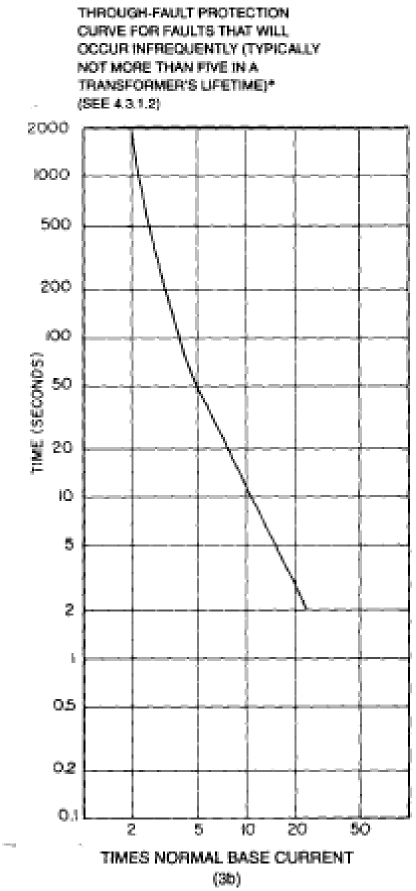
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Figure 3—Category III transformers
1668 to 10 000 kVA single-phase
5001 to 30 000 KVA three-phase





*This curve may also be used for backup protection where the transformer is exposed to frequent faults normally cleared by high-speed relaying.

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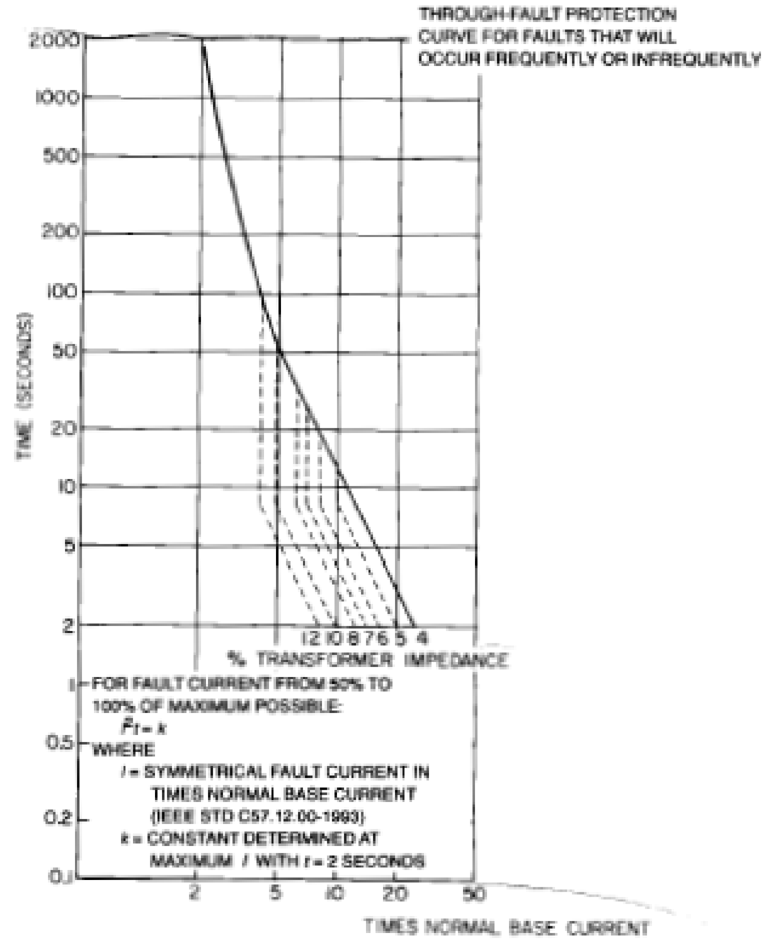
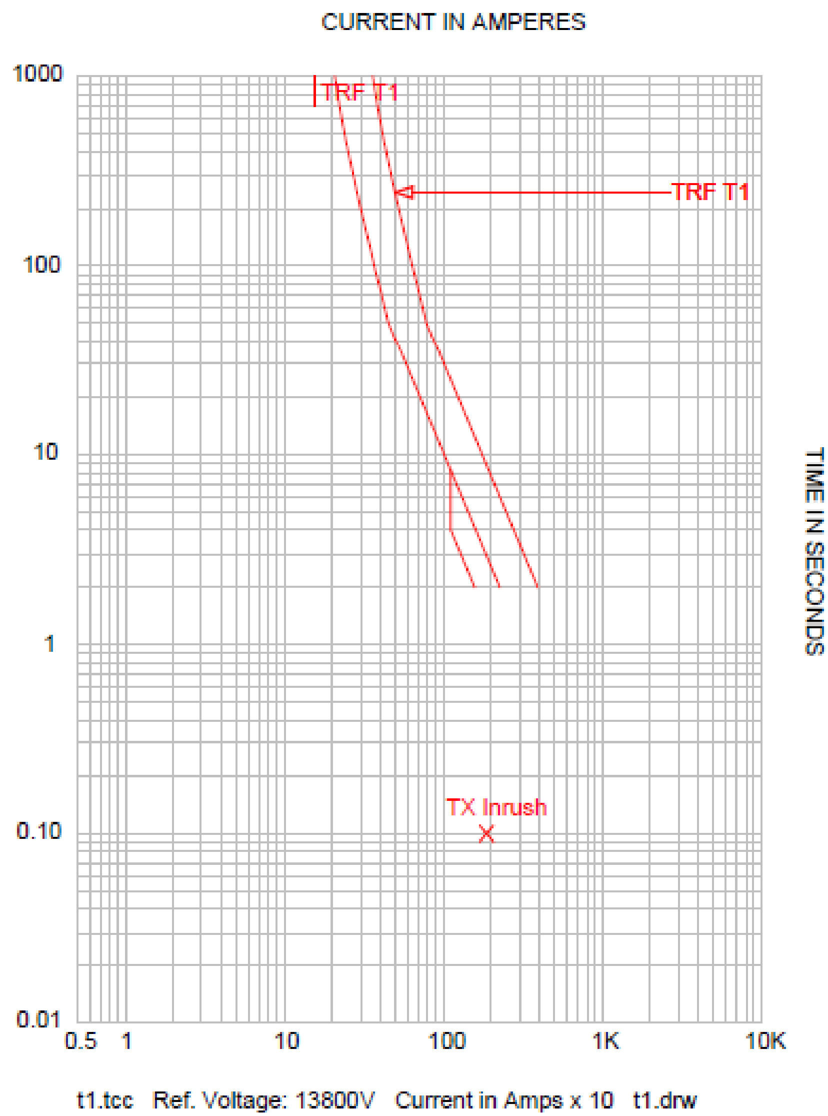
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Figure 4—Category IV transformers
above 10 000 kVA single-phase
above 30 000 kVA three-phase



Transformer Overcurrent Protection



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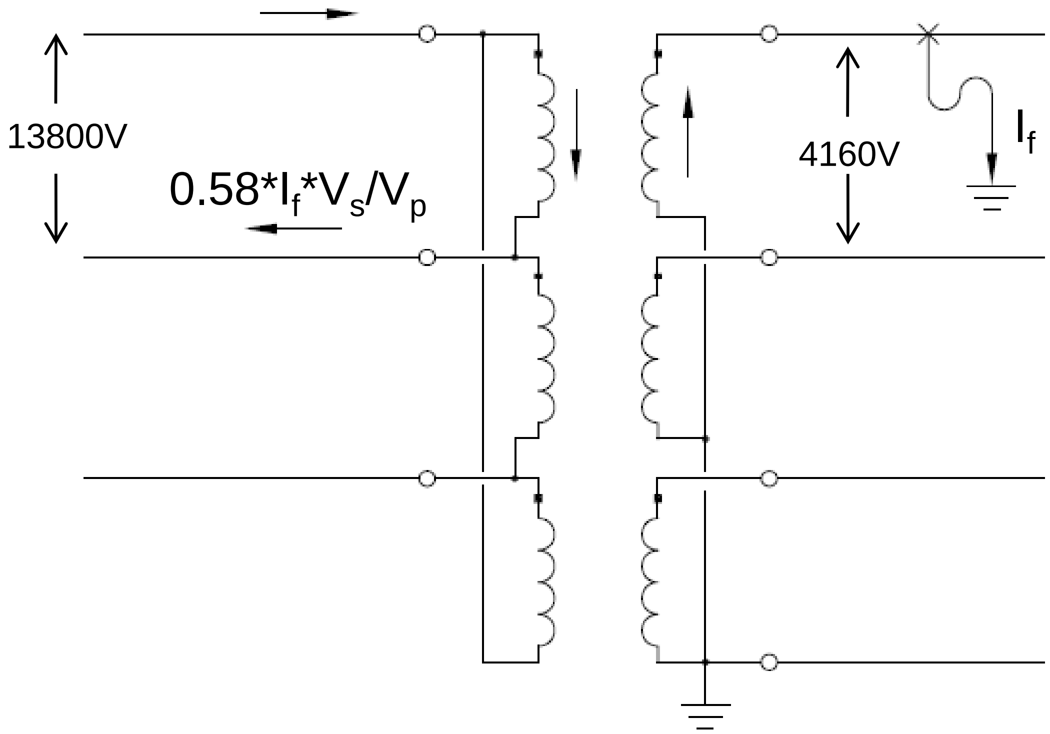
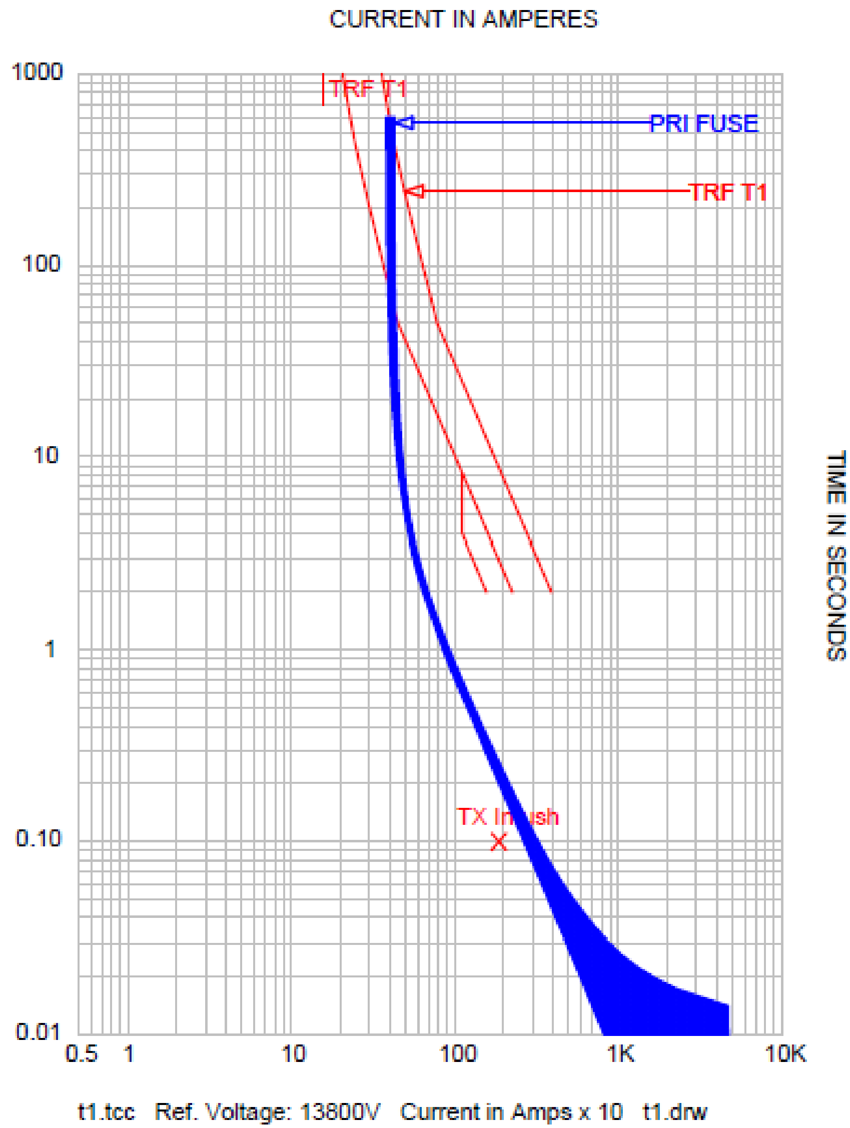
Transformer Overcurrent Protection

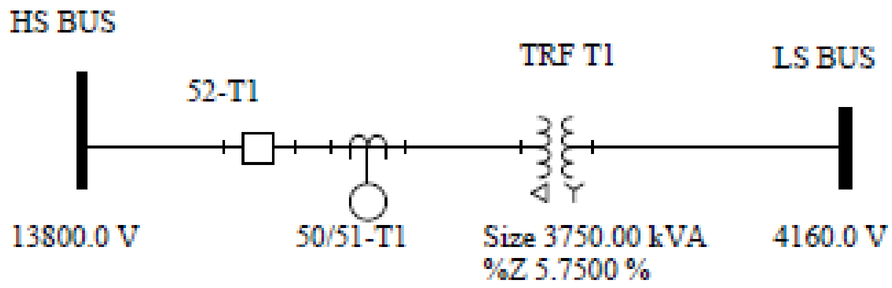
Unbalanced Fault Through Delta-Wye Transformer



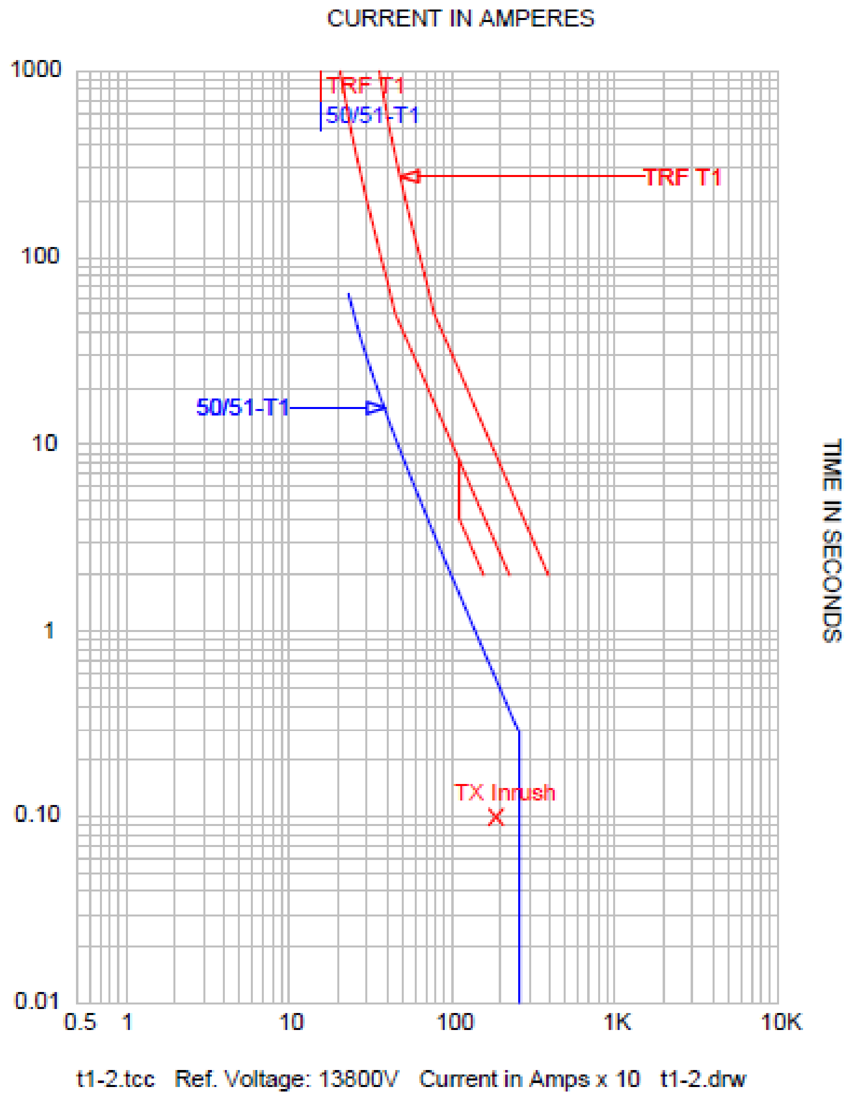
Transformer Overcurrent Protection



Transformer Overcurrent Protection

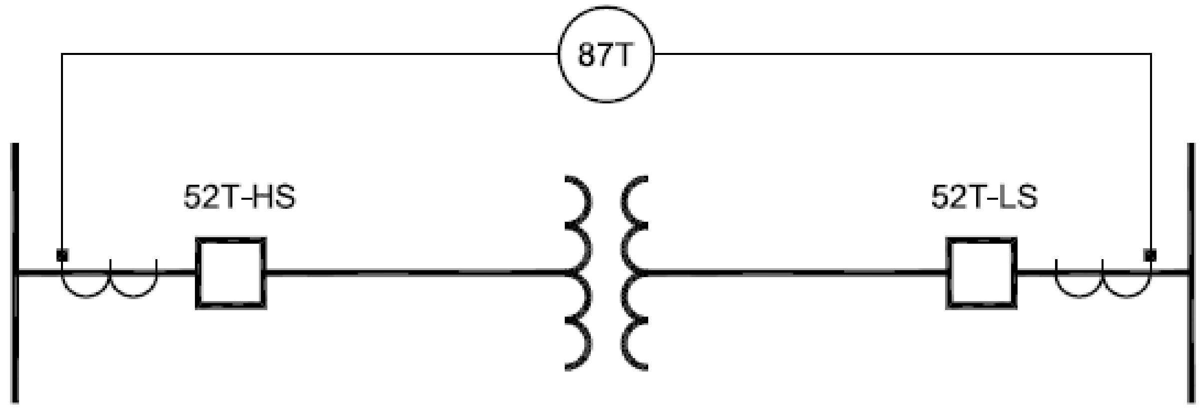


Transformer Overcurrent Protection



Transformer Overcurrent Protection

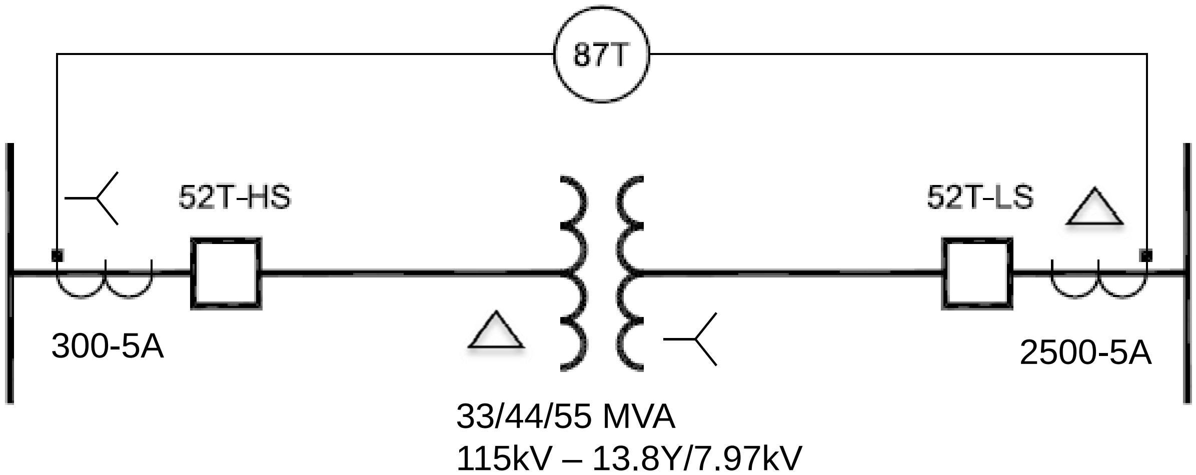
Transformer Differential Protection



High Speed, Sensitive Protection for Internal Faults
Looks at current flowing into and out of zone
Unequal currents means fault in the zone

Transformer Overcurrent Protection

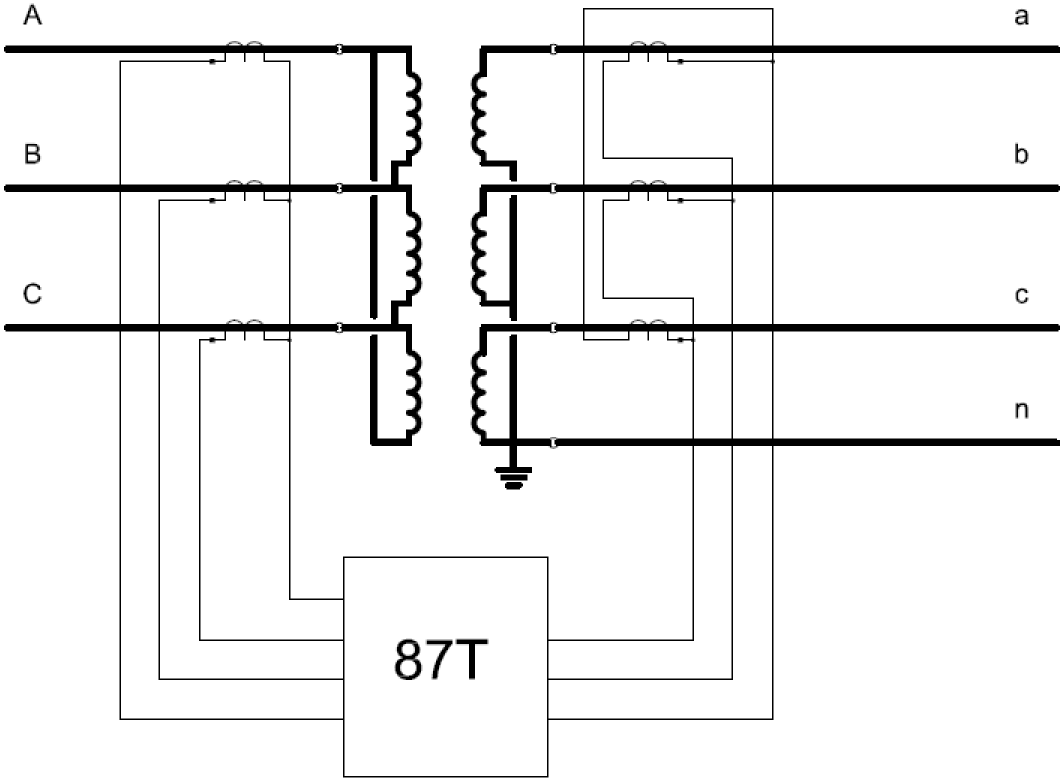
Special Considerations for Transformer Differential Relays



- Different Currents at Zone Boundaries
- Typically Have a 30º Phase Shift from Primary to Secondary
- Usually Have Mismatch in CT secondary currents, especially w/ LTC's
- Primary and Secondary CT's may have Different Saturation Characteristics
- Have to Worry About Transformer Inrush Current

Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
Traditional Method w/ Wye-Delta Connected CT's



Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
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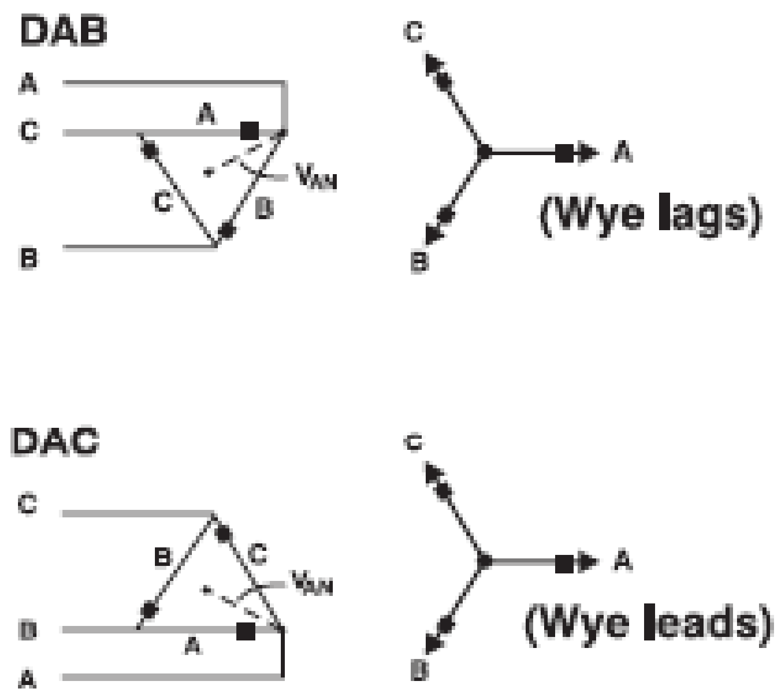
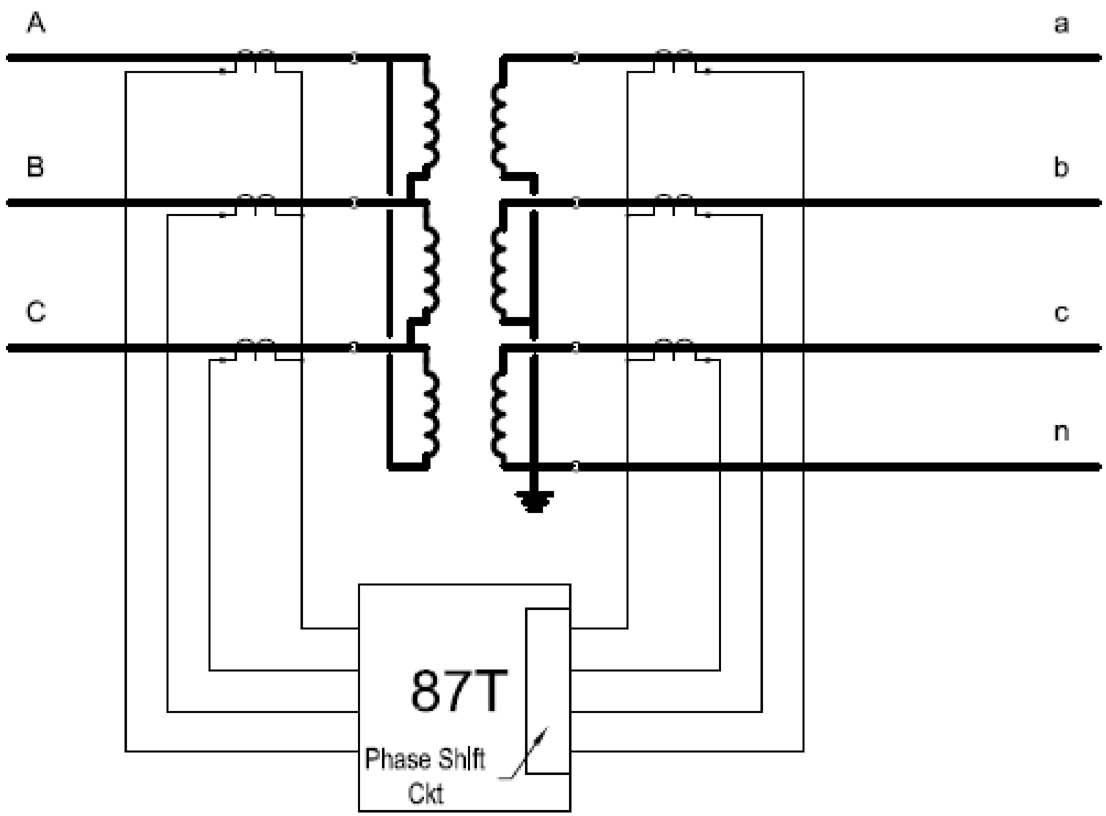


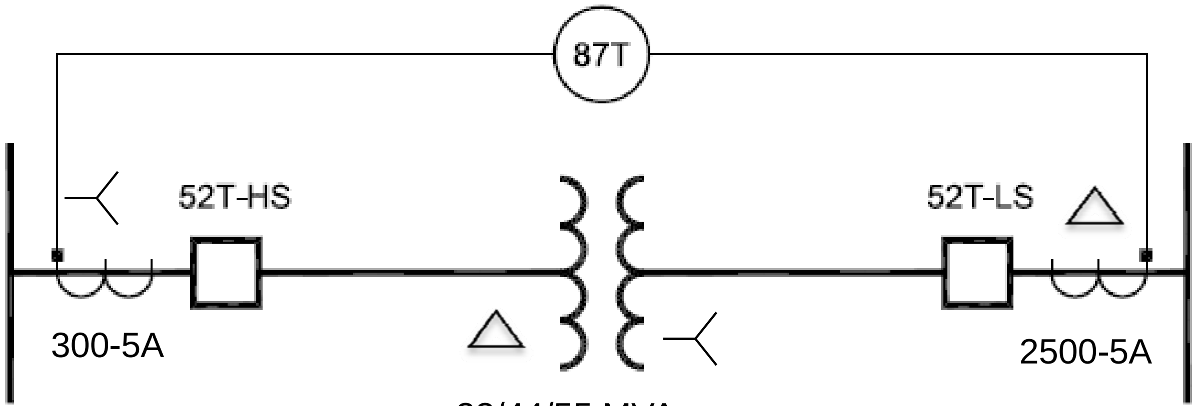
Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
New Method w/ Wye Connected CT's and Phase Shift in Relay



Transformer Overcurrent Protection

Current Mismatch, Restraint, and Slope



$$I_P = \frac{55000000}{115000 * \sqrt{3}} = 276.1A$$

$$I_{PRel} = 276.1A * \frac{5}{300} = 4.61A$$

$$I_S = \frac{55000000}{13800 * \sqrt{3}} = 2301A$$

For Wye Connected CT's

$$I_{SRel} = 2301A * \frac{5}{2500} = 4.60A$$

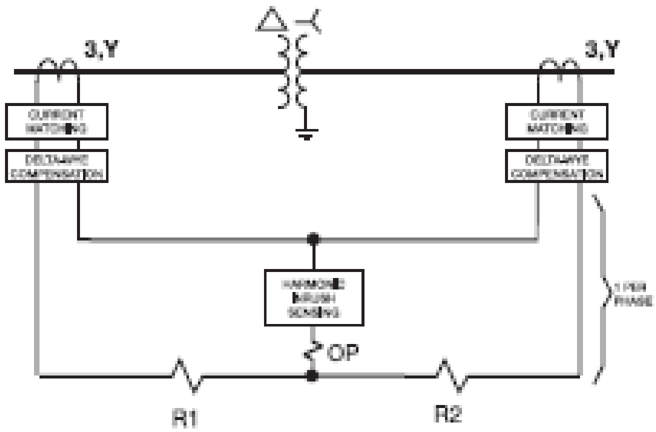
For Delta Connected CT's

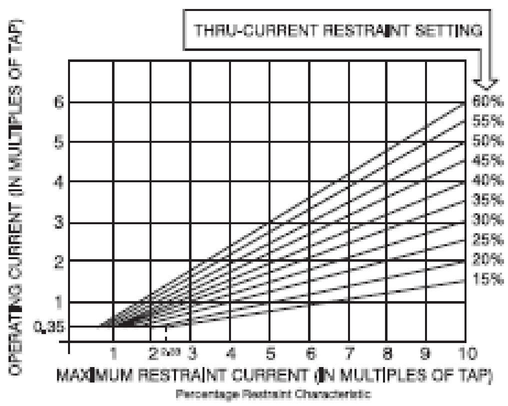
$$I_{SRel} = 2301A * \frac{5}{2500} * \sqrt{3} = 7.97A$$

Transformer Overcurrent Protection

Current Mismatch, Restraint, and Slope

- Older Style Relays Had Fixed Taps
- New Numerical Relays Have Wider Range of Tap Settings
- All bets off for LTC's
- Quality and location of CT's can affect saturation differently
- Transformer Differential Relays Use Restraint Coil to Compensate



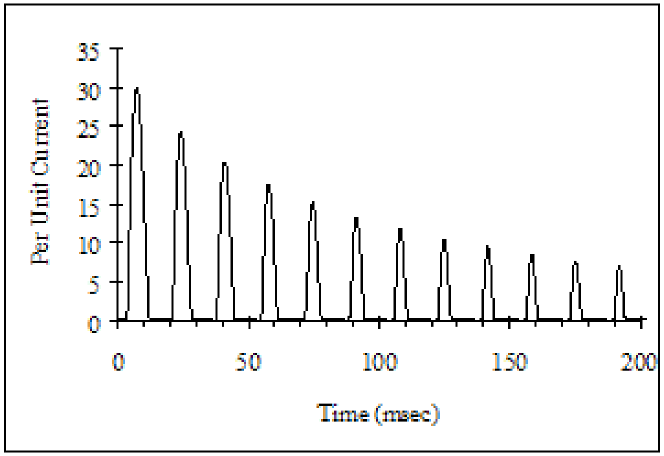


- Slope: Ratio of Operating Current to Restraint Current

Transformer Overcurrent Protection

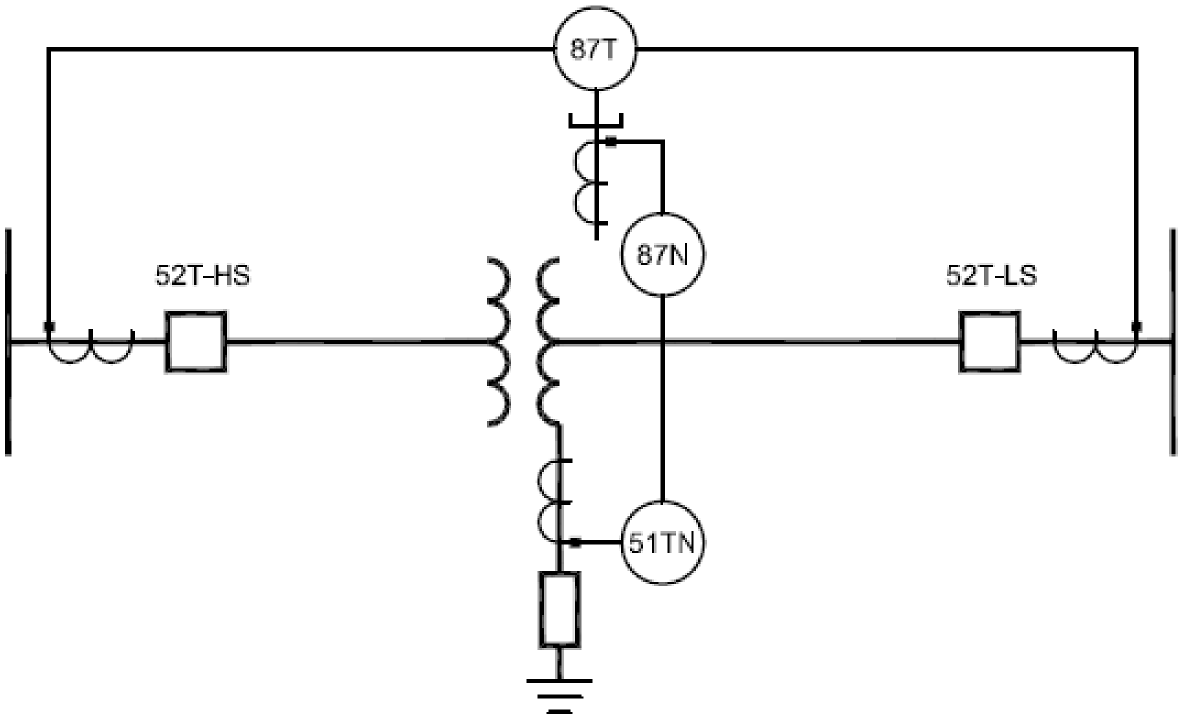
Inrush Current

- Caused by residual flux in transformer core
- Current Flows in One Set of Windings (typically the Primary) which could fool differential relays
- Characterized by DC offset and high 2nd harmonic content.
- If unloaded or lightly loaded, can also have high 5th harmonic content
- Transformer Differential Relays utilize Harmonic Filters to discriminate between Inrush Currents and Internal Faults



Transformer Overcurrent Protection

Ground Fault Sensing



Transformer Overcurrent Protection

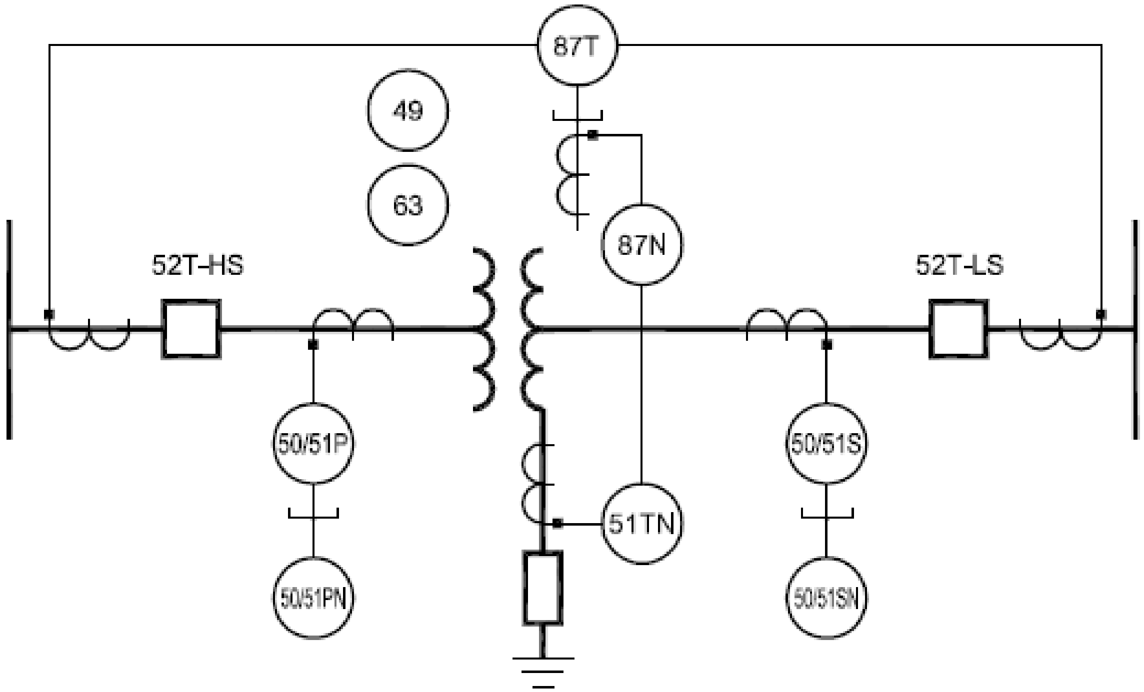
Advantages of Newer Style Numerical Relays

Transformer Overcurrent Protection

Advantages of Newer Style Numerical Relays

- Can use Wye Connected CT's for All Winding Connections
- Low Burden – Minimize CT Saturation Issues
- Wide Range of Pickups Settings – Minimize CT Mismatch Problems
- Adjustable Slop Characteristics
- Restrained and Unrestrained Differential Elements
- Typically have other functions built in such as:
  - Primary and Secondary Time and Inst OC Functions
  - Restricted Earth Fault Element
  - Thermal Element (ANSI Device 49)
- Typically include metering, fault/event recording, and communications

Other Transformer Protection



Other Transformer Protection

Sudden Pressure Relay

Buchholz Relay

ANSI Device 63
Sudden Pressure or Rate of Rise Relay

- Sudden Pressure or Rate of Rise Relay Applied on Sealed Tank Designs >5 MVA
- Detects rapid changes in tank pressure due to decomposition of transformer oil by an arc
- Designed to ignore slow changes in tank pressure due to thermal cycling.

Gas Accumulator (Buchholz) Relay

- Applied on Conservator Tank Designs
- Installed in Pipe connecting Main and Aux Tanks
- Trips for Rapid Gas Flow to Conservator Tank
- Alarms for Slow Flow

Transformer Monitoring

Standard Gauges and Indicators

- Liquid Level
- Tank Pressure
- Oil Temperature
- Hot Spot Temperature
- Gauges have contacts which can be brought back to SCADA

LTC Controls

- LTC Position
- LTC Malfunction

Fan/Pump Controls

- Fan/Pump Operating Stages
- Fan/Pump Malfunction

Transformer Monitoring

On-Line Water in Oil Monitoring

On-Line Dissolved Gas Monitoring

On-Line Acoustical and Partial Discharge Monitoring