Regional Technical Seminar

Factory Testing

Transformer Regional Technical Seminar

Austin, TX

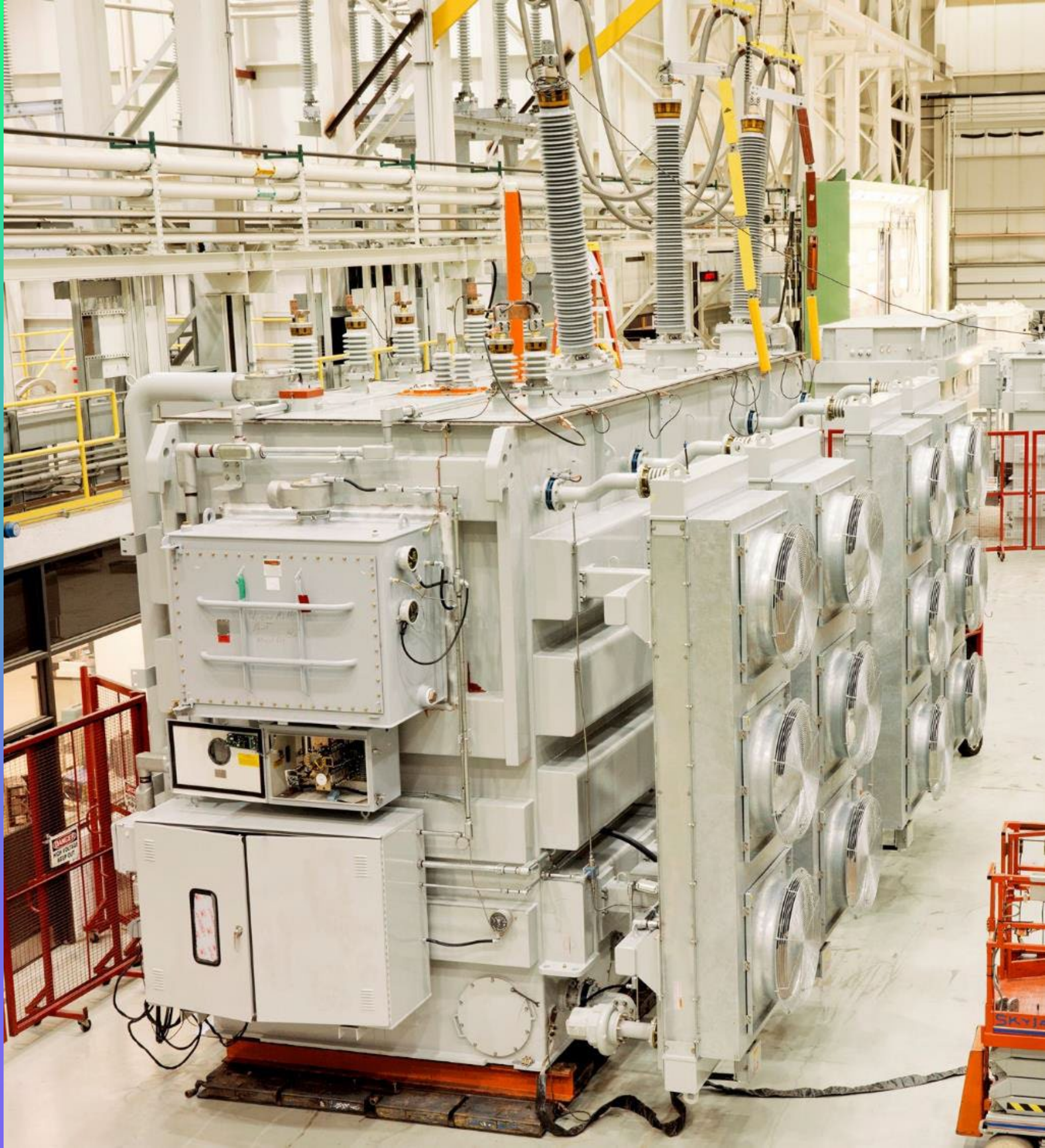
October 1, 2024

a prolec ge company

Joshua Jordan
Senior Electrical Design Engineer

Josh Jordan joined Prolec GE Waukesha in 2017 as an intern for the electrical design team in Waukesha. He has been designing medium and large power/EHV production order transformers since 2019, with ratings up to 712 MVA, 345kV class, 1175kV BIL and up to 800 MVA for quotation requests. Josh holds a Bachelor of Science Degree in Electrical Engineering from the University of Milwaukee School of Engineering.

waukesha
a prolec ge company



Reasons for Testing

- Compliance with user specifications
- Compliance with applicable industry standards
- Assessment of quality and reliability
- Verification of design calculations

waukesha
a prolec ge company

IEEE SA
STANDARDS ASSOCIATION

STANDARDS

IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.12.00™-2021
(Revision of IEEE Std C57.12.00-2015)

IEEE

IEEE SA
STANDARDS ASSOCIATION

STANDARDS

IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.12.90™-2021
(Revision of IEEE Std C57.12.90-2015)

IEEE

- C57.12.00 and C57.12.90 are two most commonly used transformer IEEE standards
- Both these standards got released in early 2022, with revision date of 2021.

IEEE C57.12.00-2021 Table 17

Routine Tests

Routine tests shall be made on every transformer to verify that the product meets the design specifications

Design Tests

Design tests shall be made to determine the adequacy of the design of a particular type, style, or model of transformer or its component parts. Test data from previous similar designs may be used for current designs, where appropriate. Once made, the tests need not be repeated unless the design is changed to modify performance.

Other Tests

Other tests are identified in product specifications and may be specified by the purchaser in addition to routine tests

Class I and Class II Power Transformers

	Nominal System Voltage (kV)	Top Nameplate Rating (KVA)
Class I	< 69 kV = 69 kV	Any <10,000 – 1φ <15,000 – 3φ
Class II	≥115 kV ≥69 kV < 115kV	Any ≥10,000 – 1φ ≥15,000 – 3φ

Preliminary Testing

Preliminary Testing

Tests	Class I	Class II
Voltage Ratio	Routine	Routine
Insulation Power factor	Routine	Routine
Insulation Resistance	Routine	Routine
1Φ Excitation test	Waukesha Routine	Waukesha Routine
CT Ratio & Polarity	Waukesha Routine	Waukesha Routine
Control Wiring Checks & Hi-pot	Routine	Routine
Auxiliary Losses	Waukesha Routine	Routine

Preliminary Tests

Voltage Ratio Test

- Performed with ratio-meter (TTR) based on voltage comparison principle to check that windings are wound with correct turns including tapped turns
- Low voltage is applied to HV winding and voltage measured across LV/other winding is fed back to ratio-meter which displays the applied/measured voltage ratio (= turns ratio)
- Turns ratio is compared with voltage ratio requirement to meet tolerance of +/- 0.5%

Taps		Nameplate	Measured Values			%Err from Nameplate		
HV	XV		ØA	ØB	ØC	ØA	ØB	ØC
A	N	9.513	9.5236	9.5236	9.5233	-0.11	-0.11	-0.11
B	N	9.284	9.2901	9.2899	9.2910	-0.07	-0.06	-0.08
C	N	9.054	9.0581	9.0580	9.0592	-0.05	-0.04	-0.06
D	N	8.824	8.8259	8.8263	8.8263	-0.02	-0.03	-0.03
E	N	8.595	8.5955	8.5927	8.5927	-0.01	+0.03	+0.03

Taps		Nameplate	Measured Values			%Err from Nameplate		
HV	XV		ØA	ØB	ØC	ØA	ØB	ØC
C	16R	8.231	8.2384	8.2403	8.2376	-0.09	-0.11	-0.08
C	15R	8.276	8.2873	8.2847	8.2873	-0.14	-0.11	-0.14
C	14R	8.325	8.3349	8.3312	8.3344	-0.12	-0.07	-0.11
C	13R	8.375	8.3802	8.3798	8.3804	-0.06	-0.06	-0.06
C	12R	8.422	8.4286	8.4288	8.4270	-0.08	-0.08	-0.06
C	11R	8.470	8.4780	8.4771	8.4758	-0.09	-0.08	-0.07
C	10R	8.521	8.5278	8.5269	8.5278	-0.08	-0.07	-0.08
C	9R	8.570	8.5784	8.5752	8.5784	-0.10	-0.06	-0.10
C	8R	8.623	8.6298	8.6271	8.6292	-0.08	-0.05	-0.07
C	7R	8.673	8.6799	8.6786	8.6790	-0.08	-0.06	-0.07
C	6R	8.727	8.7331	8.7302	8.7335	-0.07	-0.04	-0.07
C	5R	8.778	8.7836	8.7834	8.7832	-0.06	-0.06	-0.06
C	4R	8.833	8.8374	8.8375	8.8373	-0.05	-0.05	-0.05
C	3R	8.889	8.8916	8.8914	8.8919	-0.03	-0.03	-0.03
C	2R	8.942	8.9467	8.9462	8.9467	-0.05	-0.05	-0.05
C	1R	8.996	9.0026	9.0008	9.0021	-0.07	-0.05	-0.07

CT Ratio and Polarity Test

- Verify Polarity (& also Ratio) and wiring to control box

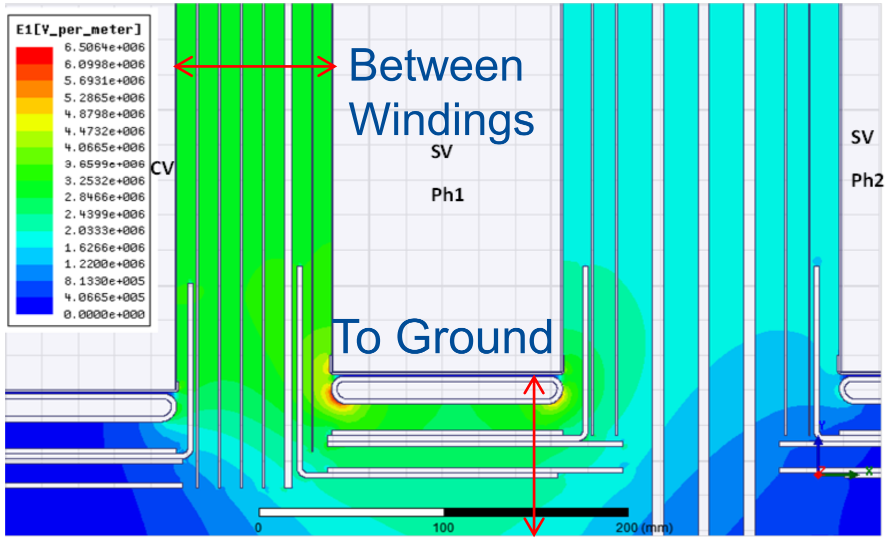
Leak Test

- 10 PSI for 10 hours minimum
- Typically Tested during Manufacturing before release to Test

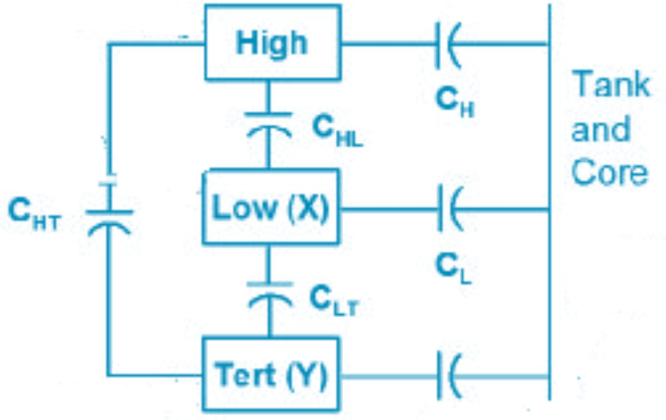
Preliminary Tests (cont.)

waukesha a prolec ge company

Insulation Power Factor C57.12.90 Sec. 10.10



TOP OF BOTTOM YOKE



- Test voltage is typically 10kV
- Power Factor is affected by temperature; Recommended 10^0 to 40^0 C
- No IEEE Limit for PF, Max 0.5% good for most units

#	Connection	Measurement	Cap. (pF)	Power Factor (%) @ 20°C	Tested
1	HV - (XV + GRND), YV @ GUARD	CHX + CH	10135.4	0.26	0.27
2	HV - GRND, XV & YV @ GUARD	CH	2630.7	0.29	0.30
3	HV - (YV + GRND), XV @ UST	CHX	7499.3	0.26	0.27
4	Calculated: #1 - #2	CHX	7504.7	0.25	0.26
5	XV - (YV + GRND), HV @ GUARD	CXY + CX	26489.6	0.23	0.23
6	XV - GRND, YV & HV @ GUARD	CX	24837.2	0.24	0.24
7	XV - (HV + GRND), YV @ UST	CXY	1643.8	0.18	0.18
8	Calculated: #5 - #6	CXY	1652.4	0.21	0.21
9	YV - (HV + GRND), XV @ GUARD	CHY + CY	22722.1	0.21	0.21
10	YV - GRND, XV & HV @ GUARD	CY	12947.4	0.23	0.23
11	YV - (XV + GRND), HV @ UST	CHY	9771.2	0.19	0.19
12	Calculated: #9 - #10	CHY	9774.6	0.19	0.19
13	(HV + XV + YV) - GRND	CH + CX + CY	40426.0	0.23	0.23

Preliminary Tests (cont.)

waukesha
a prolec ge company

Single Phase Excitation Test

- Test typically performed on HV terminal and tested at 10kV
- Test is performed one phase at a time and currents are compared
- For three phase transformers, two phases are expected to have similar and higher current compared to third; current measured on phase wound on center limb on three legged core will have lower current due to lower magnetic reluctance

Tap Positions			I (mA)		
HV	XV	YV	ØA	ØB	ØC
C	16R	-	18.732	12.433	18.876
C	15R	-	264.762	256.629	265.700
C	14R	-	18.830	12.507	18.975
C	13R	-	268.214	259.942	268.943
C	12R	-	18.970	12.589	19.097
C	11R	-	271.707	263.212	272.623
C	10R	-	19.128	12.697	19.245
C	9R	-	275.426	266.777	276.109
C	8R	-	19.317	12.819	19.420
C	7R	-	278.996	270.322	279.692
C	6R	-	19.524	12.963	19.612
C	5R	-	282.552	274.121	283.357
C	4R	-	19.749	13.123	19.835
C	3R	-	286.345	277.724	287.294
C	2R	-	20.004	13.303	20.086
C	1R	-	290.172	281.565	291.301
C	N	-	20.299	13.500	20.363

Winding Insulation Resistance C57.12.90 Sec. 10.11

- Typically tested at 1/2.5/5 kV and held for 1 minute before taking reading
- Test performed high voltage to low voltage and ground and low voltage to high voltage and ground
- Acceptable values varies with design, voltage class and cooling medium - typically is greater than 500MOhms

Connection	Megger (MΩ) @ 2.5 kV
	1 min
(HV + XV + YV) - GRND	10520
HV - (XV + YV + GRND)	22500
XV - (HV + YV + GRND)	13950
YV - (HV + XV + GRND)	16570

Performance Tests

Performance Characteristic Tests

waukesha
a prolec ge company

Tests	Class I	Class II
No Load Losses	Routine	Routine
% Excitation Tests	Routine	Routine
Load Losses	Routine	Routine
Positive Sequence Impedance	Routine	Routine
Zero Sequence Impedance	Special	Routine
Winding Resistances	Routine	Routine
Sound Test	Other	Other

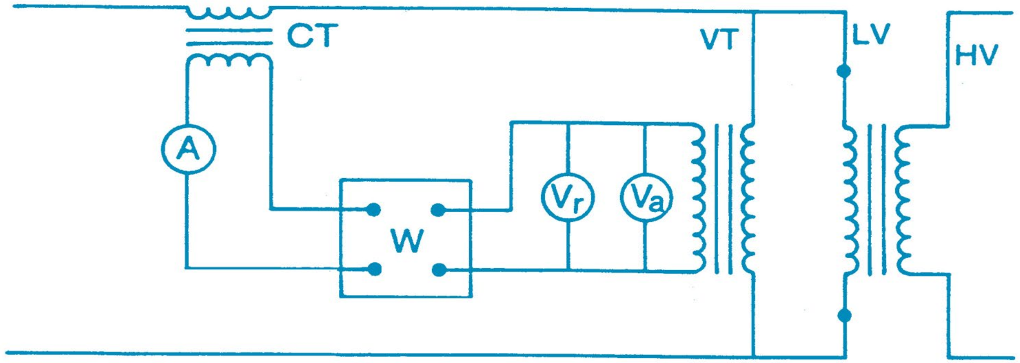
No-Load Test Connection – C57.12.90 Section: 8

No Load Loss and Excitation Current

- Core Loss ~ Hysteresis Loss, Eddy Current Loss
- Hysteresis Loss ~ Flux Density & Grade of Steel
- Eddy Current Loss ~ Frequency, Temperature

Test Circuit

- Transformer is excited from either TV/LV or HV side at 60 Hz with a variable voltage sinusoidal source
- All other terminals are left open
- Applied voltage is slowly increased to test voltage 90%, 100%, 110%
- Need high precision measurement System
- Losses corrected to 20^{o}C



Load Losses and % Impedance

Load Loss C57.12.90 Sec. 9

- Load Losses are the losses of TRANSFORMER DUE TO LOAD CURRENT
- Load Loss = I^2R loss + Eddy loss + Stray loss
- Eddy losses depend on conductor thickness and width and leakage flux distribution
- Stray loss depends on % impedance, winding dimensions and clearance to tank and clamps

Impedance

- $$\%\ \text{Impedance} = \frac{\text{VOLTAGE FOR RATED CURRENT} \times 100}{\text{RATED VOLTAGE}}$$

Load Loss Test Connection

Test Circuit

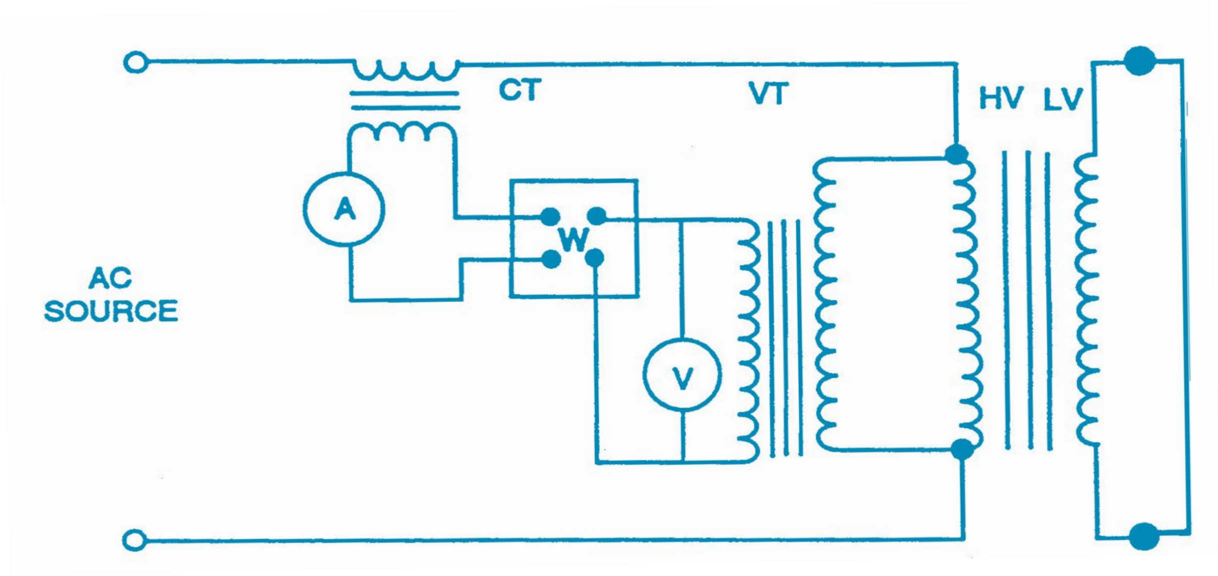
Transformer is excited, preferably from HV side at 60 Hz with a variable voltage sinusoidal source. LV terminals are shorted. Applied voltage is slowly increased to feed the rated test current in the windings.

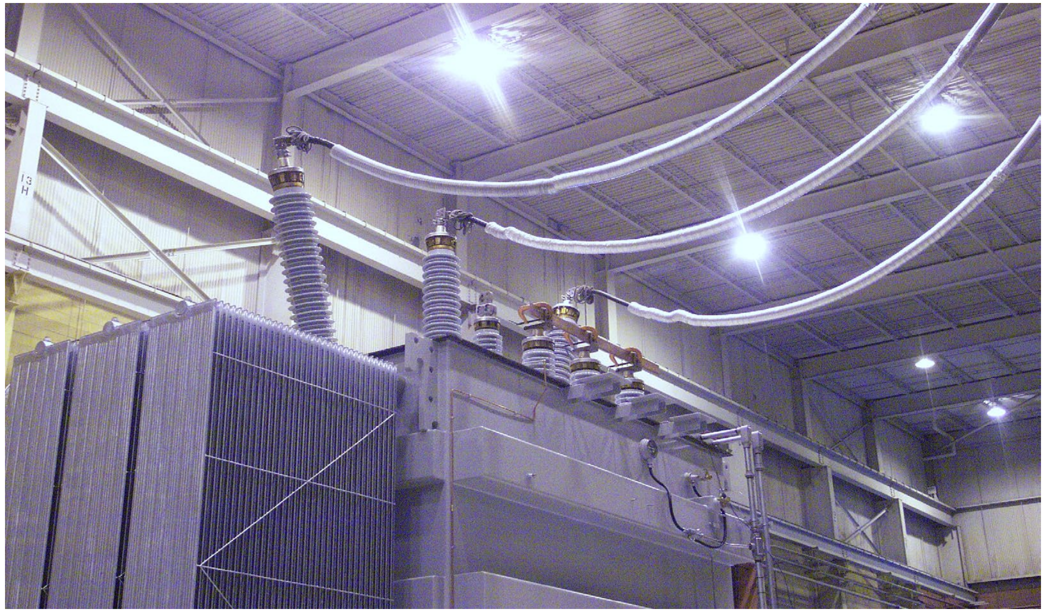
Measurement

With the help of a precision loss measurement system load current, voltage and losses are measured:

Measured loss = $I^2 R$ Loss at ambient + stray loss
$I^2 R$ Loss at 85ºC = $I^2 R$ Loss at ambient*(234.5+85)/(234.5 + ambient)
Stray Loss at 85ºC = Stray Loss at ambient*(234.5+ambient)/(234.5 + 85)

Load Loss Test Connection (cont.)





Impulse Testing – C57.12.90 Section:10.3

- Lightning Impulse **Class II – Routine, Class I – Other**
  - Reduced Wave RFW (50 – 70% of Full Wave)
  - Full Wave *
  - Two (2) Chopped Waves
  - Full Wave
  - Full Wave *

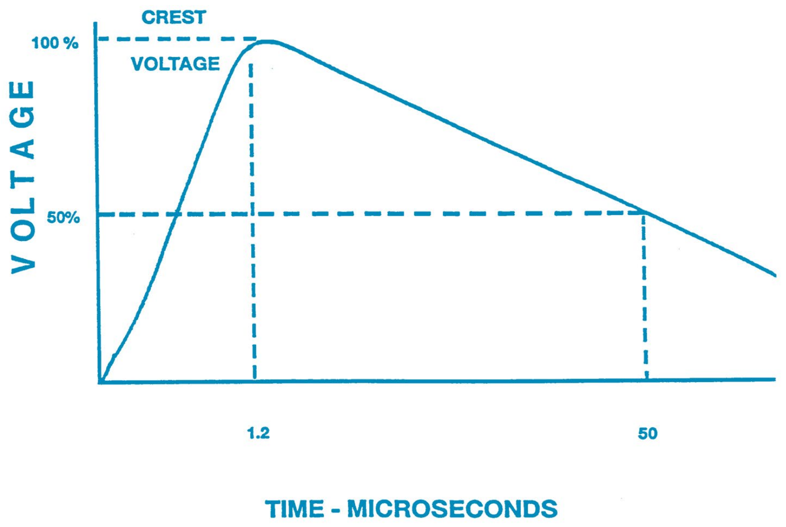
- Transformer Neutrals
  - 1 RFW
  - 2 FW
  - 1 FW*

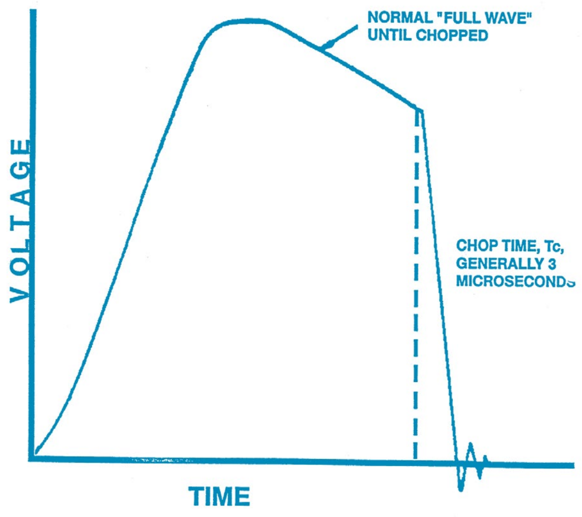
**Added in 2015 Standard*

Impulse Test

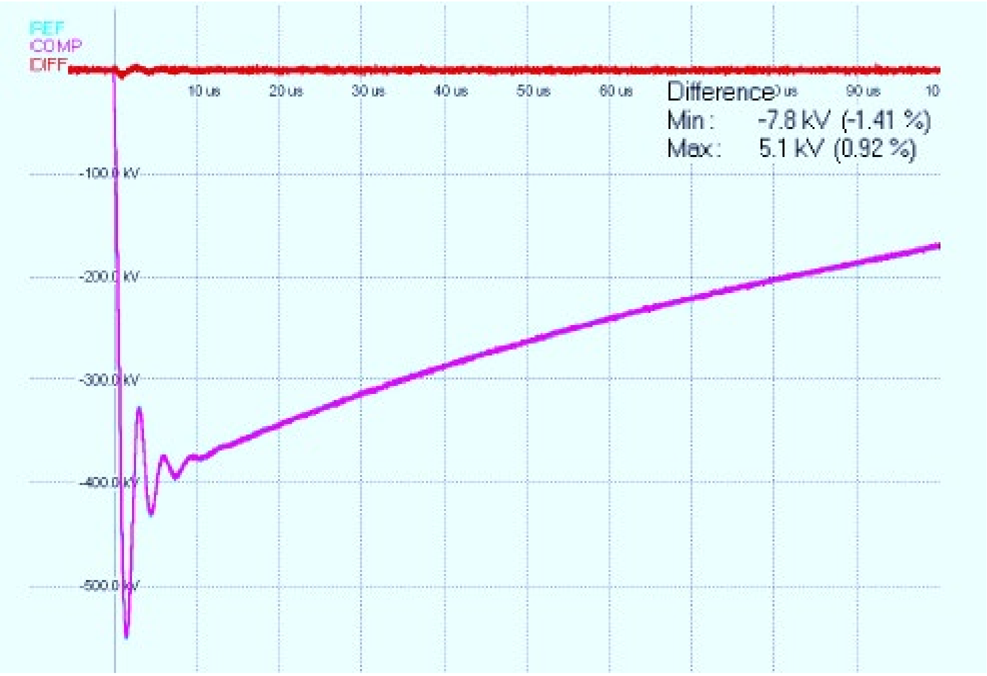
Lighting Impulse

- Front Time – 1.2 microseconds +/- 30% Tolerance (1.67 Times the time between 30% and 90% voltage)
- Tail Time – 50 microseconds +/- 20% (Time to 50% peak voltage)
- Chop Time > = 3 microseconds for > = 150 KV
  > = 2 microseconds for < 150 KV





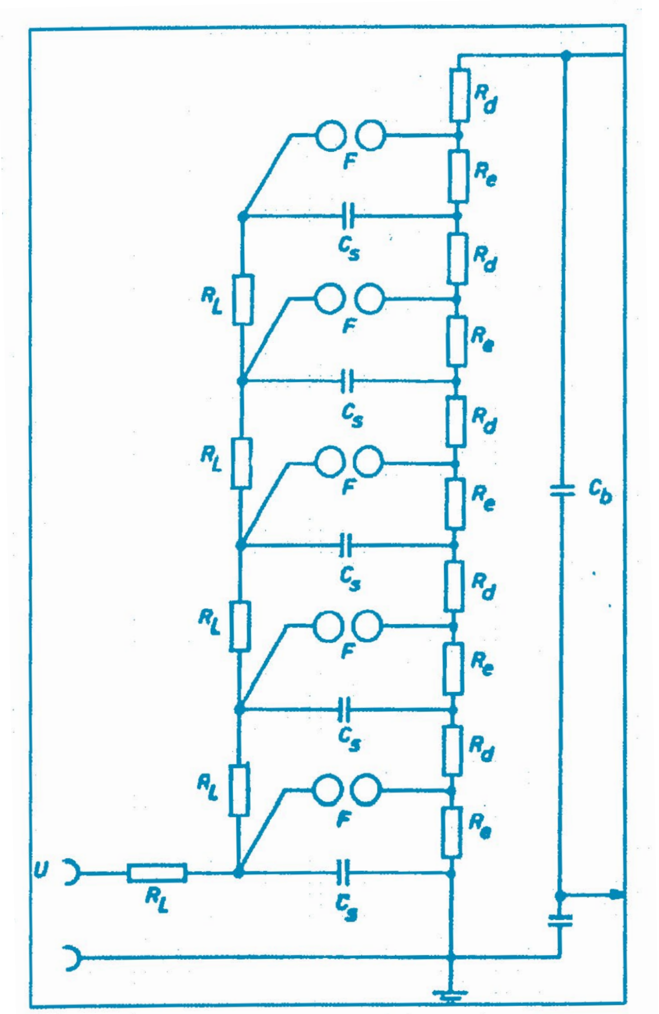
Waveform Comparisons – RFW & FW Overlay



Voltage Waveform

Current Waveform

Impulse Generator (cont.)

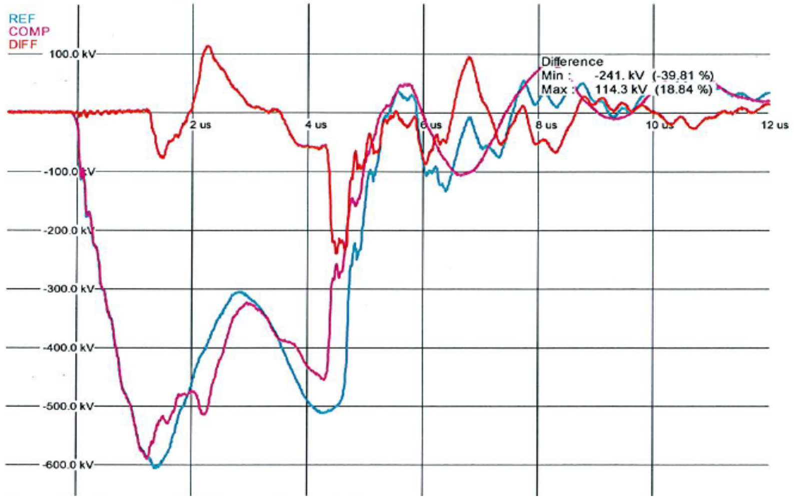


Multiplier Circuit

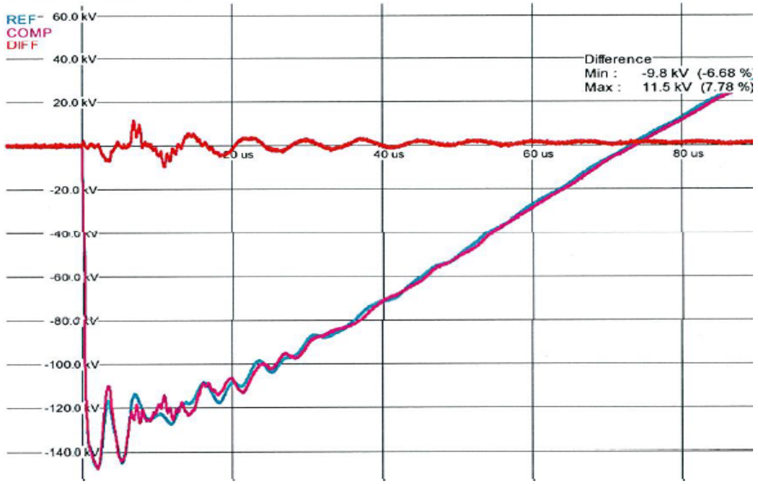
- RC circuit with circuit Inductance
- Multiplier circuit introduced by Prof. Marx
- Impulse capacitor Cs are charged in parallel and discharged in series after firing the switching gaps F
- Front Time T1 is determined by Rd whereas time to half value is determined by Re

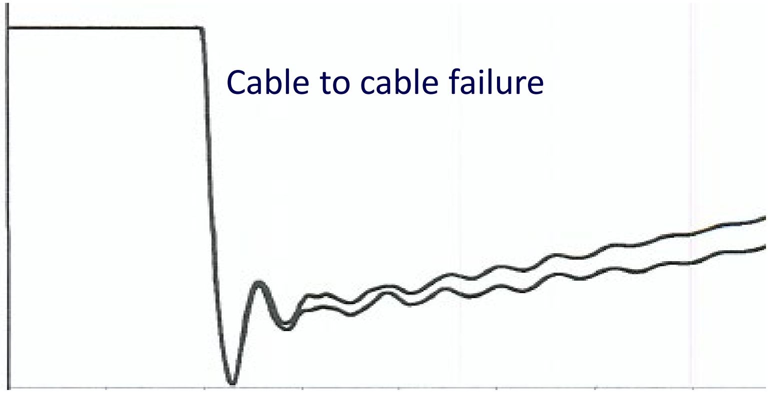
Voltage and Current Wave Shape Comparison (Reduce and Full Wave)

Chop wave failure

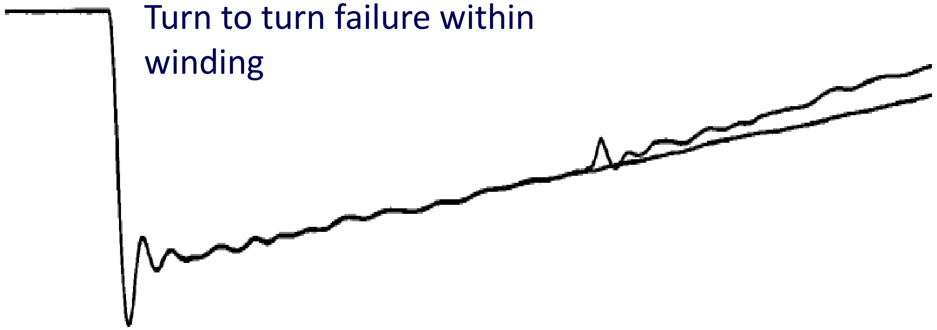


Failure between LTC Leads



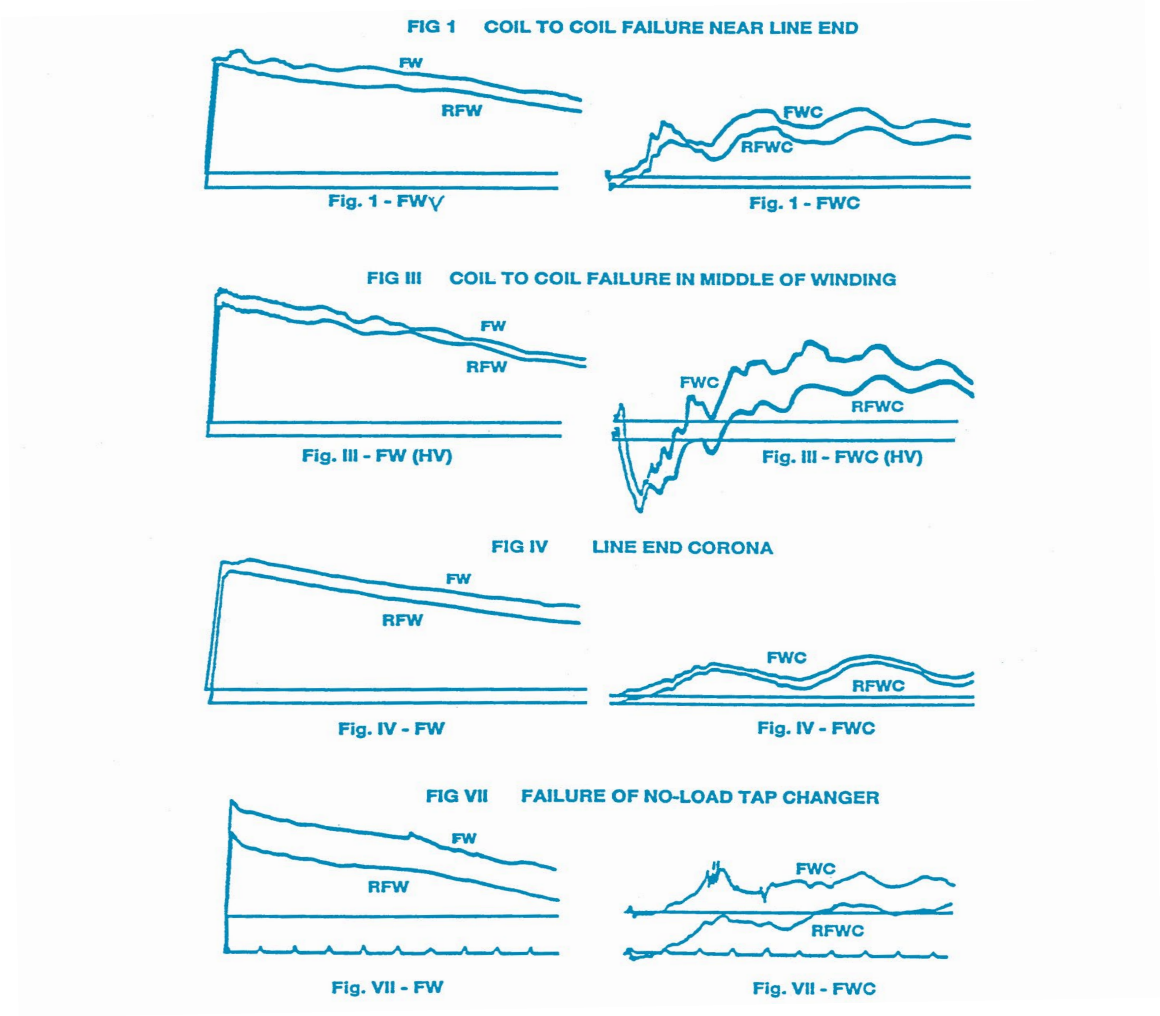


Cable to cable failure



Turn to turn failure within winding

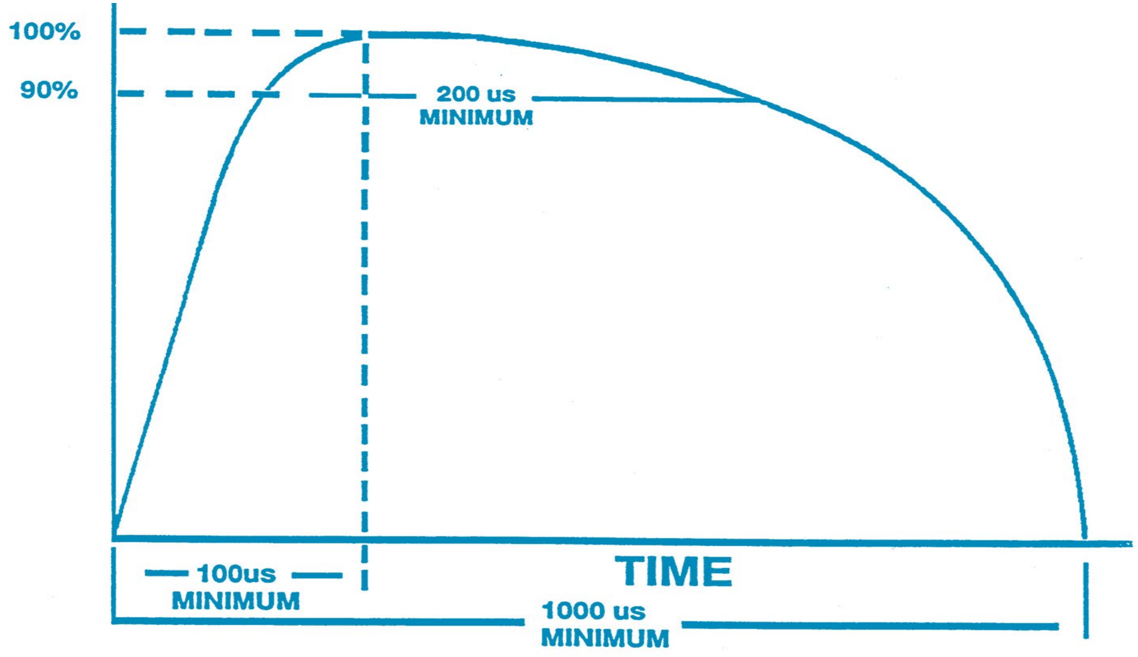
Impulse Failure Waveforms



Switching Impulse Test

Switching Impulse Test C57.12.90 Sec. 10.2

- Time to peak value > 100 microseconds
- Time for 90 % of peak Value > 200 microseconds
- Time to first zero on tail of the wave >1000 microseco



Test Circuit

- Test for each HV Line terminal
- Ground Neutral terminal for all Wye connection
- Ground other end of all Delta windings
- All Line terminals to be kept open except test terminal

Low Frequency Dielectric Test

Applied Voltage Test

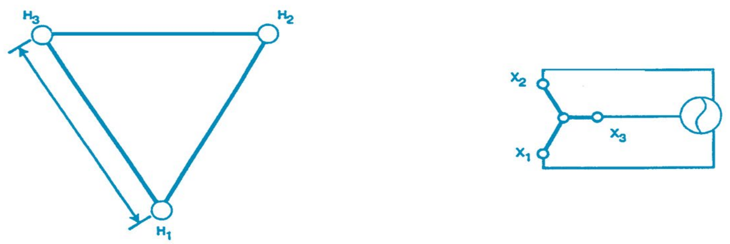
- Transformer Connections
- Test Levels

Induced Voltage Test

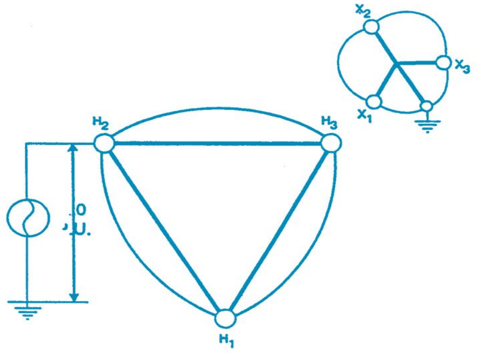
- Transformer Connections
- Test Levels – Class I & Class II
- Partial Discharge

Induced Voltage Test vs. Applied Voltage Test

A - Induced Test



B - Applied Test



Test Voltage

- For Delta connected windings, applied test voltage level corresponds to NSV

  For example:
  Equivalent applied test voltage for 230kV (750,825,900 BIL) is 345kV

- For Wye connected windings, the applied test voltage is limited to the BIL of Neutral

  For example:
  If line end BIL is 550kV and neutral end BIL is 150kV, then equivalent applied test voltage is limited to 50kV (equivalent for 150 BIL)

Induced Voltage Test – C57.12.90 Section: 10.7 to 10.9

Test Connection

- Three phase voltage is applied to LV terminals at frequency ≥2 times rated frequency; all other line terminals are left open, Neutral and Tank is grounded

Test Voltage & Duration

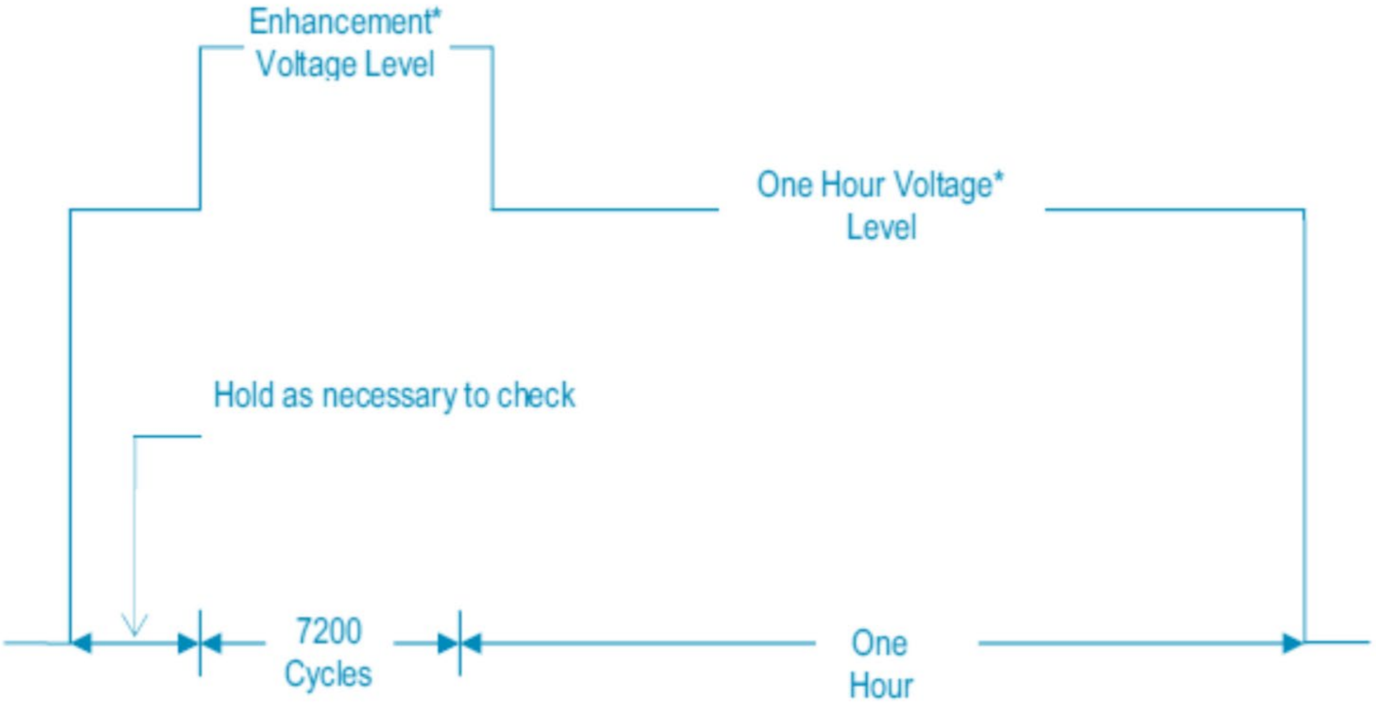
Class I Transformers

- Test voltage is equivalent to twice the volts/turn and line end is raised to achieve equivalent power frequency test voltage across phases
- Test duration is 7200 Hz; if test frequency is 180 Hz then test duration = 7200/180 = 40 seconds
- Test is considered to be passed if no collapse of voltage occurs or no audible internal sound is present

Induced Voltage Test (cont.)

Test Voltage & Duration
Class II Transformers

- Enhancement level – 173% maximum tap voltage for 7200 Hz
- One hour test voltage – 150% for 1 hour
- Partial discharge limits < = 250 pC



C57.12.00 – Table 4

waukesha
a prolec ge company

Table 4—Dielectric insulation levels for Class II power transformers, voltages in kV

Maximum system voltage (kV rms)	Nominal system voltage (kV rms)	Applied voltage test (kV rms)			Induced voltage test (phase to ground) (kV rms)		Winding line-end BIL (kV crest)				Neutral BIL (kV crest)	
		Delta & fully insulated wye	Grounded wye	Impedance Grounded wye or Grounded wye with Higher BIL	Enhanced 7200 cycle	One hour	Mini-mum	Alternates			Grounded wye	Impedance Grounded wye or Grounded wye with Higher BIL
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
17	15	34	34	34	16	14	**110**				110	110
26	25	50	34	40	26	23	**150**				110	125
36	34.5	70	34	50	36	32	**200**				110	150
48	46	95	34	70	48	42	200	**250**			110	200
73	69	140	34	95	72	63	250	**350**			110	250
121	115	173	34	95	120	105	350	**450**	550		110	250
145	138	207	34	95	145	125	450	**550**	650		110	250
169	161	242	34	140	170	145	550	**650**	750	825	110	350
242	230	345	34	140	240	210	650	**750**	**825**	**900**	110	350
362	345	518	34	140	360	315	900	1050	1175		110	350
550	500	N/A	34	140	550	475	1425	1550	1675		110	350
765	735	N/A	34	140	880	750	1950	2050			110	350
800	765	N/A	34	140	885	795	1950	2050			110	350

NOTE 1- For nominal system voltage greater than maximum system voltage, use the next higher voltage class for applied test levels.

NOTE 2- Induced voltage tests shall be conducted at 1.5 X nominal voltage for one hour and 1.80 X nominal voltage for enhanced 7200 cycle test.

NOTE 3-Column 6 and Column 7 provide phase-to-ground test levels that would normally be applicable to wye windings. When the test voltage level is to be measured phase-to-phase (as is normally the case with delta windings), the levels in Column 6 and Column 7 must be multiplied by 1.732 to obtain the required phase-to-phase induced-voltage test level.

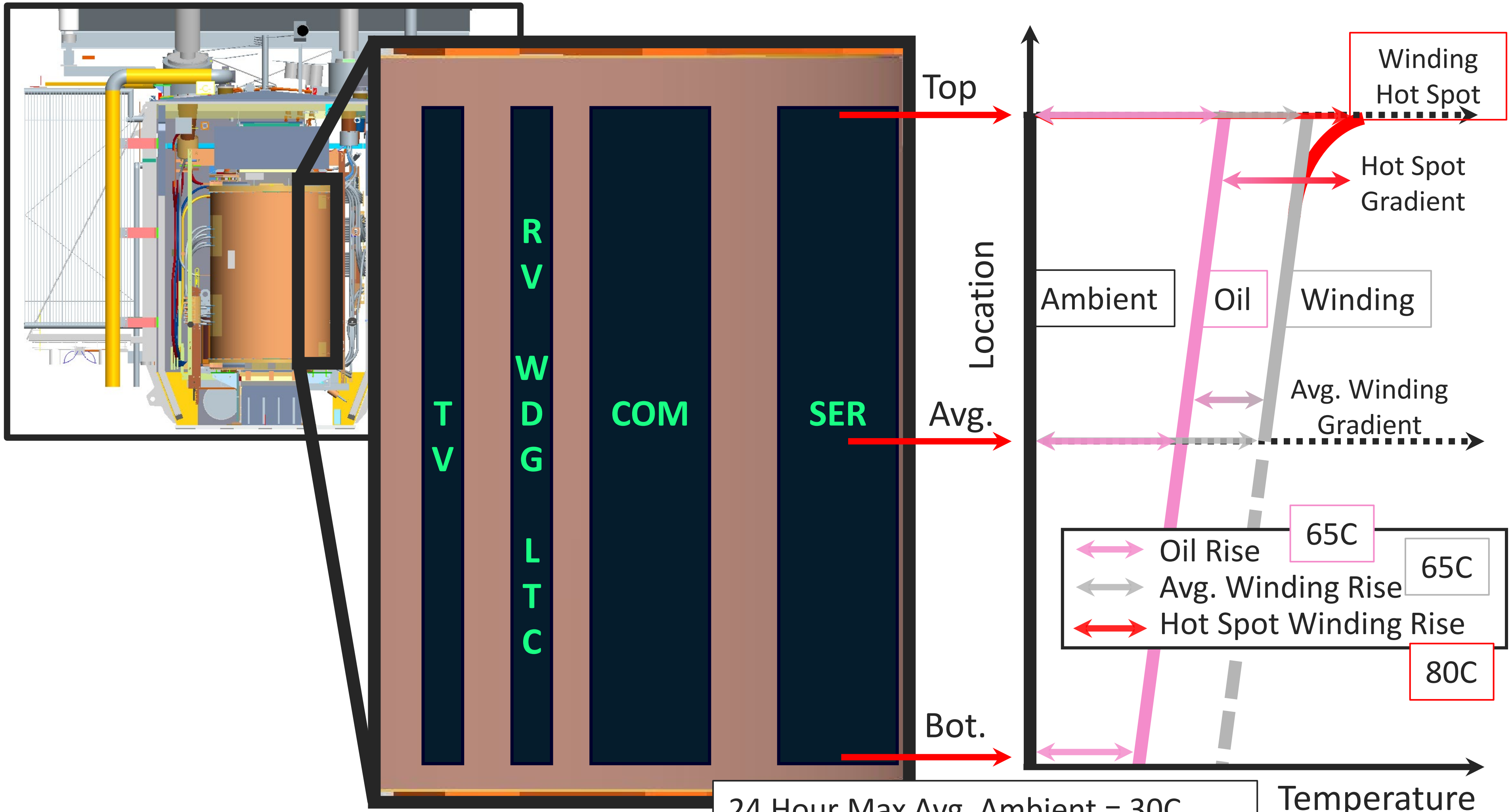
NOTE 4-Bold typeface BILs are the most commonly used standard levels.

NOTE 5-Y-Y connected transformers using a common solidly grounded neutral may use neutral BIL selected in accordance with the low-voltage winding rating.

NOTE 6-For 500kV to 765 kV nominal system voltages, induced voltage test levels do not follow rules in Note 2, and 1950 kV BIL is not a standard IEEE level.

NOTE 7- For Neutral BILs greater than 350 KV, Applied Voltage test level shall be specified by user.

Temperature Distribution Model



24 Hour Max Avg. Ambient = 30C
(Max Ambient = 40C)

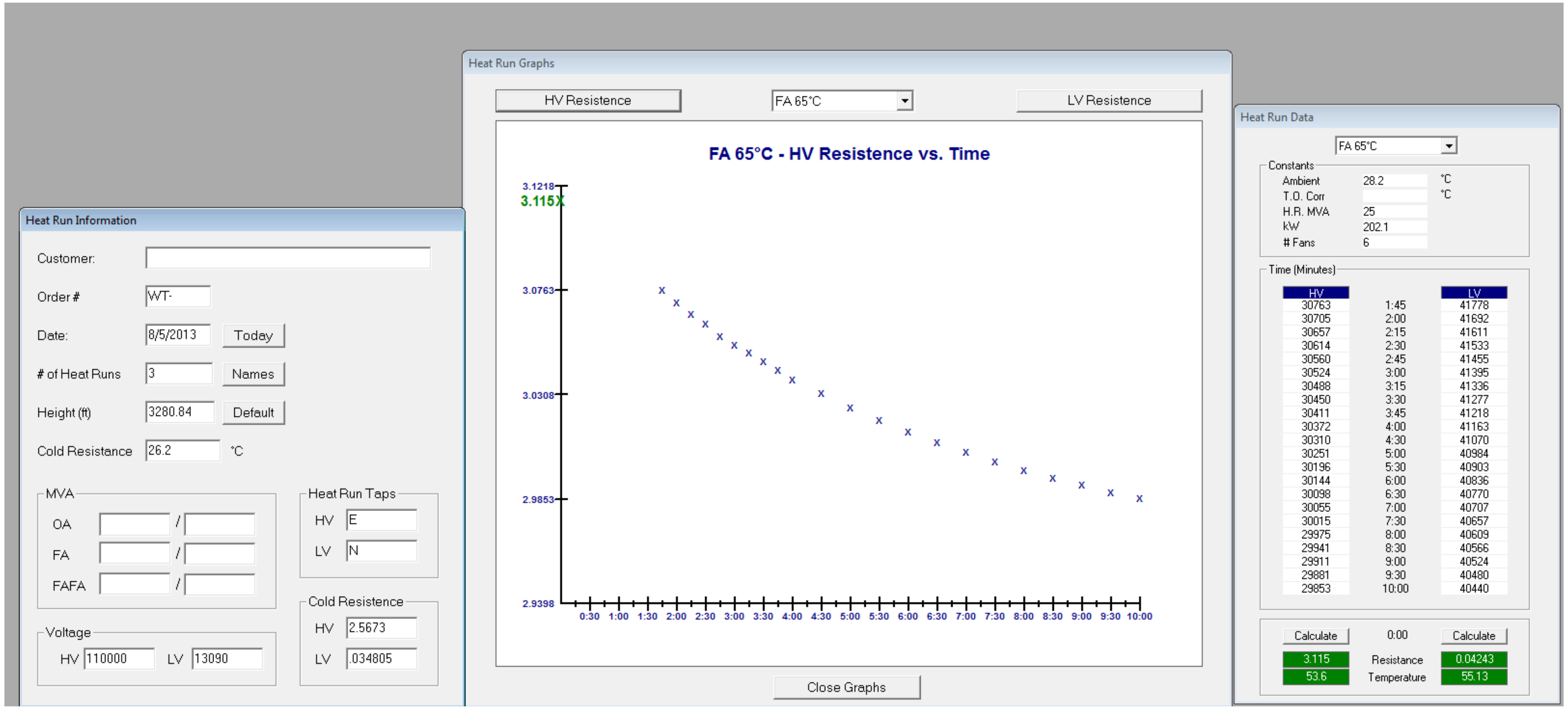
Temperature Rise Test – C57.12.90 Section: 11

- Measurements during temperature rise test
  - Top oil temperature
  - Ambient temperatures
  - Top and bottom radiator temperature
  - Hot winding resistance at shut down
- Top Oil Rise = Top oil temperature – Average ambient
- Mean oil rise = Top oil temperature – Average of top & bottom header temp
- Average winding rise

  = { (Hot Resistance/Cold Resistance) X (234.5+ambient temp) } – Ambient
- Gradient = Average winding rise – Mean oil rise
- Hot spot Rise = Top oil rise + Hot spot gradient
- Hot spot gradient = Gradient (1 + k); k = hot-spot factoralculate

Average Winding Rise

waukesha
a prolec ge company



$$\theta_2 = \frac{R_2}{R_1}(235+\theta_1)-235$$

θ_2 : *Temperature of the winding when the circuit is opened*

θ_1 : *Average oil temperature at he beginning of test (cold case)*

R_2 : *Resistance at temperature θ_2 (hot case)*

R_1 : *Resistance at temperature θ_1 (cold case)*

DGA

- Before Test , After Dielectric, Before/After Temp Rise test, After all Tests
- Gassing rate depend on many factors - Winding temperature rise, Ambient Temperature, Duration of test, Design characteristics like current and flux density
- Expect significant difference lab to lab .. Requires ASTM D3612 Method C

Limits per C57.130

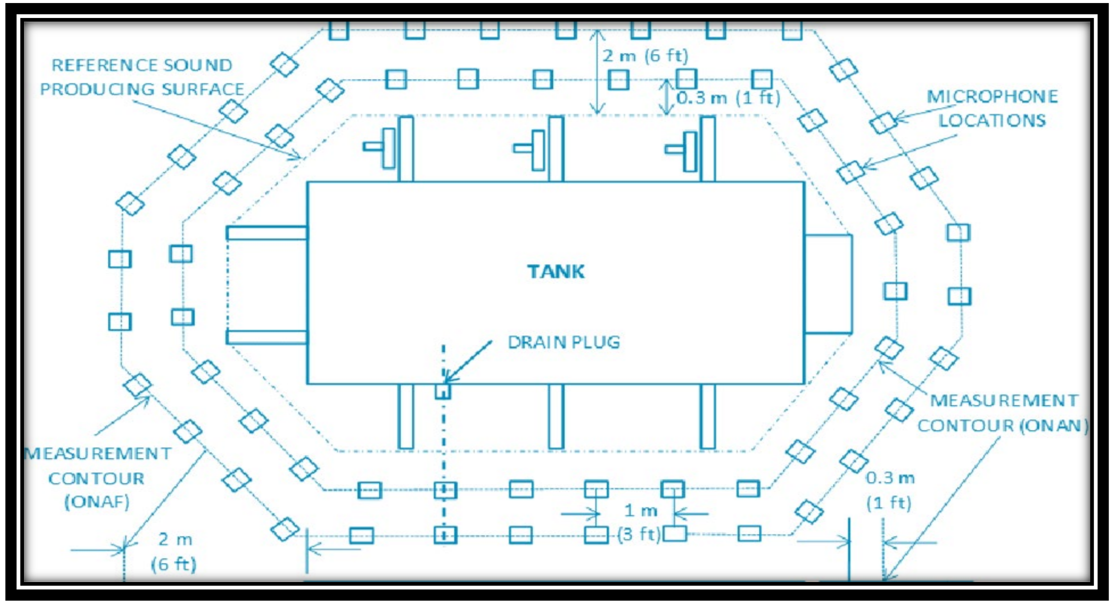
	Gas Generation During Temp Rise Test PPM/ Hour
Hydrogen H_2	< 1
Carbon Monoxide CO	< 2
Carbon dioxide CO_2	< 18
Methane CH_4	
Ethane C_2H_6	< 0.4
Ethylene C_2H_4	
Acetylene C_2H_2	0

Sound Test – C57.12.90 Section: 13

- **Core audible sound:** This sound component originates in the transformer core
- **Load audible sound:** This sound component is primarily produced by vibrations of the windings and tank walls when the transformer is loaded.
  - When a transformer is highly loaded, load sound can be a significant contributor to the total sound of the transformer ,especially for low no-load noise medium and large power transformers.
- **Cooling system audible sound:** typically consists of broadband fan noise, plus discrete tones (of low levels) at the fan blade passage frequency and its harmonics.
- The sum of core and cooling system sound components is typically referred to as the **no-load noise** of a transformer.
- **The total audible sound of the transformer**, however, is the sum of all three components, 2015 standard outlines measurement methods for Load sound and calculation to arrive Total sound.
- **Sound levels are specified in NEMA-TR1 and that is only No-Load Sound Level**
- **Load Sound is not significant for smaller transformers (< 100 MVA) unless No load sound required is below NEMA**

Sound Test – Measurement

- Measurements are generally taken on a weighted scale as per NEMA standard
- Location of measurements start at drain plug and around the transformer at approximate 3 foot intervals, 12 inches away from transformer tank/radiators as applicable at 1/3 and 2/3 heights for transformers over 9 feet
- With fans running – readings are taken 6 feet distance



Other Tests

- Bushing Cap & PF – C1/C2
- Core excitation test – typically 110% for 24 Hours
- Leakage Reactance test
- Front of Wave Impulse testing
- Frequency response analysis (FRA)
- Fast Front Switching Impulse (FFSI)
- LTC Tests
  - Operate LTC at No Load Voltage
  - Operate LTC under Load
  - Dynamic Resistances
  - DGA from LTC

waukesha
a prolec ge company

Questions

waukesha
a prolec ge company

Contact

Joshua Jordan
Senior Electrical Design Engineer

Prolec-GE Waukesha, Inc.
Waukesha WI 53186
Joshua.Jordan@prolec.energy
T: (262) 446-8894

www.waukeshatransformers.com