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Power Transformers Basics

Transformers


Transformer Basic Objective

- Introduce Basic Transformer Theory as it Relates to Diagnostics
- Provide a Better Understanding of the Diagnostic Test Environment
- Identify Important Information that should be collected in the Diagnostic Test Process

Topics of Discussion

- Definition
- Transformer Types and Classifications
- Transformer Configurations
- Vector Groups
- Life Expectance
- Oil Preservation Systems
- Insulating Materials and Fluids
- Construction Forms
- Core Steel
- Nameplates
- Ratings
- Cooling Schemes
- Tap Changers (OLTC, DETC)

Transformer Categories

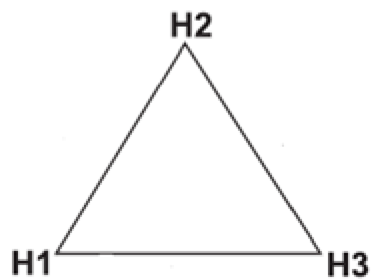
- Insulation System
  - Liquid Immersed
  - Dry Type
  - Gas Filled
- Construction
  - Tank Type
  - Core Type / Shell Type
  - 1 Phase / 3 Phase
  - Double-Wound, Multi-Winding, Auto
  - Winding Configuration and Type
- Application

Winding Configurations

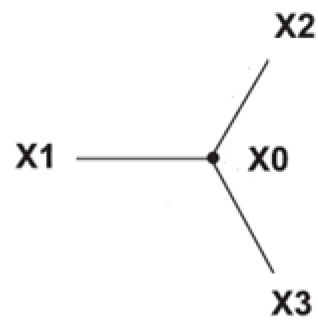
- Delta
- Wye
- Auto
- Zig-Zag

Vector Groups

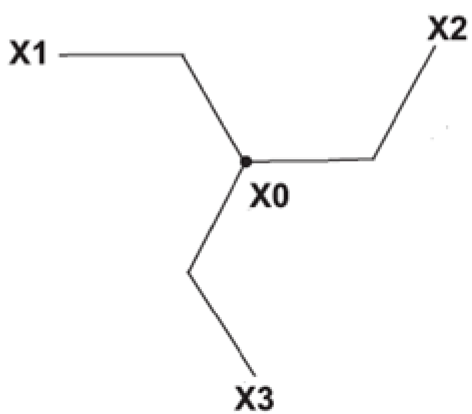
DELTA



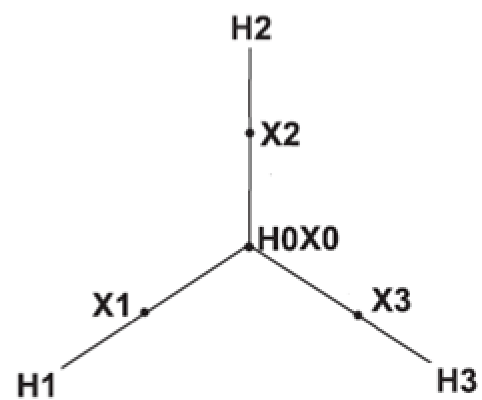
WYE-STAR



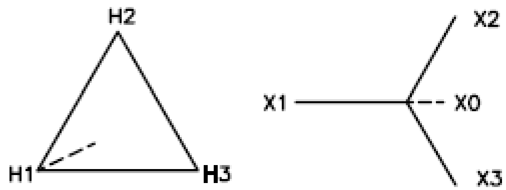
ZIG-ZAG

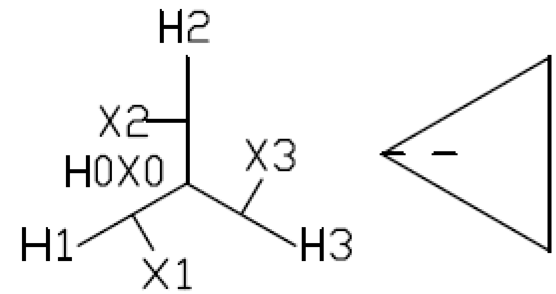


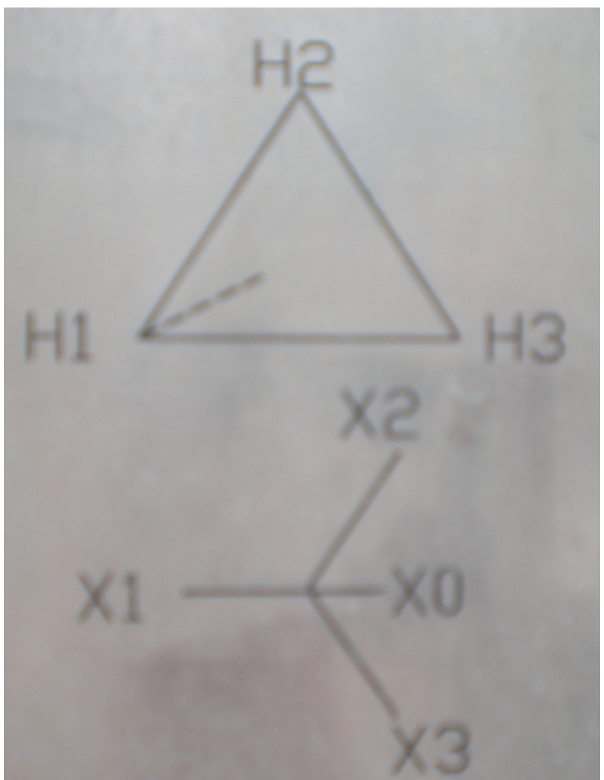
AUTO

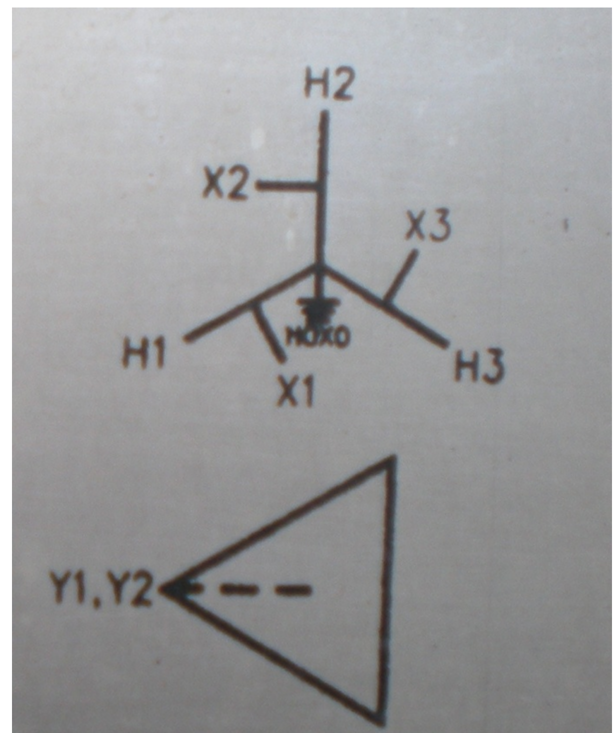


Vector Groups

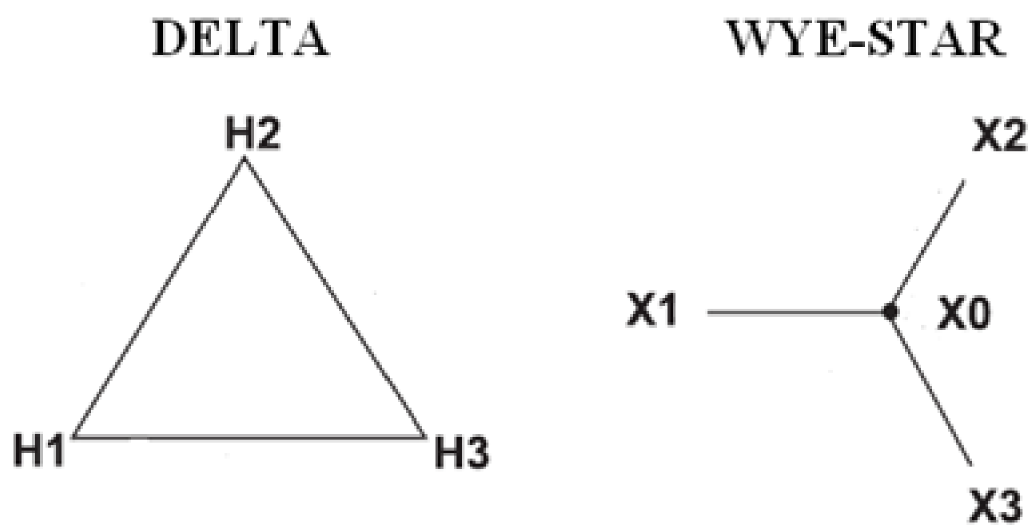








Vector Groups – Head to Tail Relationship



	HV	LV
Phase A	H1-H3	X1-X0
Phase B	H2-H1	X2-X0
Phase C	H3-H2	X3-X0

Life Expectancy of Transformer Insulation

- 180,000 hrs or 20.55 years
- 110 °C Hottest Spot for 65 °C Temp Rise insulation
- Degree of Polymerization (200 -1200 DP)
- 1200 DP - New Paper
- 200 DP at 150,000 hrs (end of life)

> - Heat
> - Moisture
> - Oxygen

Oil

- Most insulating fluids have very good properties, however the unique characteristics and attributes of each product must be considered when selecting an insulating fluid for a specific application.
- Purpose
    a. Dielectric Withstand
    b. Heat Exchange (Cooling)
    c. Arc Mitigation

Winding Types

1. Disk Winding
2. Pancake Winding
3. Helical Winding
4. Cylindrical or Layer Winding

Disk Winding

- Each disk is wound in series
- Disks are stacked in parallel
- Uses crossovers (inner-outer)
- Used mostly in 34.5 kV
  and above core types

Courtesy of Delta Star, San Carlos, CA

Disk Winding “Crossover” Close-up

Courtesy of Delta Star, San Carlos, CA

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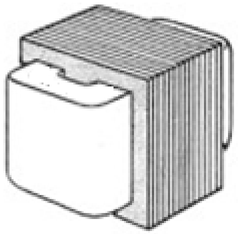
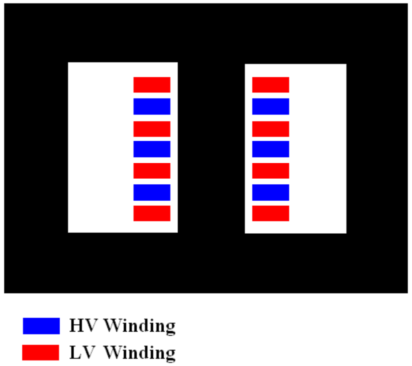
Disk Winding – Autotransformer Common Winding

Courtesy of Delta Star, San Carlos, CA

Pancake Winding



- Used in Shell-Type Transformers
- Stacked by Interleaved Scheme

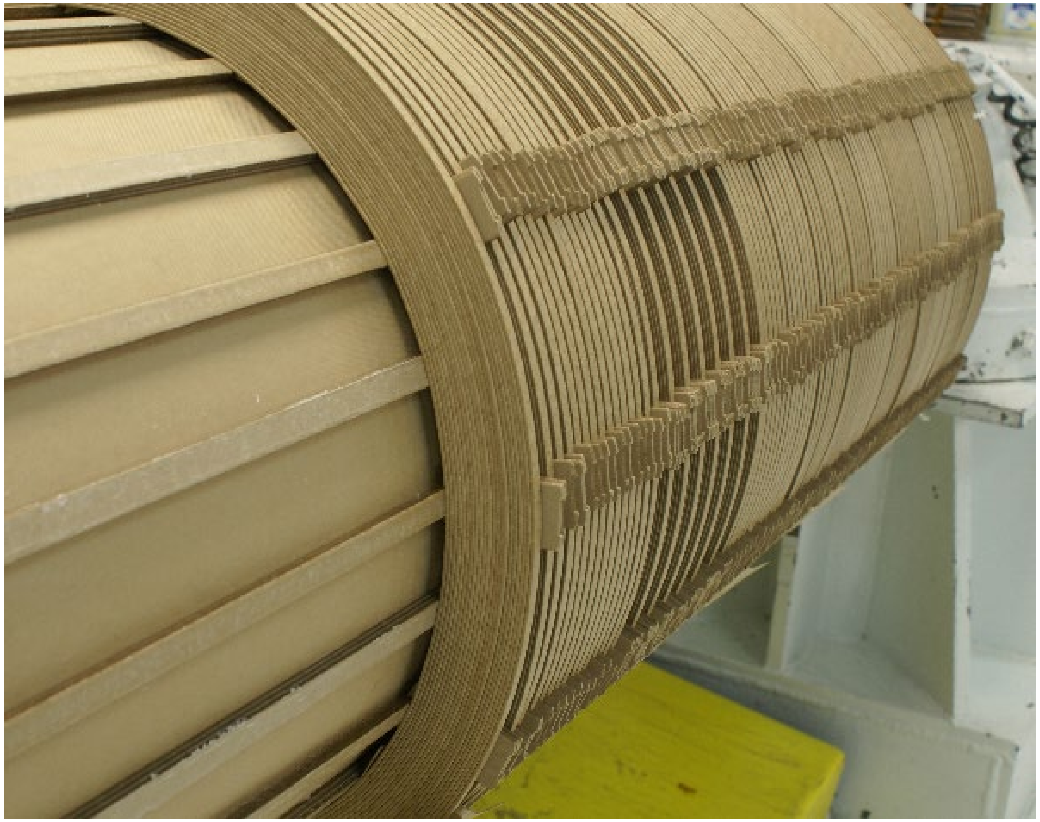


Courtesy of ABB TRES - ABB Inc., Saint Louis, MO

Helical Winding

- Strands wound in parallel
- High-Current
- Low Voltage

Low-Voltage Winding



Courtesy of Delta Star, San Carlos, CA

Helical Winding – Low Voltage Winding

Courtesy of Delta Star, San Carlos, CA

Layer or Barrel Winding

- Conductors wound side by side
- Layers can be wound on top each other
- Regulating Windings
- Tertiary Windings

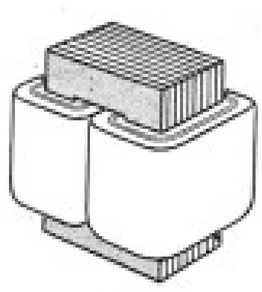
Regulating Winding

Courtesy of Delta Star, San Carlos, CA

Construction Forms

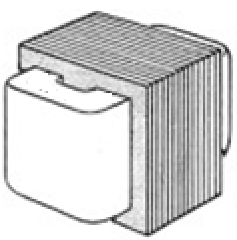
Core Form

- Concentric
- Less Iron
- More CU

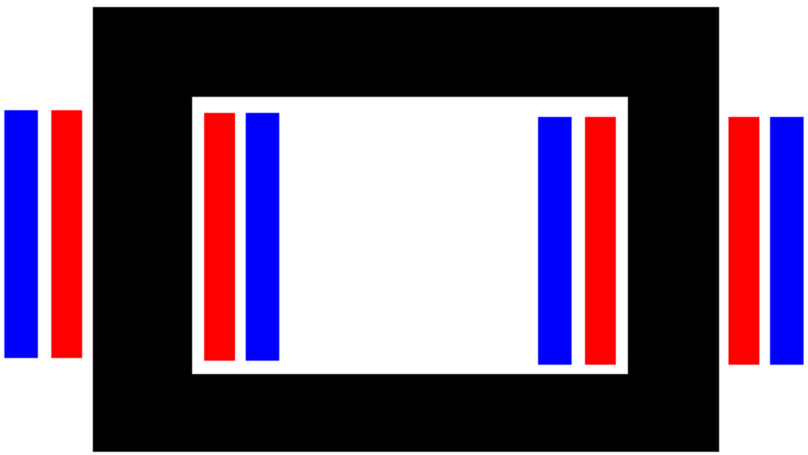


Shell Form

- Interleaved
- More Iron
- Less CU

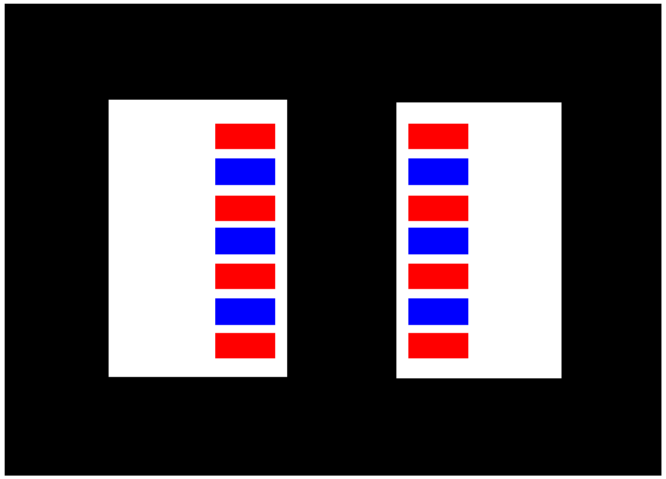


Core Form



HV Winding
LV Winding

Shell Form



HV Winding
LV Winding

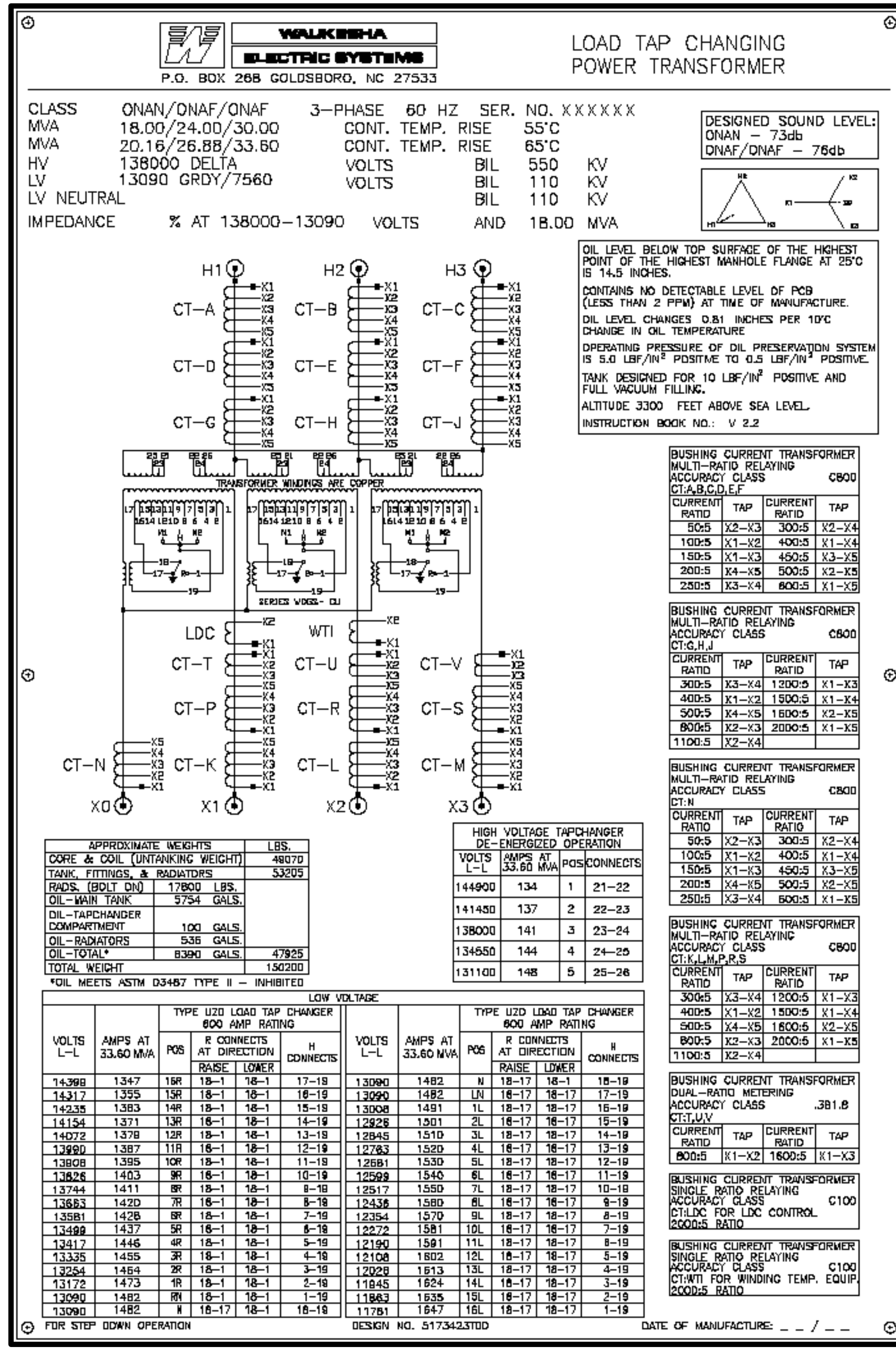
Core Steel

- Goal – Minimize cost of ownership by minimizing losses
- Constructed from steel sheets (0.25 mm) that has a coating (insulation); stacked laminations
- Eddy Losses – Proportional to the sheet thickness
- Hysteresis Losses – Influenced by the metallurgical recipe and process
- Grain Oriented – Align magnetic domains for the best performance in plane of intended flux paths.

Nameplates

- Identification: Manufacturer, Year, Serial Number
- Ratings
  - MVA, kV, BIL, Amperes, %Z p.u.
  - Cooling Class
  - Insulation Temperature Rise
- Vector Diagram
- Wiring Diagram
- Weights and Volumes
- OLTC, DETC Rating and Connection Mapping

Nameplate Drawing



WAUKESHA ELECTRIC SYSTEMS
P.O. BOX 268 GOLDSBORO, NC 27533

LOAD TAP CHANGING POWER TRANSFORMER

CLASS ONAN/ONAF/ONAF 3–PHASE 60 HZ SER. NO. XXXXXX
MVA 18.00/24.00/30.00 CONT. TEMP. RISE 55°C
MVA 20.16/26.88/33.60 CONT. TEMP. RISE 65°C
HV 138000 DELTA VOLTS BIL 550 KV
LV 13090 GRDY/7560 VOLTS BIL 110 KV
LV NEUTRAL BIL 110 KV
IMPEDANCE % AT 138000–13090 VOLTS AND 18.00 MVA

DESIGNED SOUND LEVEL:
ONAN – 73db
ONAF/ONAF – 76db

OIL LEVEL BELOW TOP SURFACE OF THE HIGHEST POINT OF THE HIGHEST MANHOLE FLANGE AT 25°C IS 14.5 INCHES.
CONTAINS NO DETECTABLE LEVEL OF PCB (LESS THAN 2 PPM) AT TIME OF MANUFACTURE.
OIL LEVEL CHANGES 0.81 INCHES PER 10°C CHANGE IN OIL TEMPERATURE.
OPERATING PRESSURE OF OIL PRESERVATION SYSTEM IS 5.0 LBF/IN² POSITIVE TO 0.5 LBF/IN² POSITIVE.
TANK DESIGNED FOR 10 LBF/IN² POSITIVE AND FULL VACUUM FILLING.
ALTITUDE 3300 FEET ABOVE SEA LEVEL.
INSTRUCTION BOOK NO.: V 2.2

TRANSFORMER WINDINGS ARE COPPER
SERIES WDGS.- CU

APPROXIMATE WEIGHTS		LBS.
CORE & COIL (UNTANKING WEIGHT)		49070
TANK, FITTINGS, & RADIATORS		53205
RADS. (BOLT ON)	17800 LBS.	
OIL–MAIN TANK	5754 GALS.	
OIL–TAPCHANGER COMPARTMENT	100 GALS.	
OIL–RADIATORS	536 GALS.	
OIL–TOTAL*	6390 GALS.	47925
TOTAL WEIGHT		150200

*OIL MEETS ASTM D3487 TYPE II – INHIBITED

HIGH VOLTAGE TAPCHANGER DE–ENERGIZED OPERATION

VOLTS L–L	AMPS AT 33.60 MVA	POS	CONNECTS
144900	134	1	21–22
141450	137	2	22–23
138000	141	3	23–24
134550	144	4	24–25
131100	148	5	25–26

LOW VOLTAGE

VOLTS L–L	AMPS AT 33.60 MVA	POS	R CONNECTS AT DIRECTION RAISE	R CONNECTS AT DIRECTION LOWER	H CONNECTS	VOLTS L–L	AMPS AT 33.60 MVA	POS	R CONNECTS AT DIRECTION RAISE	R CONNECTS AT DIRECTION LOWER	H CONNECTS
14398	1347	16R	18–1	18–1	17–19	13090	1482	N	18–17	18–1	18–19
14317	1355	15R	18–1	18–1	16–19	13090	1482	LN	18–17	18–17	17–19
14235	1363	14R	18–1	18–1	15–19	13008	1491	1L	18–17	18–17	16–19
14154	1371	13R	18–1	18–1	14–19	12926	1501	2L	18–17	18–17	15–19
14072	1378	12R	18–1	18–1	13–19	12845	1510	3L	18–17	18–17	14–19
13990	1387	11R	18–1	18–1	12–19	12763	1520	4L	18–17	18–17	13–19
13908	1395	10R	18–1	18–1	11–19	12681	1530	5L	18–17	18–17	12–19
13826	1403	9R	18–1	18–1	10–19	12599	1540	6L	18–17	18–17	11–19
13744	1411	8R	18–1	18–1	9–19	12517	1550	7L	18–17	18–17	10–19
13663	1420	7R	18–1	18–1	8–19	12436	1560	8L	18–17	18–17	9–19
13581	1428	6R	18–1	18–1	7–19	12354	1570	9L	18–17	18–17	8–19
13499	1437	5R	18–1	18–1	6–19	12272	1581	10L	18–17	18–17	7–19
13417	1446	4R	18–1	18–1	5–19	12190	1591	11L	18–17	18–17	6–19
13335	1455	3R	18–1	18–1	4–19	12108	1602	12L	18–17	18–17	5–19
13254	1464	2R	18–1	18–1	3–19	12028	1613	13L	18–17	18–17	4–19
13172	1473	1R	18–1	18–1	2–19	11945	1624	14L	18–17	18–17	3–19
13090	1482	RN	18–1	18–1	1–19	11863	1635	15L	18–17	18–17	2–19
13090	1482	N	18–17	18–1	18–19	11781	1647	16L	18–17	18–17	1–19

BUSHING CURRENT TRANSFORMER
MULTI–RATIO RELAYING
ACCURACY CLASS C800
CT:A,B,C,D,E,F

CURRENT RATIO	TAP	CURRENT RATIO	TAP
50:5	X2–X3	300:5	X2–X4
100:5	X1–X2	400:5	X1–X4
150:5	X1–X3	450:5	X3–X5
200:5	X4–X5	500:5	X2–X5
250:5	X3–X4	600:5	X1–X5

BUSHING CURRENT TRANSFORMER
MULTI–RATIO RELAYING
ACCURACY CLASS C800
CT:G,H,J

CURRENT RATIO	TAP	CURRENT RATIO	TAP
300:5	X3–X4	1200:5	X1–X3
400:5	X1–X2	1500:5	X1–X4
500:5	X4–X5	1600:5	X2–X5
800:5	X2–X3	2000:5	X1–X5
1100:5	X2–X4		

BUSHING CURRENT TRANSFORMER
MULTI–RATIO RELAYING
ACCURACY CLASS C800
CT:N

CURRENT RATIO	TAP	CURRENT RATIO	TAP
50:5	X2–X3	300:5	X2–X4
100:5	X1–X2	400:5	X1–X4
150:5	X1–X3	450:5	X3–X5
200:5	X4–X5	500:5	X2–X5
250:5	X3–X4	600:5	X1–X5

BUSHING CURRENT TRANSFORMER
MULTI–RATIO RELAYING
ACCURACY CLASS C800
CT:K,L,M,P,R,S

CURRENT RATIO	TAP	CURRENT RATIO	TAP
300:5	X3–X4	1200:5	X1–X3
400:5	X1–X2	1500:5	X1–X4
500:5	X4–X5	1600:5	X2–X5
800:5	X2–X3	2000:5	X1–X5
1100:5	X2–X4		

BUSHING CURRENT TRANSFORMER
DUAL–RATIO METERING
ACCURACY CLASS .3B1.8
CT:T,U,V

CURRENT RATIO	TAP	CURRENT RATIO	TAP
800:5	X1–X2	1600:5	X1–X3

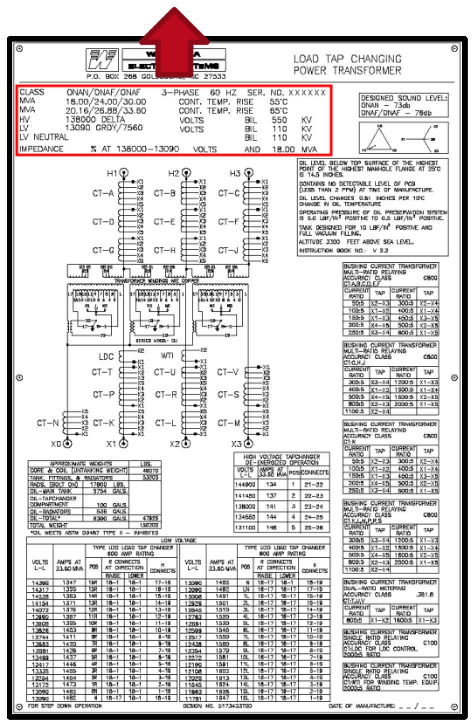
BUSHING CURRENT TRANSFORMER
SINGLE RATIO RELAYING
ACCURACY CLASS C100
CT:LDC FOR LDC CONTROL
2000:5 RATIO

BUSHING CURRENT TRANSFORMER
SINGLE RATIO RELAYING
ACCURACY CLASS C100
CT:WTI FOR WINDING TEMP. EQUIP.
2000:5 RATIO

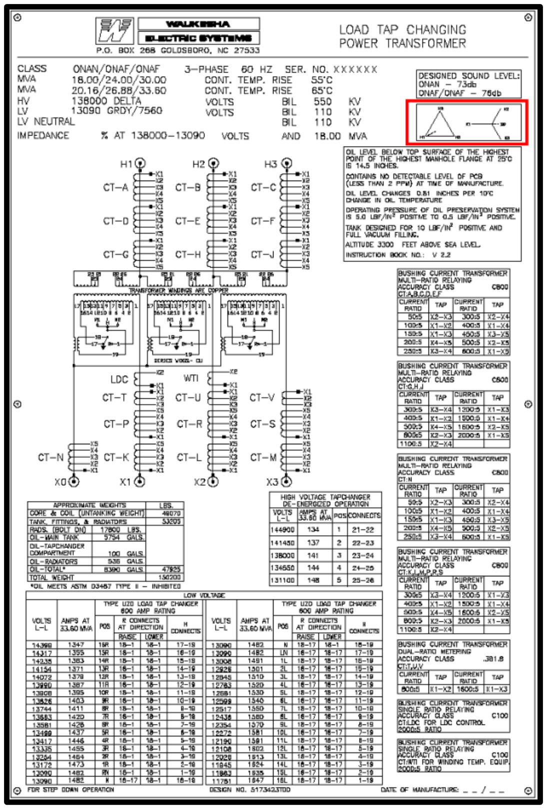
FOR STEP DOWN OPERATION
DESIGN NO. 5173423T00
DATE OF MANUFACTURE: _ _ / _ _

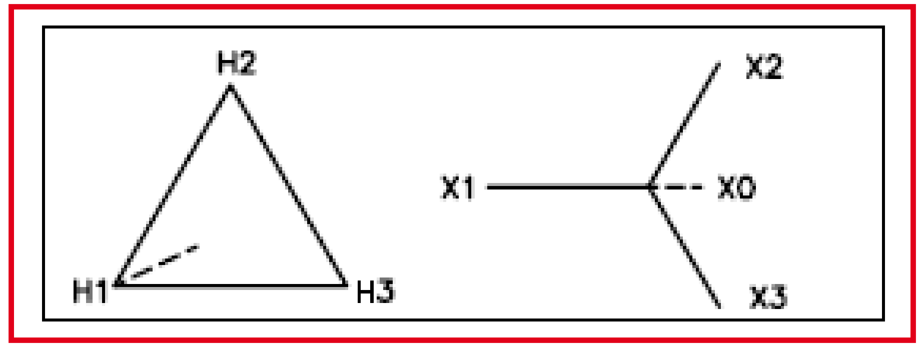
Ratings

CLASS	ONAN/ONAF/ONAF	3–PHASE 60 HZ	SER. NO.		
MVA	18.00/24.00/30.00	CONT. TEMP. RISE	55°C		
MVA	20.16/26.88/33.60	CONT. TEMP. RISE	65°C		
HV	138000 DELTA	VOLTS	BIL	550	KV
LV	13090 GRDY/7560	VOLTS	BIL	110	KV
LV NEUTRAL			BIL	110	KV
IMPEDANCE	% AT 138000–13090	VOLTS	AND	18.00	MVA

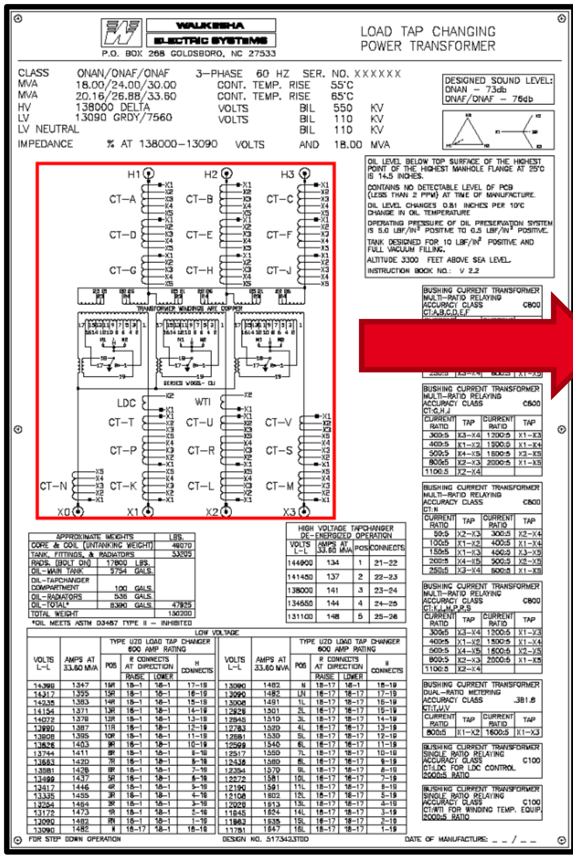


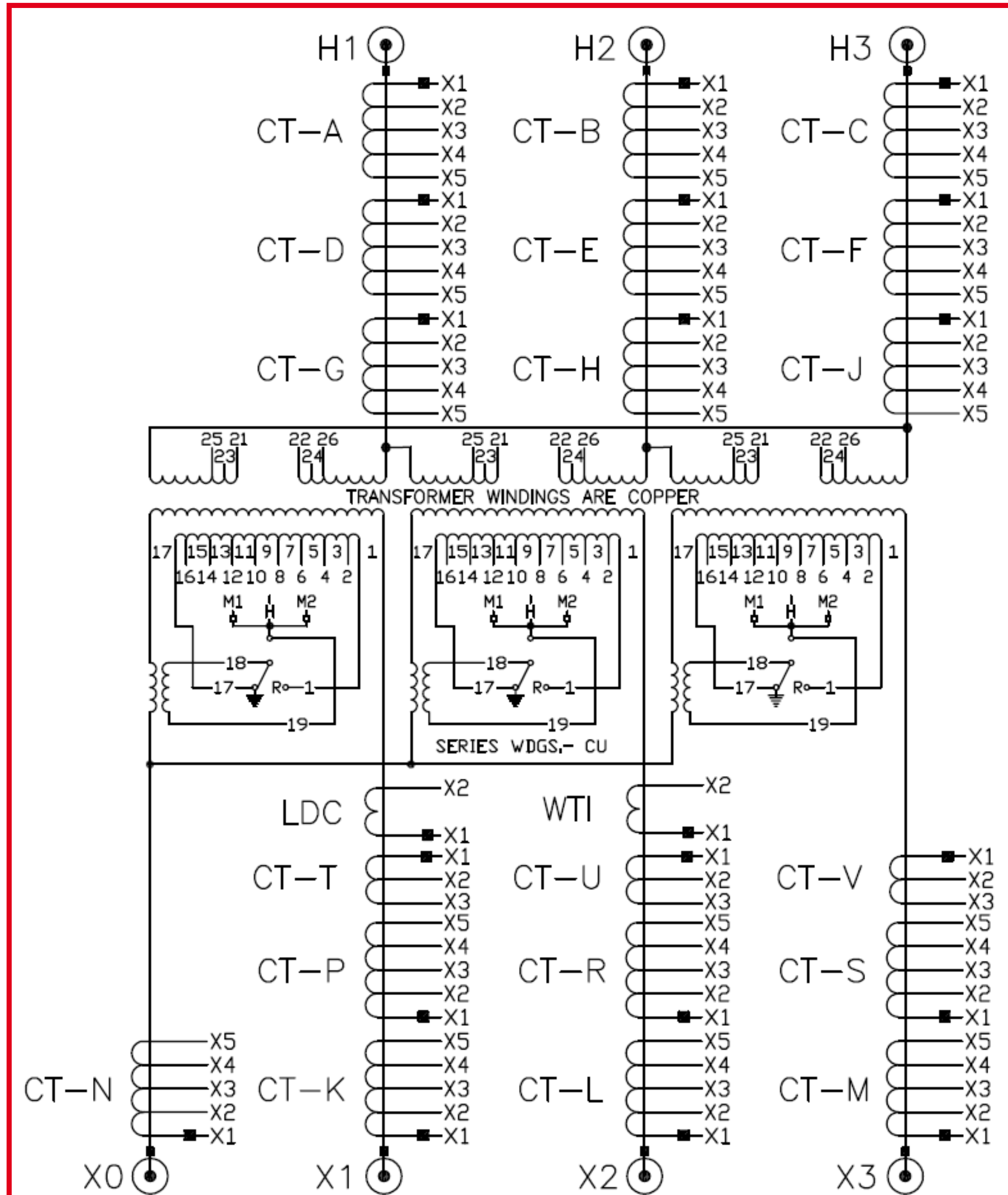
Vector Diagram





Wiring Diagram

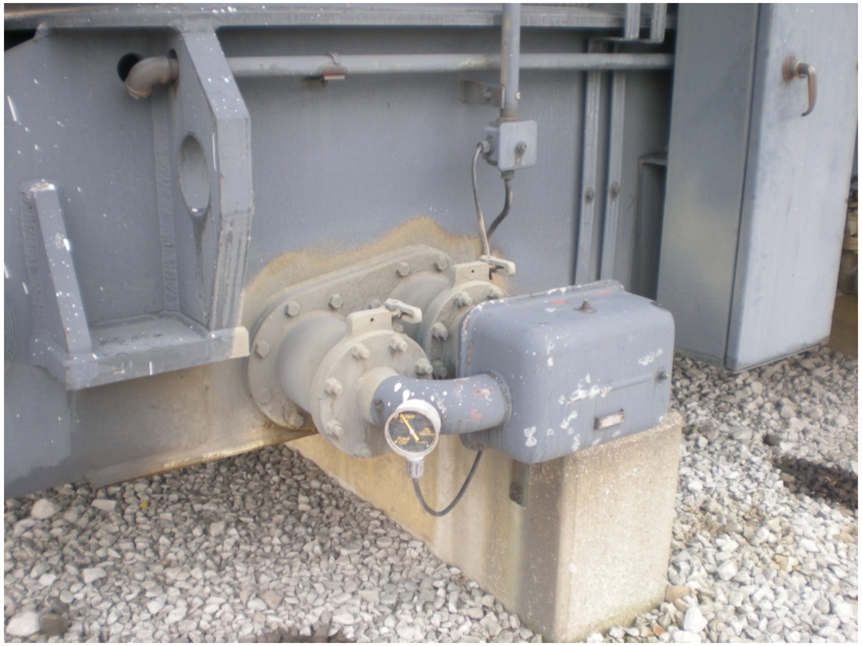




Cooling

- Prevent damage and loss of life to the insulation system
- Ages paper, pressboard, and oil
- Natural Convection
- Fans
- Pumps
- Water
- Directed Flow

Pumps, Fans, Radiators



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Temperatures

- Top Oil
- Bottom Oil
- Average Oil
- Average Winding
- Hot Spot

Diagnostic Testing - OVERALL

- DGA
- Oil Screen
- Power Factor / Capacitance
- Exciting Current
- Transformer Turns Ratio
- Leakage Reactance
- DC Winding Resistance
- SFRA (Sweep Frequency Response Analysis)
- DFR (Dielectric Frequency Response)
- Thermal Imaging
- Insulation Resistance
- Partial Discharge

Transformer Tests

Dielectric	Thermal	Mechanical
DGA	DGA	SFRA
Oil Screen	Oil Screen	Leakage Reactance
PF/TD CAP	IR	PF/TD CAP
Exciting Ima	DC Winding RES	Exciting Ima
Turns Ratio Tests		DC Winding RES
DFR		
Insulation Resistance		
Partial Discharge		

Diagnostic Testing - FOCUS

1. Power Factor / Capacitance
2. Exciting Current
3. Transformer Turns Ratio
4. Leakage Reactance
5. Insulation Resistance
6. DC Winding Resistance

1. Overall PF/CAP
2. Bushing PF/CAP (C1, C2, EC)
3. Exciting Current (Phase A, B, C)
4. Surge Arresters
5. Insulating Fluids (Main Tank, LTC)
6. Turns Ratio (H-X, H-Y, H-T, X-Y, X-T)
7. Leakage Reactance (3ϕ Equiv, Per ϕ)
8. Insulation Resistance
9. DC Winding Resistance (H, X, Y)

Power Factor Tests

1. Overall PF/CAP
2. Bushing PF/CAP (C1, C2, EC)
3. Surge Arresters
4. Insulating Fluids (Main Tank, LTC)

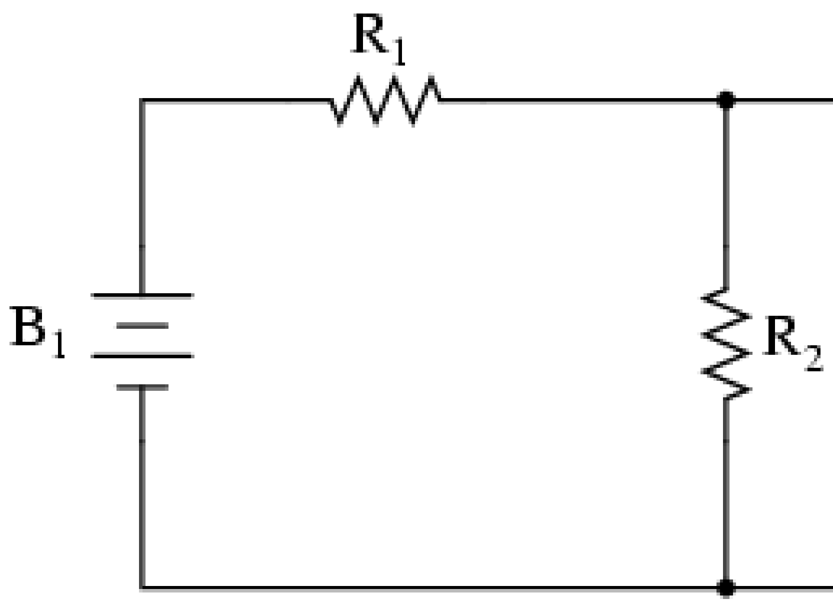
Dependent on Transformer Type

- 2-Winding XFMR
- 3-Winding XFMR
- Autotransformers
- Will cause variances in test plans and protocols.

Instrument Basics

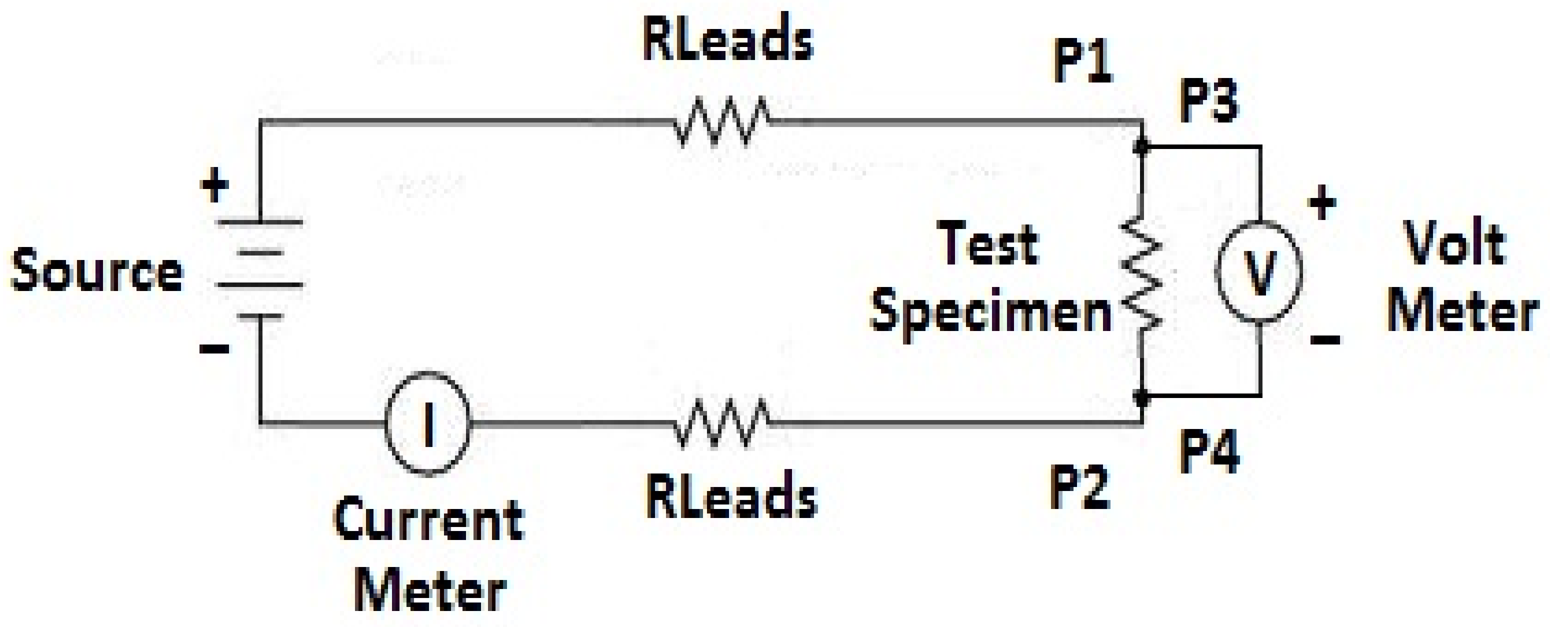
- Burden
- VA
- Sources – V and I
- Meters – V and I
- KVL and KCL
- Kelvin Connection

KVL and KCL



Kelvin Connection

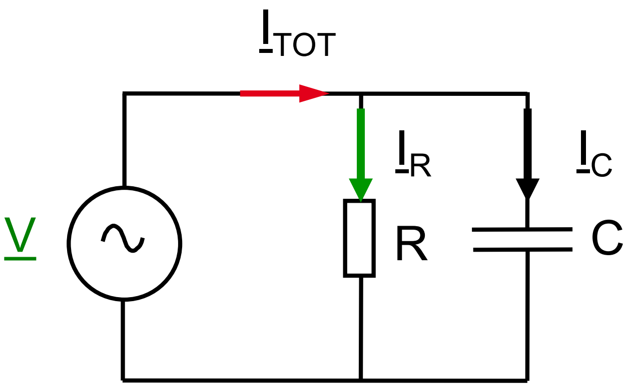
- 4-Wire Technique
- Exclude the resistance from the measurement circuit leads and any contact resistance at the connection points of these leads
- Voltage sense leads (P3 and P4) "inside" the current leads (P1 and P2)

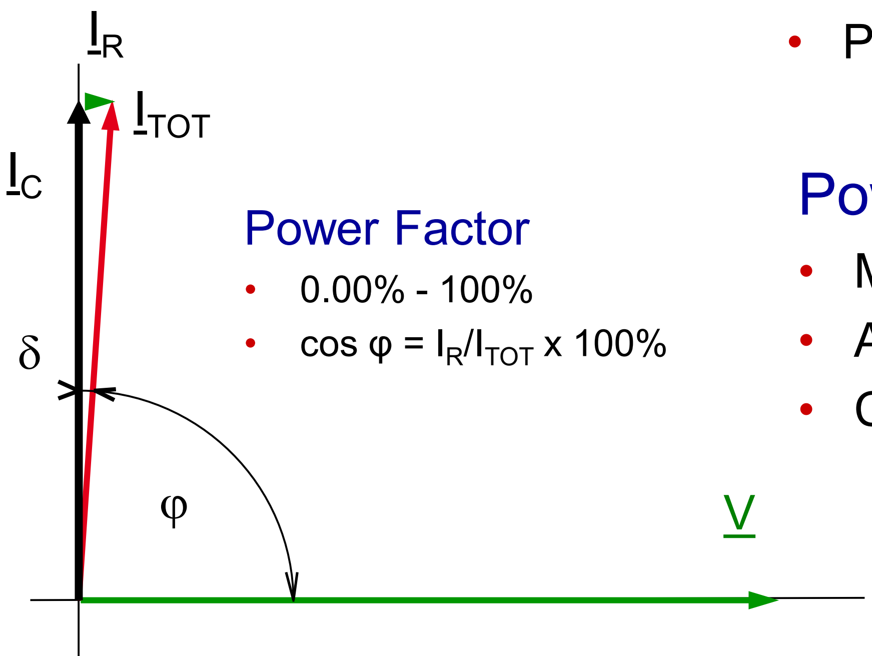


Overall PF/CAP

Type	Main Insulation	Bushings	Surge Arresters	Insulation Fluids
2-Winding	CH, CL, CHL	Up to 8 C1, C2, EC	Up to 6 Stacks	Main Tank Tap Changer
3-Winding	CH, CL, CT CHL, CHT, CLT	Up to 12 C1, C2, EC	Up to 9 Stacks	Main Tank Tap Changer
Auto w/Tert	CAuto, CT, CAutoT	Up to 10 C1, C2, EC	Up to 9 Stacks	Main Tank Tap Changer
Auto wo/Tert	CAuto	Up to 7 C1, C2, EC	Up to 6 Stacks	Main Tank Tap Changer

Power Factor / Capacitance Measurement





Power Factor

- 0.00% - 100%
- $\cos \varphi = I_R/I_{TOT} \times 100\%$

Insulation can be modeled through:

- Capacitance (Physical Geometry)
- Resistance (Losses)

Losses can be categorized as:

- Conductive
- Polarization (60 Hz Range)

Power Factor measures bulk degradation:

- Moisture
- Aging
- Contamination

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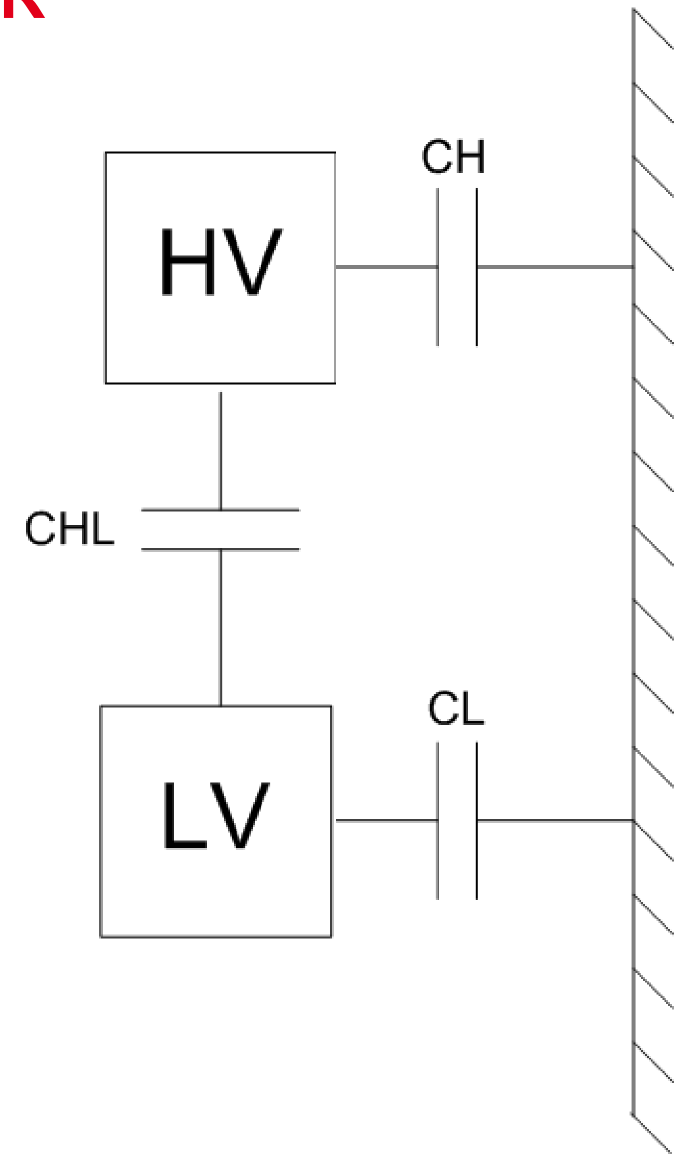
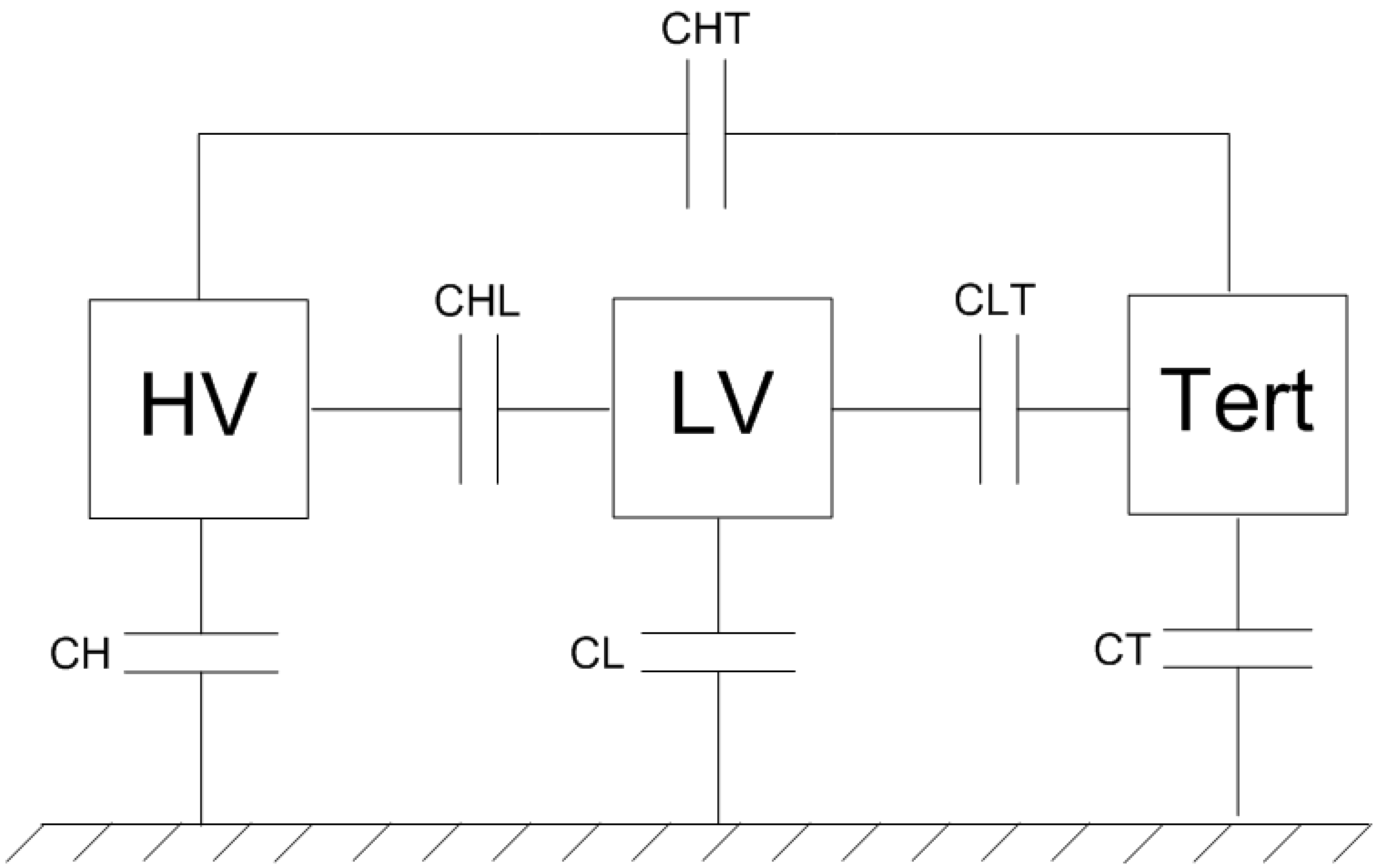
Power Factor / Capacitance

- "Applied Test" at Rated Frequency (60 Hz)
- Measurements Normalized to 20°C.
- Test voltages for a typical field test set range from below 100 V to as high as 12 kV. (IEEE Std. 62)
- 10 kV is Normally Applied
    a) 2000 VA
    b) 80,000 pF
- Data should be analyzed by:
    a) Limits
    b) Trending
    c) Nameplate

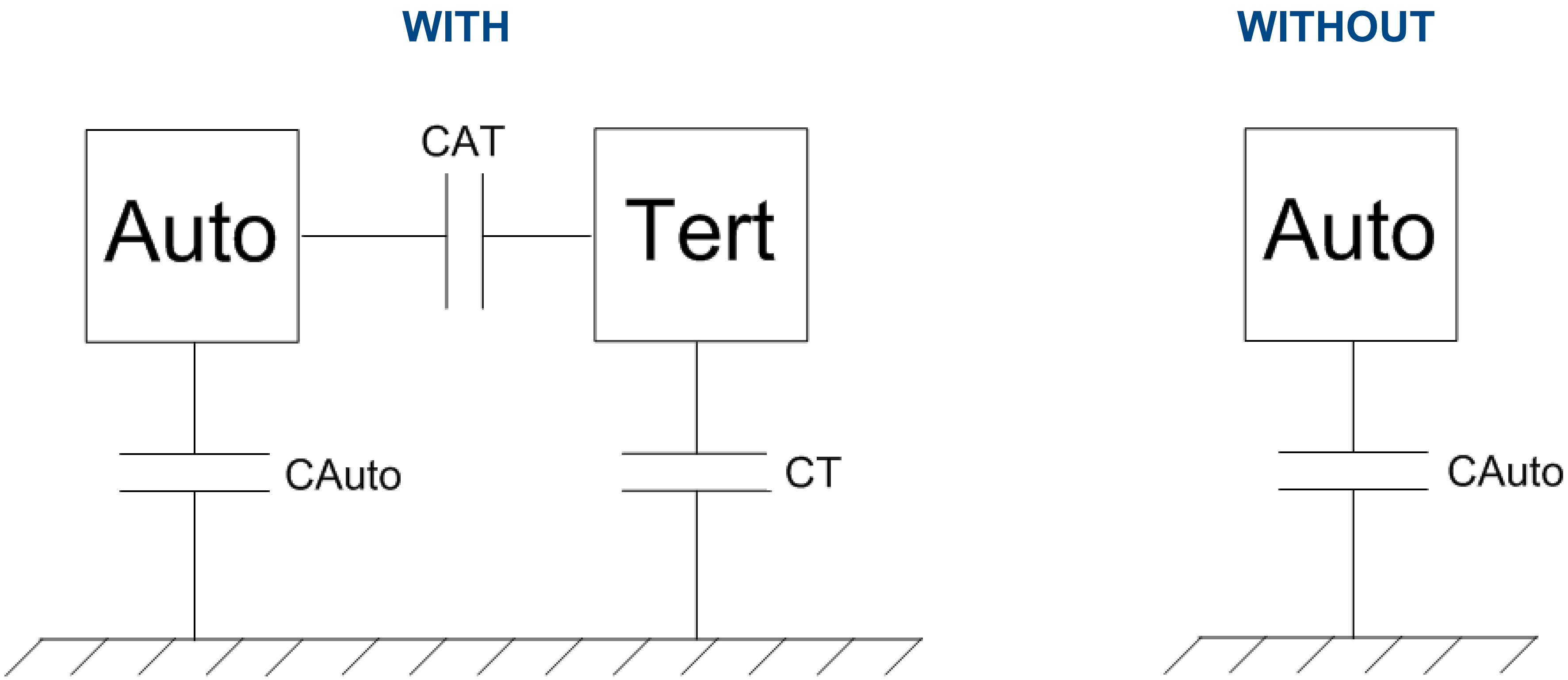
2-Winding XFMR



3-Winding XFMR

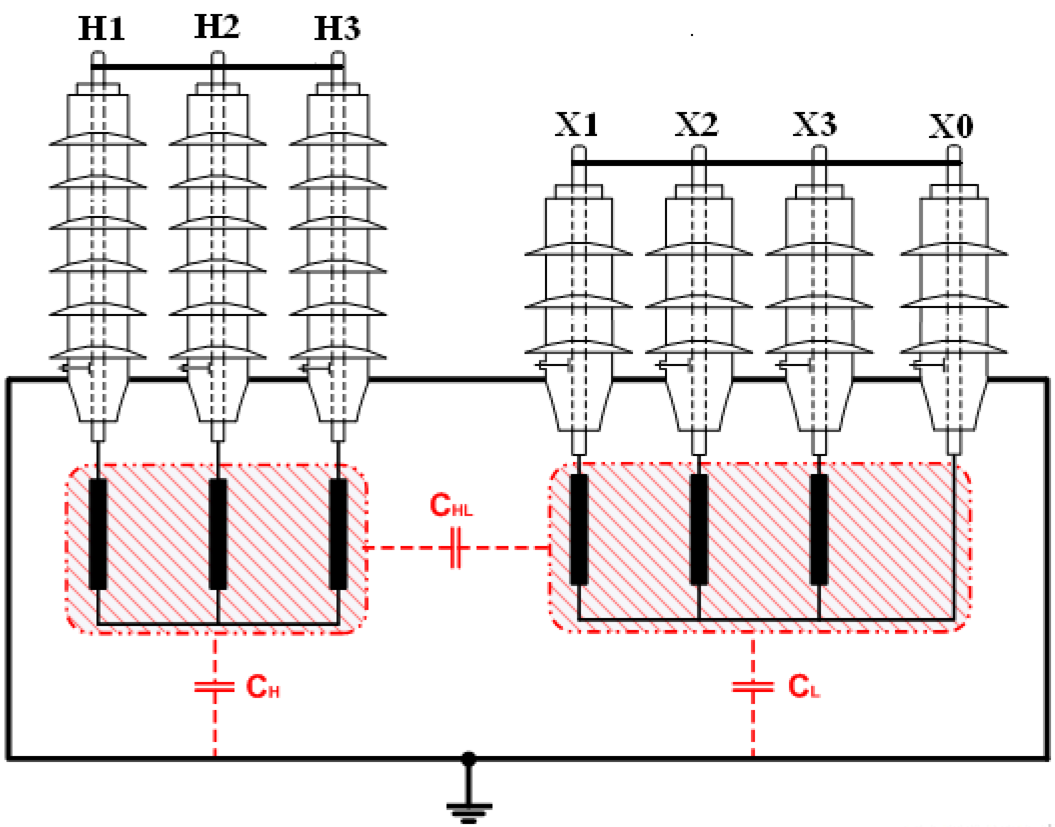


Autotransformers WITH & WITHOUT Tertiary



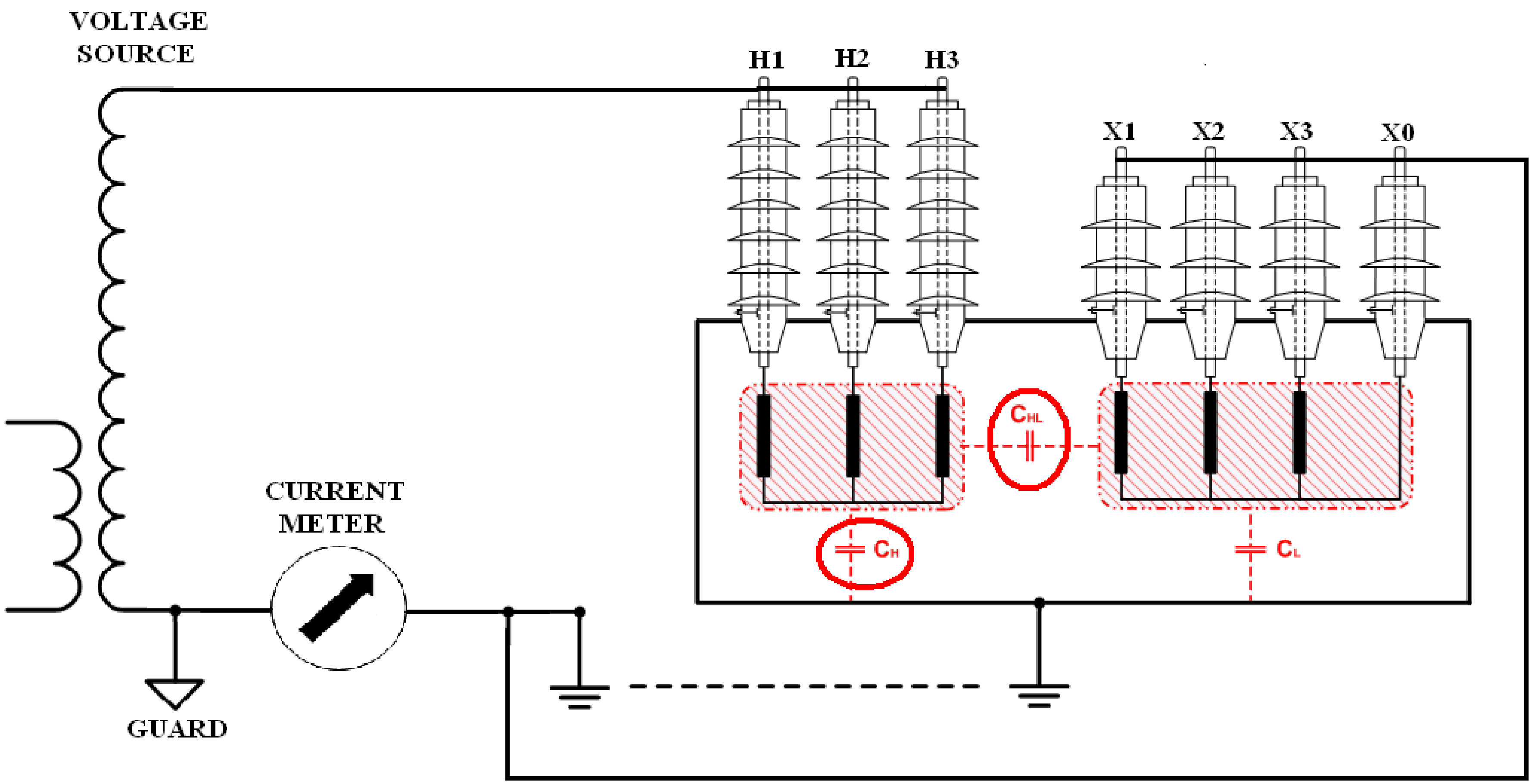
Two-Winding Transformer Model

- Windings are short-circuited to remove unwanted inductance
- CH, CL and CHL insulation systems
- CH includes H-C1
- CL includes X-C1



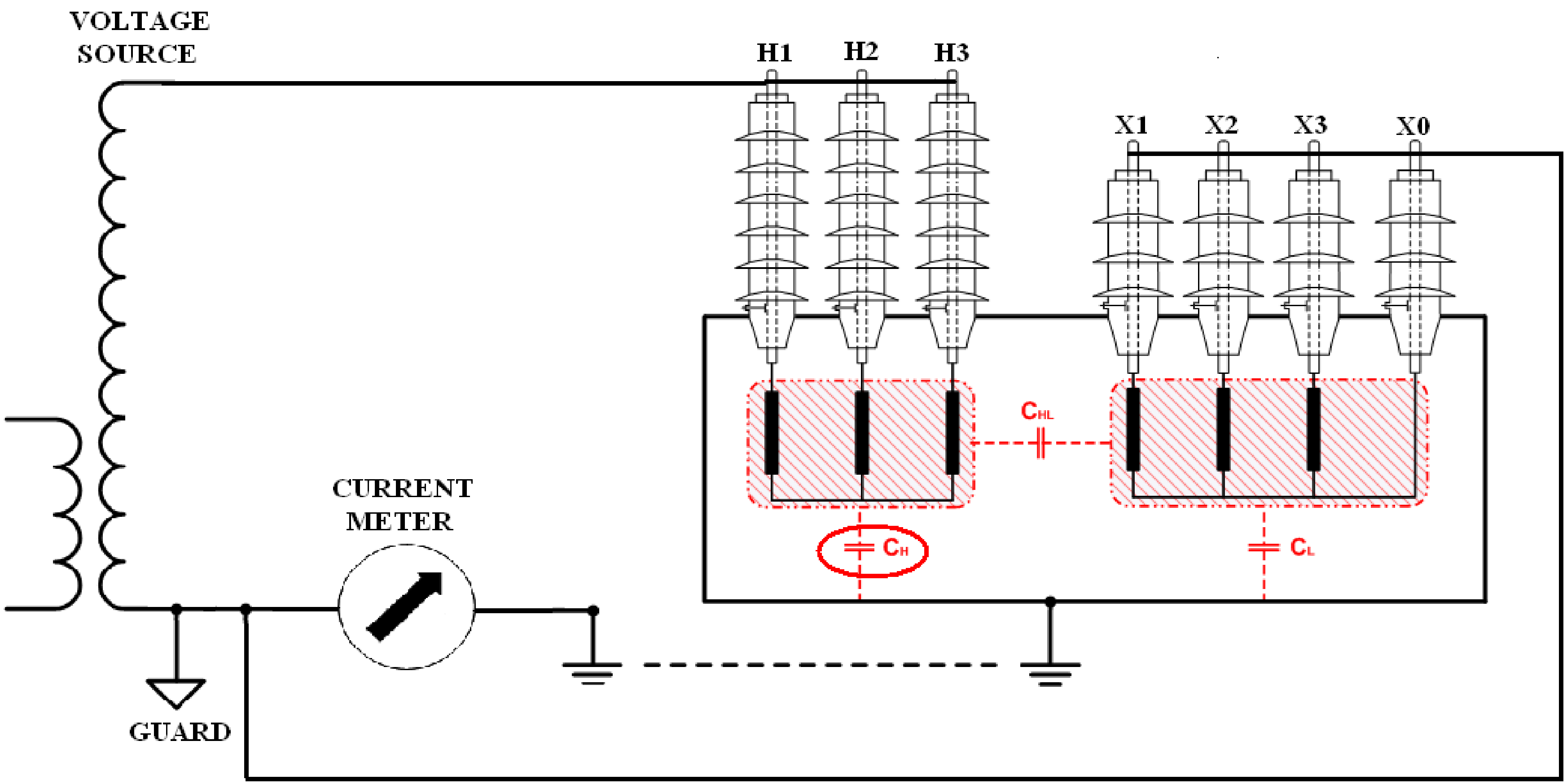
GST Measurement

- Both CH and CHL are measured together



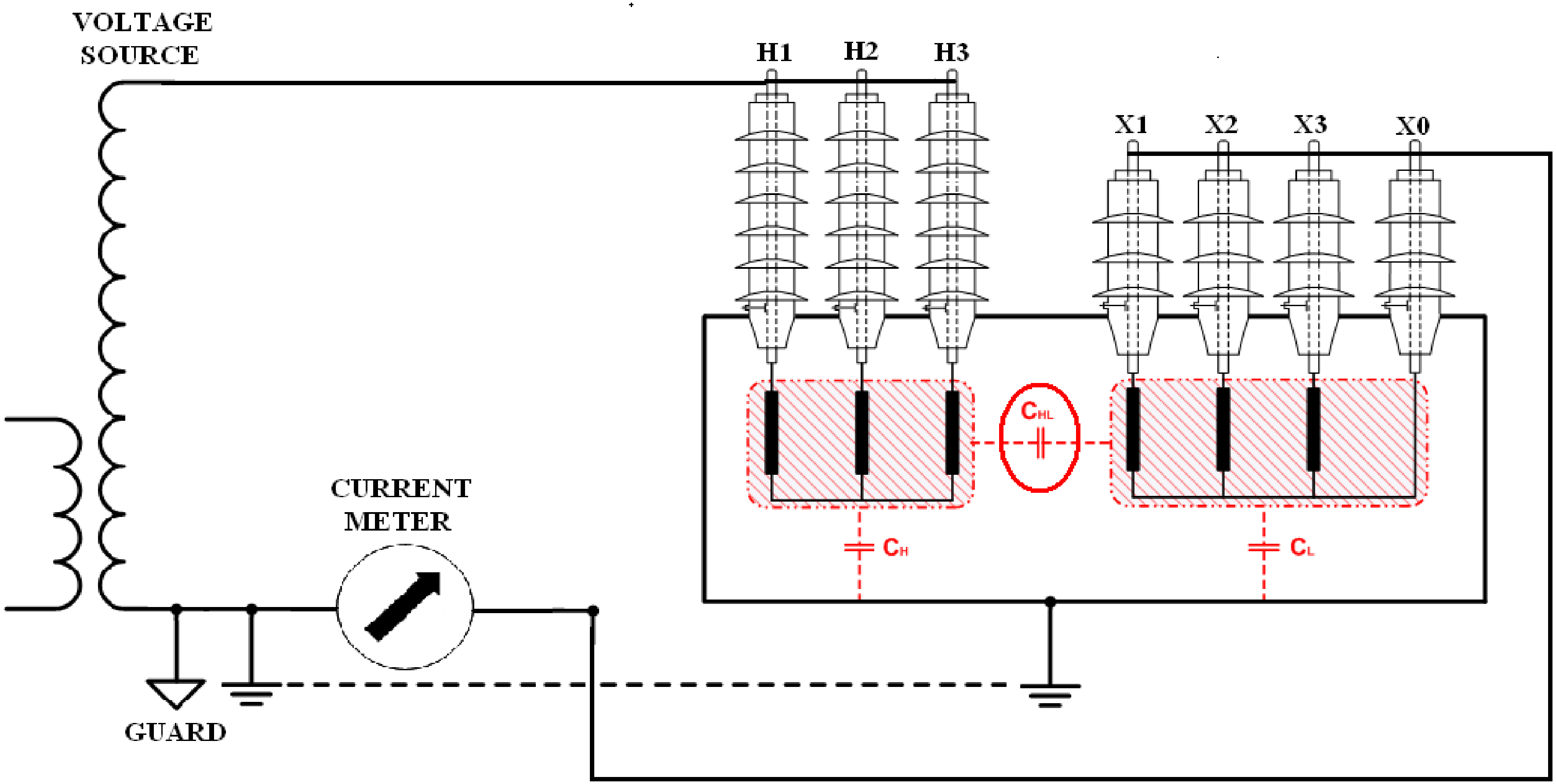
GST GUARD Measurement - CH

- CH is isolated by use of the GSTg measurement circuit



UST Measurement - CHL

- CHL is isolated by use of the UST measurement circuit



Overall Test Data

2-WINDING TRANSFORMER – OVERALL													
Measurement Type	Ref@10 kV												
Test #	Energize	Ground	Guard	UST	Test kV	I mA	Cap pF	Watt Loss	PF [%] Measured	PF [%] Corrected	Correction Factor	Mode	Insulation Condition
ICH+ICHL	H (prim)	L (sec)			10.013	33.241	8814.88	0.746			1.00	GST	
ICH	H (prim)		L (sec)		10.010	7.889	2089.50	0.217	0.28	0.28	1.00	GST gA	PASS
ICHL	H (prim)			L (sec)	10.013	25.355	6725.82	0.526	0.21	0.21	1.00	UST A	PASS
	Calculated ICHL					25.353	6725.38	0.529	0.21	0.21	1.00		PASS
	ICH-C1 = ICH minus H (prim) bushings; HV C1 ONLY					5.206	1377.91	0.156	0.30	0.30	1.00		PASS
ICL+ICHL	L (sec)	H (prim)			7.500	94.449	25051.64	2.375			1.00	GST	
ICL	L (sec)		H (prim)		7.501	69.096	18325.39	1.864	0.27	0.27	1.00	GST gA	PASS
ICHL	L (sec)			H (prim)	7.500	25.356	6725.70	0.519	0.20	0.20	1.00	UST A	PASS
	Calculated ICHL					25.353	6726.25	0.511	0.27	0.27	1.00		PASS
	ICL-C1 = ICL minus L (sec) bushings; LV C1 ONLY					58.678	15562.15	1.619	0.37	0.37	1.00		PASS

Bushing Taps

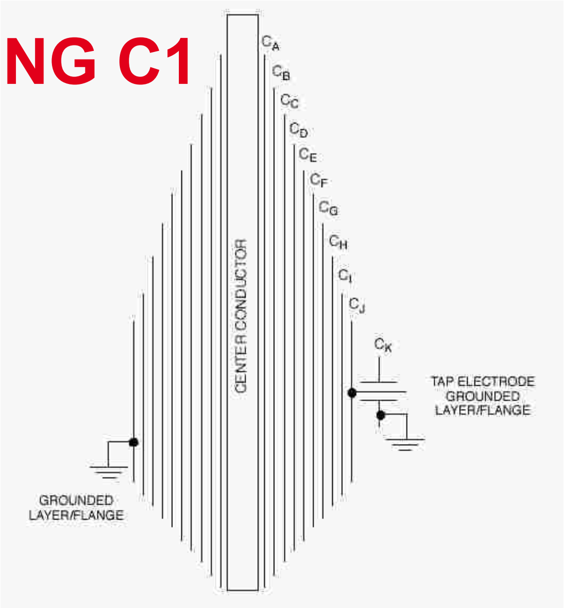
Field Tests

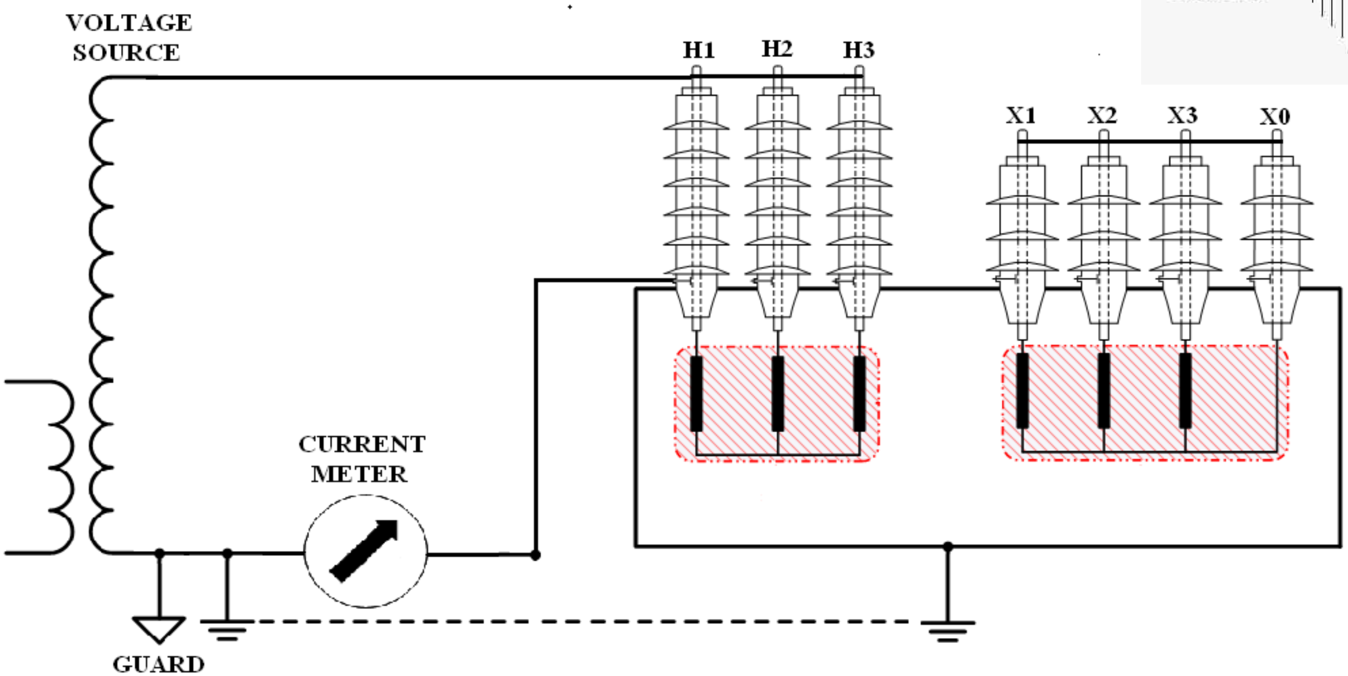
The following test are electrical field tests performed with portable test equipment to determine bushing suitability for service.

Condenser Bushing with Potential Tap	Condensers Bushing with Test Tap	Non Condenser
Visual Inspection	Visual Inspection	Visual Inspection
C1 Power Factor (60 Hz)	C1 Power Factor (60 Hz)	Energize Collar Test
C1 Capacitance (60 Hz)	C1 Capacitance (60 Hz)	Infrared Test
C2 Power Factor (2.5 kV)	C2 Power Factor (0.5 kV)	
C2 Capacitance (2.5 kV)	C2 Capacitance (0.5kV)	
Advance Power Factor Measurements	Advance Power Factor Measurements	
Power Factor Tip Up Test	Power Factor Tip Up Test	
Infrared Test	Infrared Test	

Power Factor / Capacitance - BUSHING C1

- Bushing H1-C1 → UST
- All Terminals Remain Shorted





Bushing C1 Test Data

Bushings - NAMEPLATE

Bushing	Manufact.	Model/ Type	Year	Serial Number	Catalog Number	Drawing Number	BIL kV	kV Rating	A Rating	C1 PF[%]	C1 Cap (pF)	C2 PF[%]	C2 Cap (pF)
H1	ABB	O+C	1993				350	44.00	400	0.35	238		
H2	ABB	O+C	1993				350	44.00	400	0.26	240		
H3	ABB	O+C	1993				350	44.00	400	0.32	239		
H0													
X1	ABB	O+C	1993				150	25.00	2000	0.33	695		
X2	ABB	O+C	1993				150	25.00	2000	0.30	692		
X3	ABB	O+C	1993				150	25.00	2000	0.31	699		
X0	ABB	O+C	1993				150	25.00	2000	0.29	693		

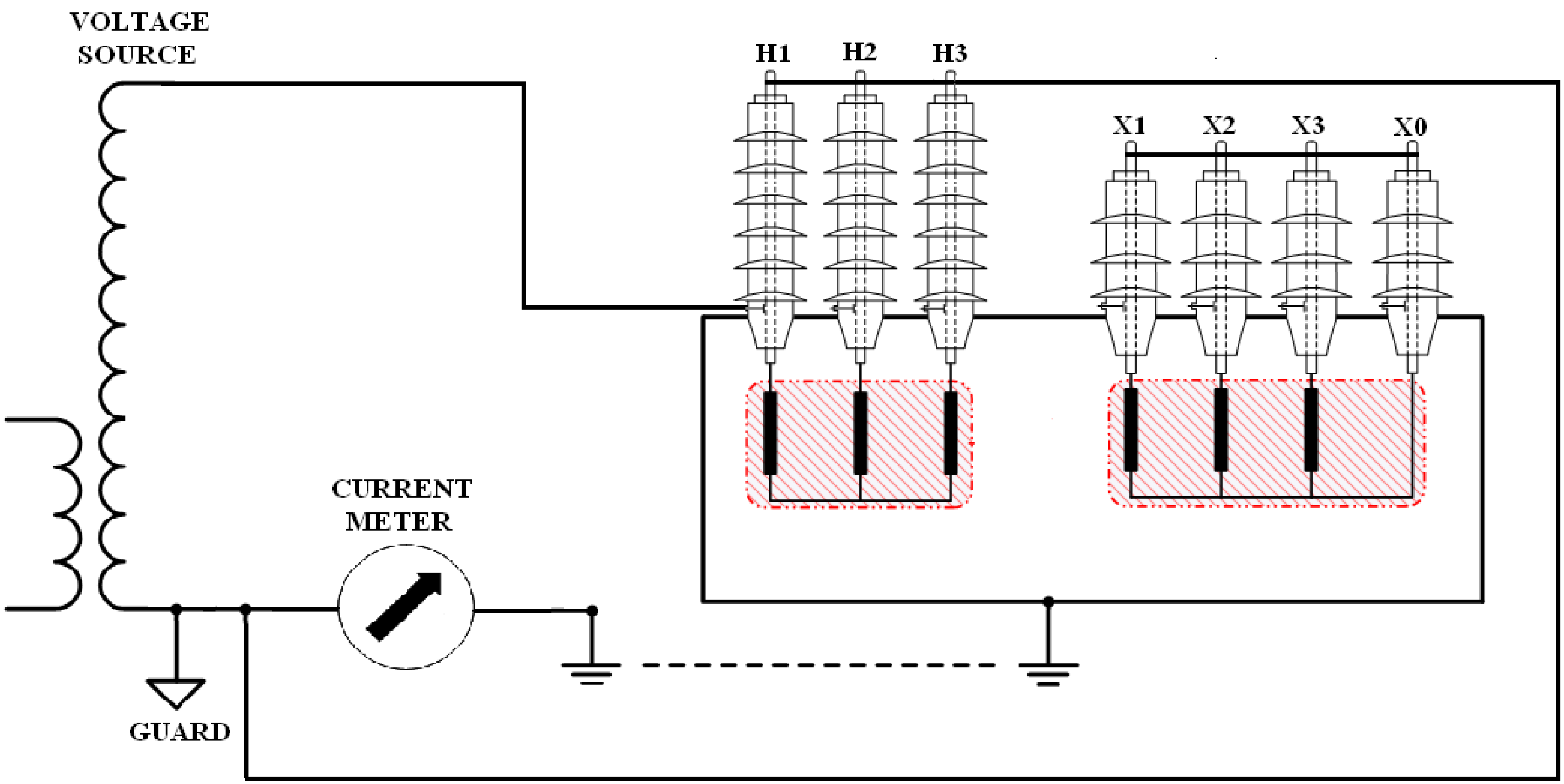
Bushings - C1

Measurement Type Ref@10 kV

Bushing	Energize	Ground	Guard	UST	Test kV	I mA	Cap pF	Watt Loss	PF [%] Measured	PF [%] Corrected	Correction Factor	Mode	Insulation Condition
H1	Conductor	-	-	Tap	10.022	0.891	236.25	0.020	0.22	0.22	1.00	UST A	PASS
H2	Conductor	-	-	Tap	10.014	0.896	237.67	0.021	0.23	0.23	1.00	UST A	PASS
H3	Conductor	-	-	Tap	10.022	0.896	237.68	0.021	0.24	0.24	1.00	UST A	PASS
H0	Conductor	-	-	Tap							1.00	UST A	
X1	Conductor	-	-	Tap	7.505	2.617	694.15	0.062	0.24	0.24	1.00	UST A	PASS
X2	Conductor	-	-	Tap	7.506	2.560	679.08	0.058	0.23	0.23	1.00	UST A	PASS
X3	Conductor	-	-	Tap	7.506	2.631	697.78	0.061	0.23	0.23	1.00	UST A	PASS
X0	Conductor	-	-	Tap	7.505	2.610	692.23	0.063	0.24	0.24	1.00	UST A	PASS

Power Factor / Capacitance - BUSHING C2

- H1-C2 ➡ GST gA

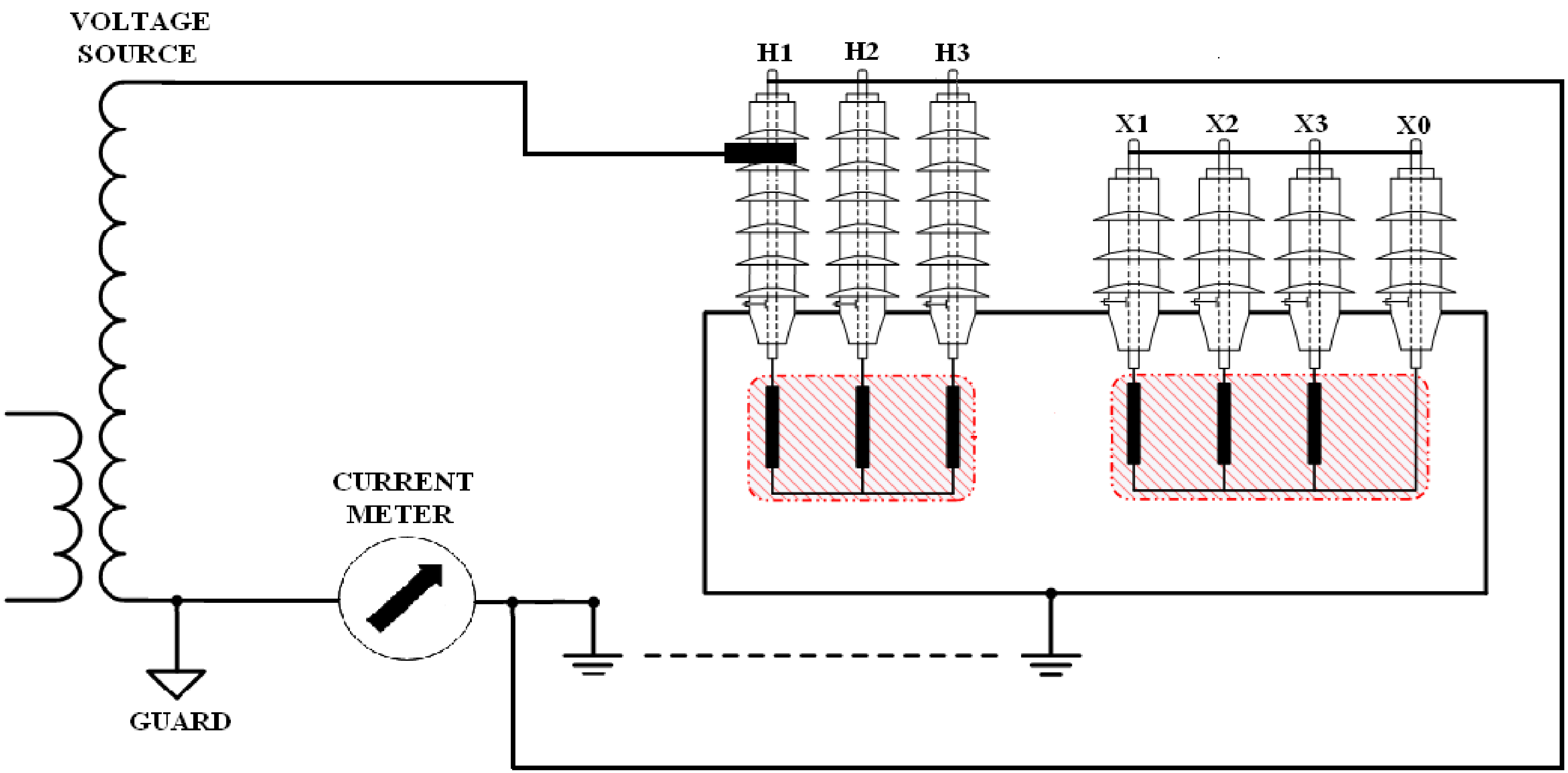


Bushing C2 Test Data

Bushings - C2														
Measurement Type Ref@10 kV														
Bushing	Energize	Ground	Guard	UST	Test kV	I mA	Cap pF	Watt Loss	PF [%] Measured	PF [%] Corrected	Correction Factor	Mode	Insulation Condition
H1	Tap	-	Conductor	-	0.507	2.099	553.67	0.058	0.28	0.28	1.00	GST gA	PASS
H2	Tap	-	Conductor	-	0.505	2.301	607.14	0.074	0.32	0.32	1.00	GST gA	PASS
H3	Tap	-	Conductor	-	0.502	2.165	571.03	0.063	0.29	0.29	1.00	GST gA	PASS
H0	Tap	-	Conductor	-							1.00	GST gA	
X1	Tap	-	Conductor	-	0.508	0.887	232.41	0.063	0.71	0.71	1.00	GST gA	PASS
X2	Tap	-	Conductor	-	0.507	0.879	230.15	0.029	0.33	0.33	1.00	GST gA	PASS
X3	Tap	-	Conductor	-	0.507	0.873	228.82	0.023	0.27	0.27	1.00	GST gA	PASS
X0	Tap	-	Conductor	-	0.507	0.844	221.01	0.014	0.16	0.16	1.00	GST gA	PASS

Power Factor / Capacitance - BUSHING EC

- H1-EC ➡ GST or UST
- UST and GUARD circuits can be used for external contamination investigation and/or isolation



Energized “Hot” Collar Test Data

Bushings - Energized Collar

Measurement Type Ref@10 kV

Bushing	Energize	Ground	Guard	UST	Test kV	I mA	Watt Loss	Mode	Insulation Condition
H1	Collar	-	-	-	10.022	0.891	0.020	GST	PASS
H2	Collar	-	-	-	10.014	0.896	0.021	GST	PASS
H3	Collar	-	-	-	10.022	0.896	0.021	GST	PASS
H0	Collar	-	-	-				GST	
X1	Collar	-	-	-	10.006	1.973	0.061	GST	PASS
X2	Collar	-	-	-	10.016	1.974	0.060	GST	PASS
X3	Collar	-	-	-	10.008	1.973	0.062	GST	PASS
X0	Collar	-	-	-	10.020	1.975	0.061	GST	PASS

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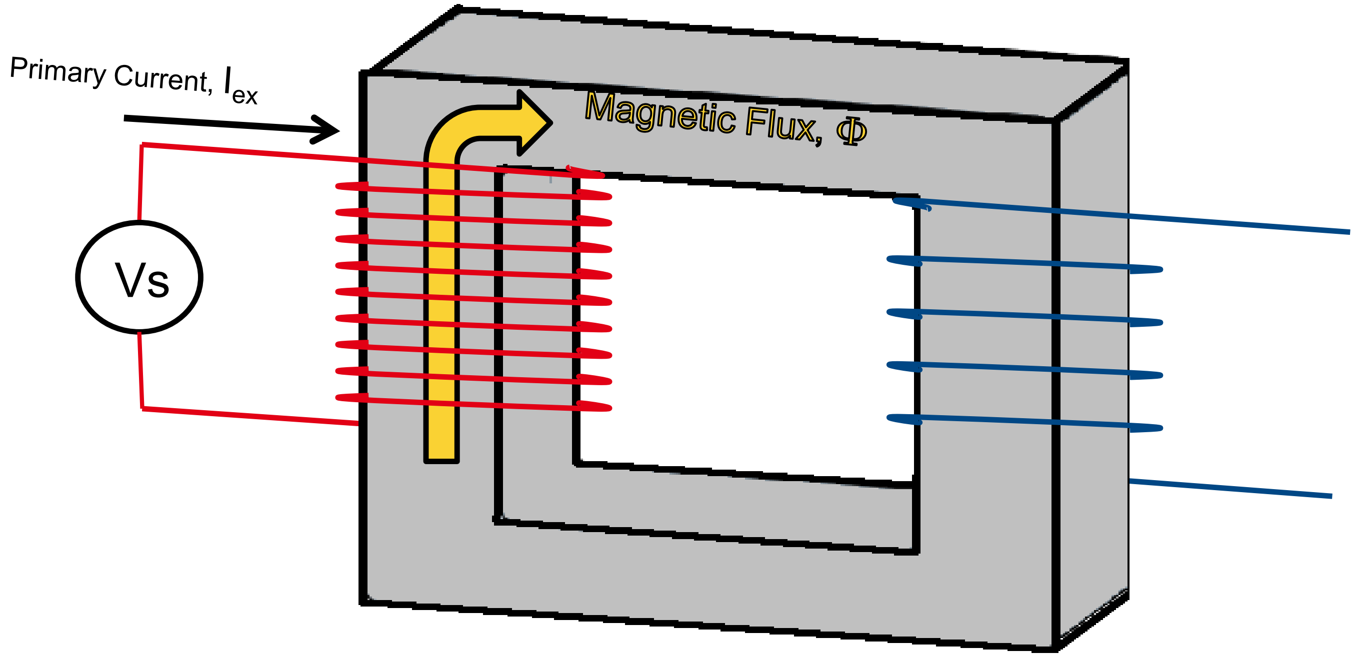
Transformer Exciting Current Test



1. Apply Voltage Vs on on primary phase, secondary winding left floating
2. Measure currurent I_{ex}
3. The current required to force ``transformer action´´ (the use of one winding to induce a voltage in the second winding).

Exciting Current Test Procedure

Routine Test

- Perform test on each phase with the DETC on its “as found” position.

- DETC should not be moved unless specified by company or manufacturer

- Ideally test should be performed on all phases at each LTC positions

Analyzing Results

- Confirm Expected Phase Pattern
- Confirm Expected LTC Pattern

  (For load tap changing transformers)
- Compare to Previous Results
  - Make sure same voltage is applied
  - Magnitudes do not have to match
    - Any change should be uniform across phases (similar percent change).

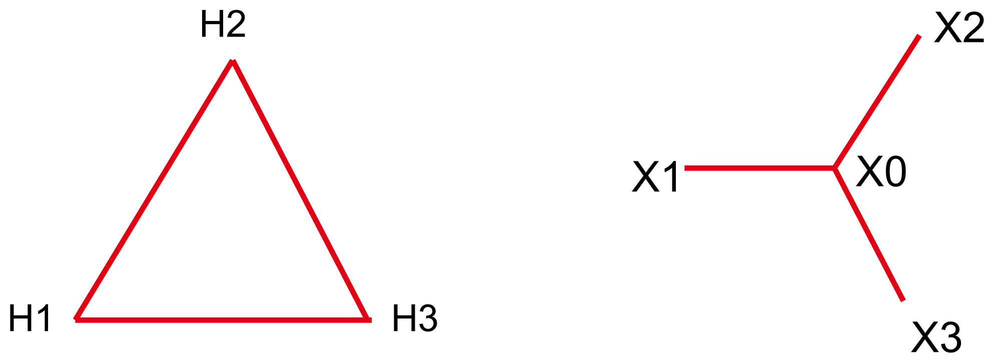
Analyzing Results

Confirming the Expected Phase Pattern:

1. High – Low – High (**HLH**) Pattern
   - Expected for a 3-legged core type transformer.
   - Expected for a 5-legged core (or shell) type transformer with a Delta connected secondary winding.
2. Low – High – Low (**LHL**) Pattern
   - Will be obtained on a 3-legged core type transformer ***if*** the traditional test protocals are not followed.
     - ⇨Neutral on high side Wye-configured transformer is inaccessible
     - ⇨Forget to ground 3rd terminal on a Delta-connected transformer
   - Expected for a 4-legged core type transformer.
3. All 3 Similar Pattern
   - Expected for a 5-legged core (or shell) type transformer with a non-delta secondary winding.

Exciting Current Test

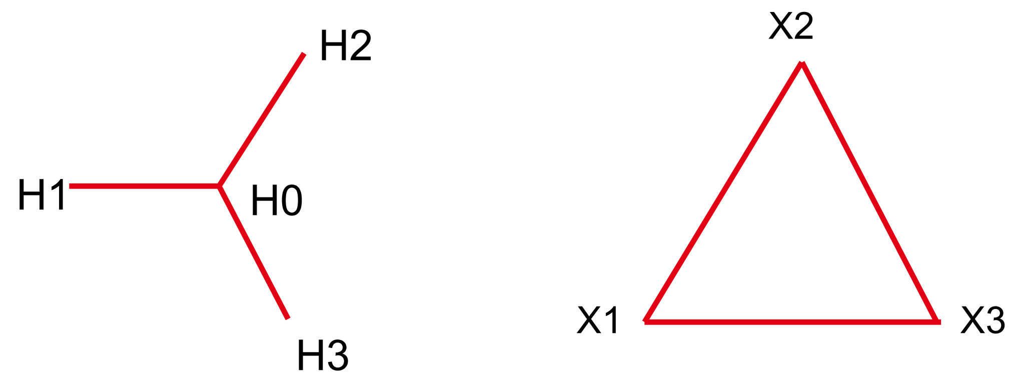
Transformer: HV – Delta LV - Wye



Test	HV Lead	LV Lead	Ground	Float	Mode	Measure	Result
1	H1	H3	H2, X0	X1,X2,X3	UST	H1-H3	63.8 mA
2	H2	H1	H3, X0	X1,X2,X3	UST	H2-H1	48.6 mA
3	H3	H2	H1, X0	X1,X2,X3	UST	H3-H2	64.2 mA

Exciting Current Test

Transformer: HV – Wye LV - Delta

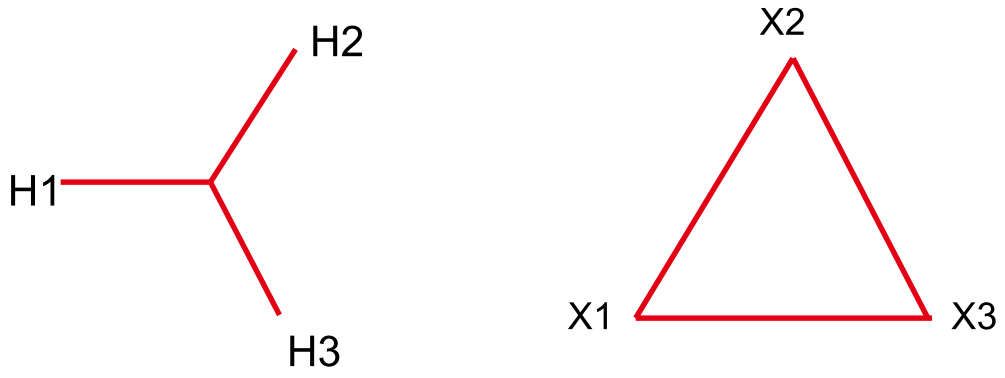


Test	HV Lead	LV Lead	Ground	Float	Mode	Measure	Result
1	H1	H0	NONE	X1,X2,X3	UST	H1-H0	78.8 mA
2	H2	H0	NONE	X1,X2,X3	UST	H2-H0	62.4 mA
3	H3	H0	NONE	X1,X2,X3	UST	H3-H0	80.2 mA

Exciting Current Test

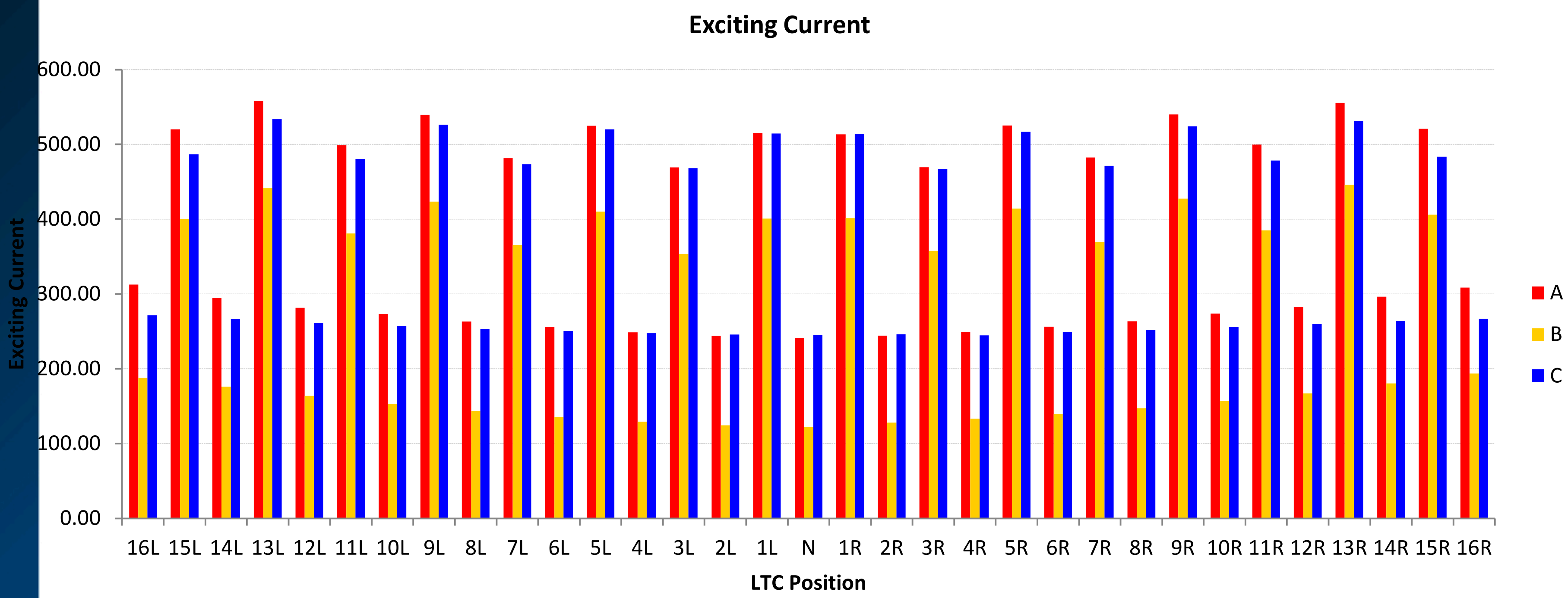
Transformer: HV – Wye LV - Delta

Inaccessible Neutral Bushing (H0)



Test	HV Lead	LV Lead	Ground	Float	Mode	Measure	Result
1	H1	H2	NONE	X1,X2,X3	UST	H1-H2	75.1 mA
2	H2	H3	NONE	X1,X2,X3	UST	H2-H3	73.2 mA
3	H3	H1	NONE	X1,X2,X3	UST	H3-H1	89.4 mA

Exciting Current LTC Pattern – Reactor Type



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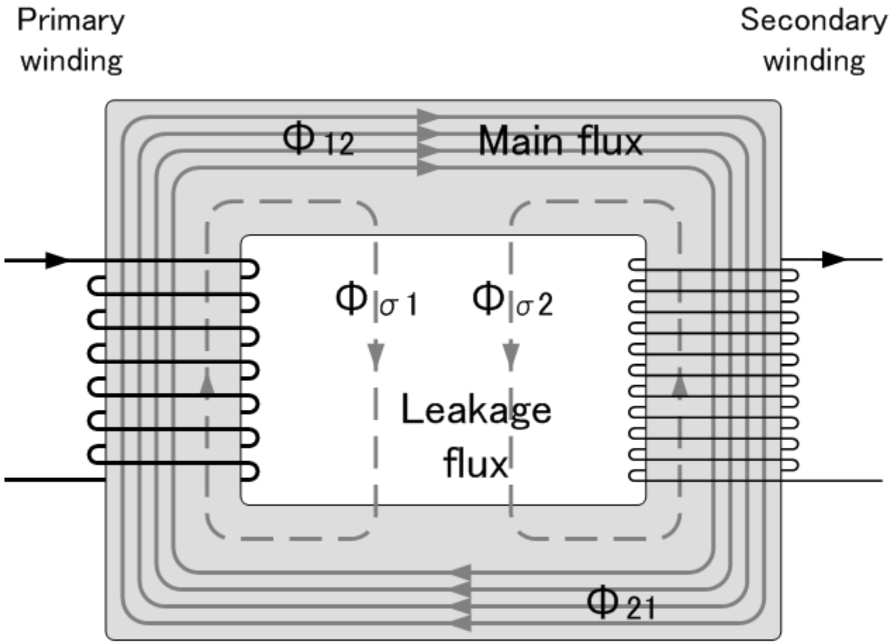
Leakage Reactance

- Leakage flux is flux that does not link all the turns of the winding
- Leakage flux creates reactive magnetic energy that behaves like an inductor in series in the primary and secondary circuits
- Winding movement changes the reluctance of the leakage flux path, resulting in a change in the expected leakage reactance measurement.



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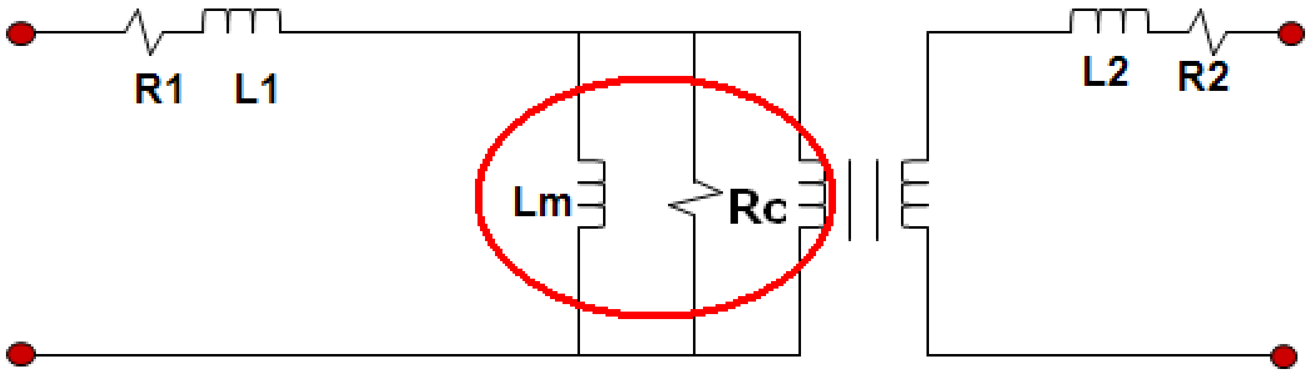
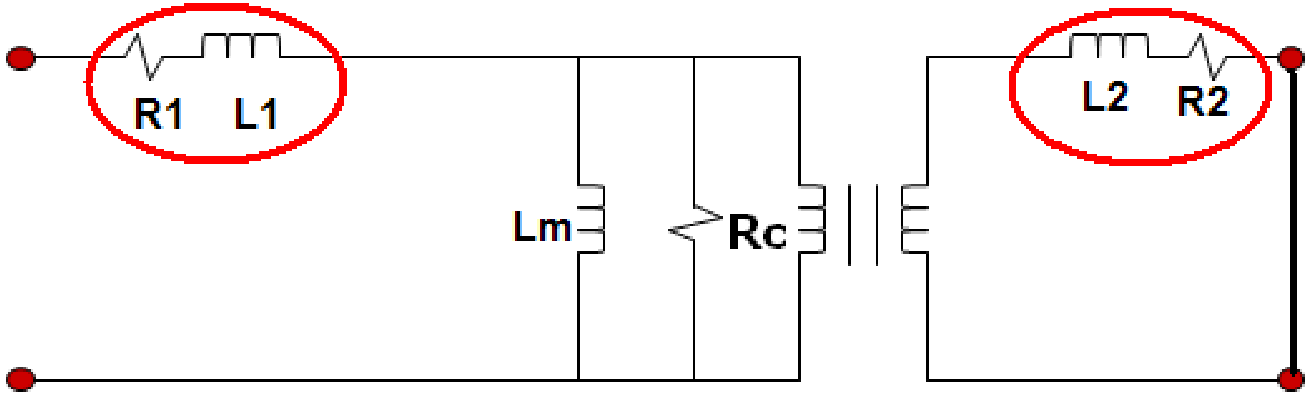
Leakage Reactance





Leakage Reactance

- Short circuit LV winding or “winding pairs”
- Inject 0.5 - 1.0% of rated current 60 Hz (Line-to-Line)
- A variable 280 VAC source is recommended
- Measure Series Current and Terminal Voltage
- RESULT - ZΩ, RΩ, and XΩ

- There are two ways to perform the measurement
    1. 3 Phase Equivalent
    2. Per Phase

Leakage Reactance – 3 Phase Equivalent

- Short LV terminals; do not include neutral
- Compare to nameplate +/- 3%

Inject	Short	Measure
H_1-H_3	X_1, X_2, X_3	Z_A, R_A, X_A, L_A
H_2-H_1	X_1, X_2, X_3	Z_B, R_B, X_B, L_B
H_3-H_2	X_1, X_2, X_3	Z_C, R_C, X_C, L_C

1ϕ UNIT ➡ $$\%Z = \frac{1}{10}\left[(Z)\left(\frac{BasekVA_1}{kV^2}\right)\right]$$

3ϕ UNIT ➡ $$\%Z = \frac{1}{60}\left[(Z_{AC} + Z_{BA} + Z_{CB})\left(\frac{BasekVA_3}{kV_{ll}^2}\right)\right]$$

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Leakage Reactance – Per Phase

- Short corresponding LV terminals
- Compare deviation from average

Inject	Short	Measure
H_1-H_3	X_1-X_0, X_1-X_3	Z_A, R_A, X_A, L_A
H_2-H_1	X_2-X_0, X_2-X_1	Z_B, R_B, X_B, L_B
H_3-H_2	X_3-X_0, X_3-X_2	Z_C, R_C, X_C, L_C

Leakage Reactance – NAMEPLATE

CLASS	ONAN/ONAF/ONAF	3–PHASE 60 HZ		SER. NO.		
MVA	18.00/24.00/30.00	CONT. TEMP. RISE			55°C	
MVA	20.16/26.88/33.60	CONT. TEMP. RISE			65°C	
HV	138000 DELTA	VOLTS		BIL	550	KV
LV	13090 GRDY/7560	VOLTS		BIL	110	KV
LV NEUTRAL				BIL	110	KV
IMPEDANCE	9.60 % AT 138000–13090		VOLTS	AND	18.00	MVA

$$\%Z = \frac{1}{60}[(Z_{AC} + Z_{BA} + Z_{CB})(\frac{BasekVA_3}{kV_{ll}^2})]$$

$$\%Z = \frac{1}{60}[(Z_{AC} + Z_{BA} + Z_{CB})(\frac{18,000}{138^2})]$$

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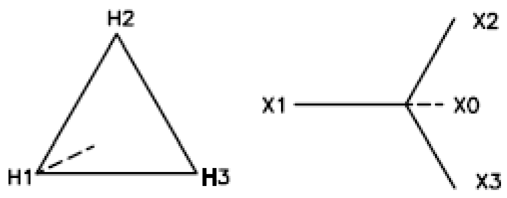
Leakage Reactance – Example

Nameplate: 6.85% 69 kV 12.5 MVA



Phase	V	I	Z	R	X	L
H1-H3	55.22	1.05	51.59	4.38	51.41	136.4
H2-H1	54.68	1.05	51.15	4.37	50.96	135.2
H3-H2	54.46	1.05	50.96	4.46	50.76	134.2

$$\%Z = \frac{1}{60}\left[(Z_{AC} + Z_{BA} + Z_{CB})\left(\frac{BasekVA_3}{kV_{ll}^2}\right)\right]$$

$$\%Z = \frac{1}{60}\left[(51.59 + 51.15 + 50.96)\left(\frac{12,500}{69^2}\right)\right]$$

$$\%Z = 6.73$$

$$\Delta Z = \frac{6.85 - 6.73}{6.85}(100) \qquad \Delta Z = 2.04\%$$

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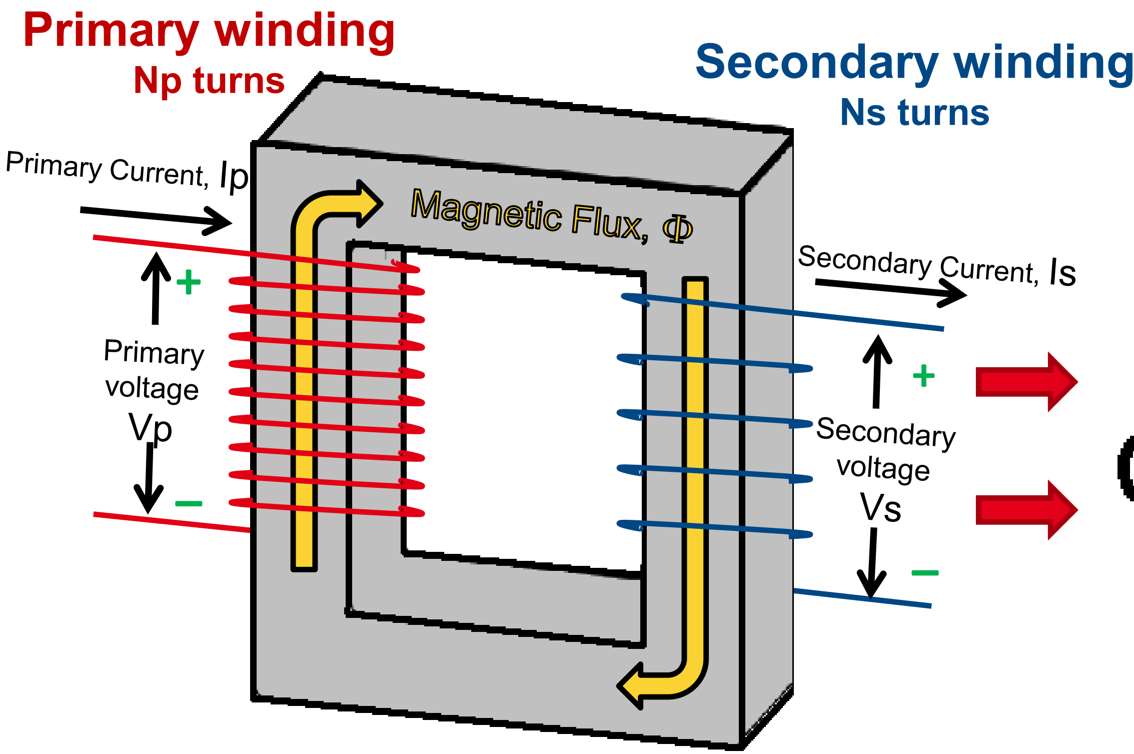
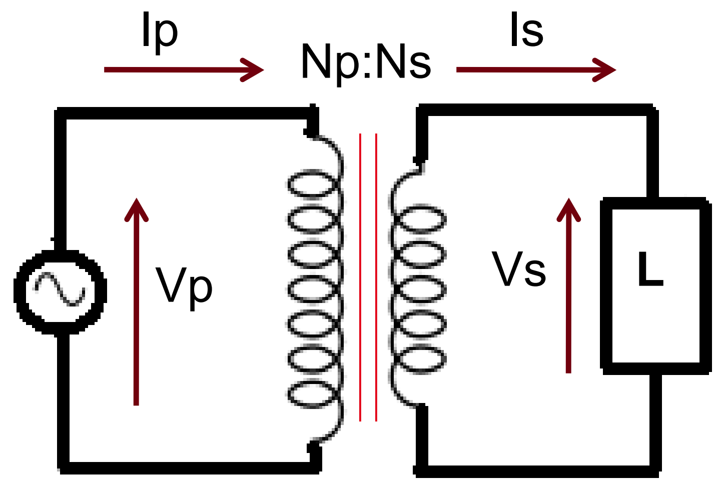
Transformer Turns Ratio



Basic Ideal Transformer Circuit



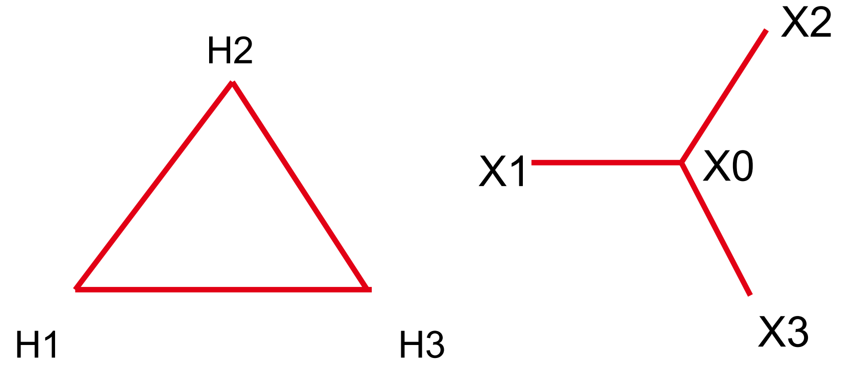
Turn Ratio (N) Equation

$$N = \frac{Np}{Ns} = \frac{Vp}{Vs} = \frac{Is}{Ip}$$

$$Vs = \left\{\frac{Np}{Ns}\right\} Vp$$

Turns Ratio Test

How is it performed?



Three Phase Transformer

HV 34500GRDY/19920 Volts
LV 13200 Volts

A Phase

Calculated Ratio

$$\frac{19920}{13200} = 1.51$$

Test	Input	Measure	Phase Ratio
1	H1-H3	X1-X0	A
2	H2-H1	X2-X0	B
3	H3-H2	X3-X0	C

Measurement

Ratio	% Dev	Angle
1.509	0.06%	0.05

Turns Ratio Test Procedure

Routine Test

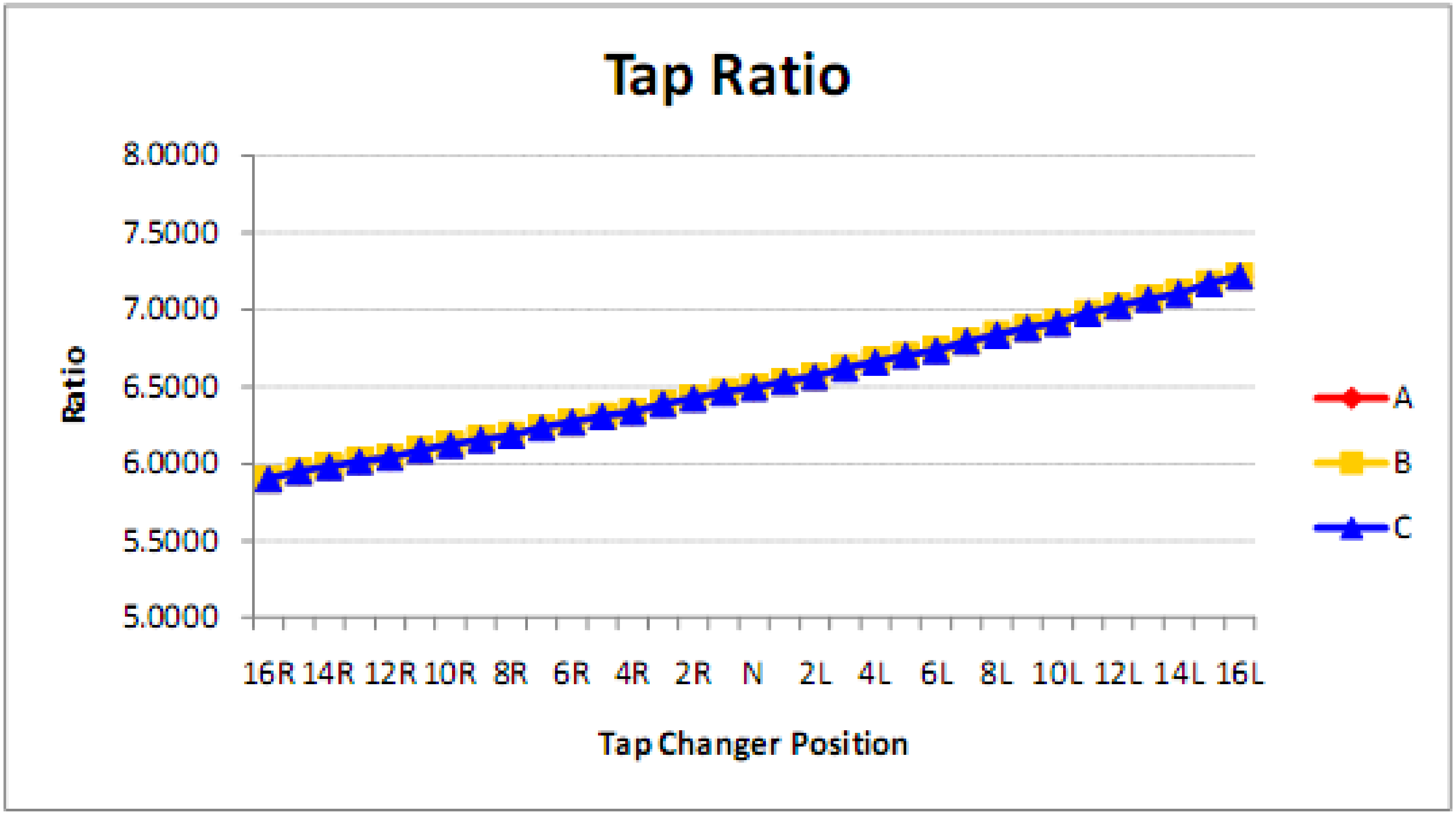
- Should perform turns ratio test on “as found” DETC positions
- Unless specified by company or manufacturer
- Ideally turns ratio test on all LTC positions
- Place DETC in “as found” position

Analyzing Results

- ⇨The turn ratio measurement results should be within 0.5% of nameplate markings according to IEEE C57.12.00-2006
  - ⇨Results should also compare very closely among phases
  - ⇨Any winding open circuits, short circuits and turn to turn shorts will show up change this measurement

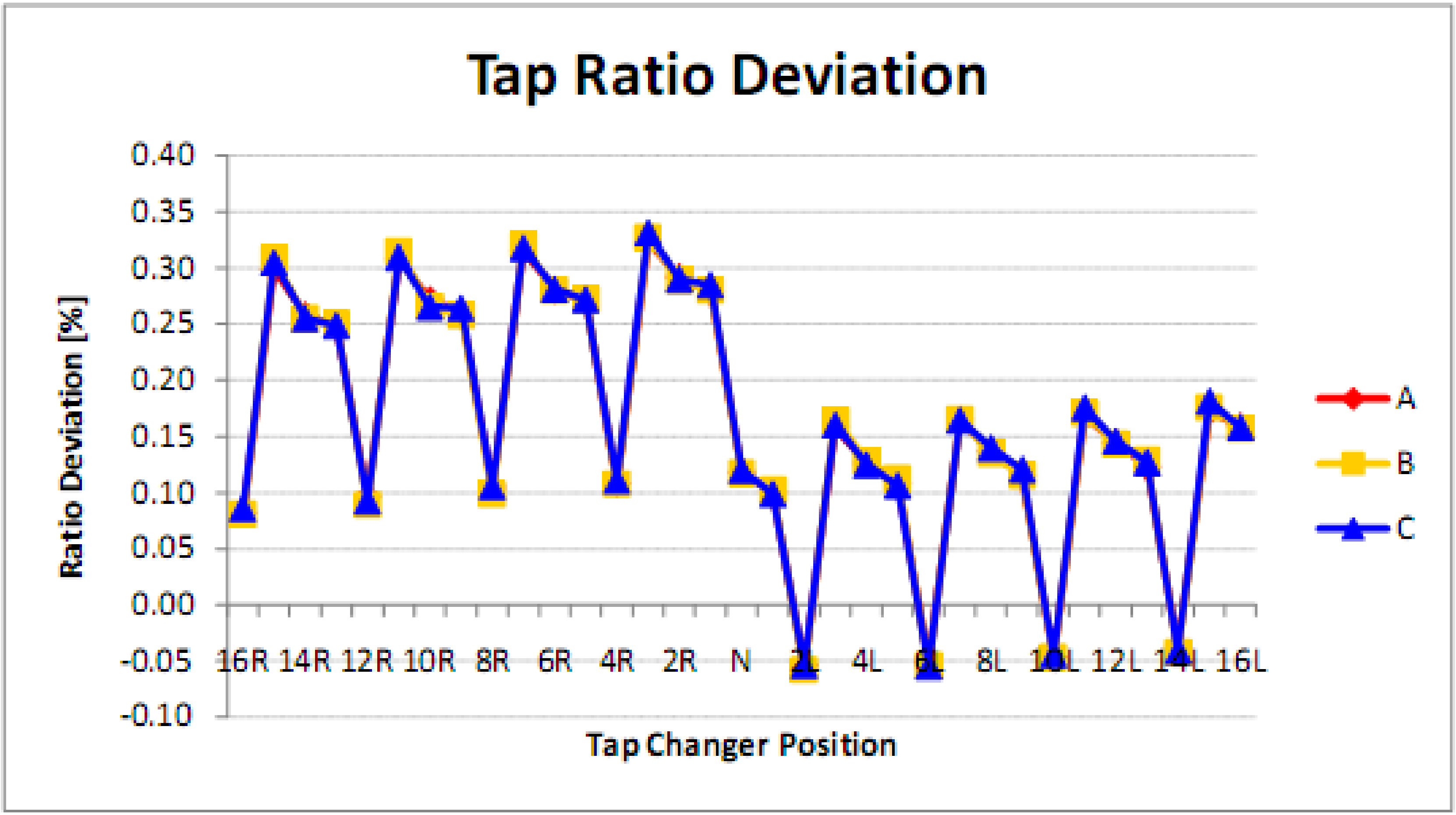
- ⇨The phase angle measured between the high voltage and low voltage winding is generally very low.
  - ⇨Damage or deterioration in the core will increase the phase angle

Turn Ratio



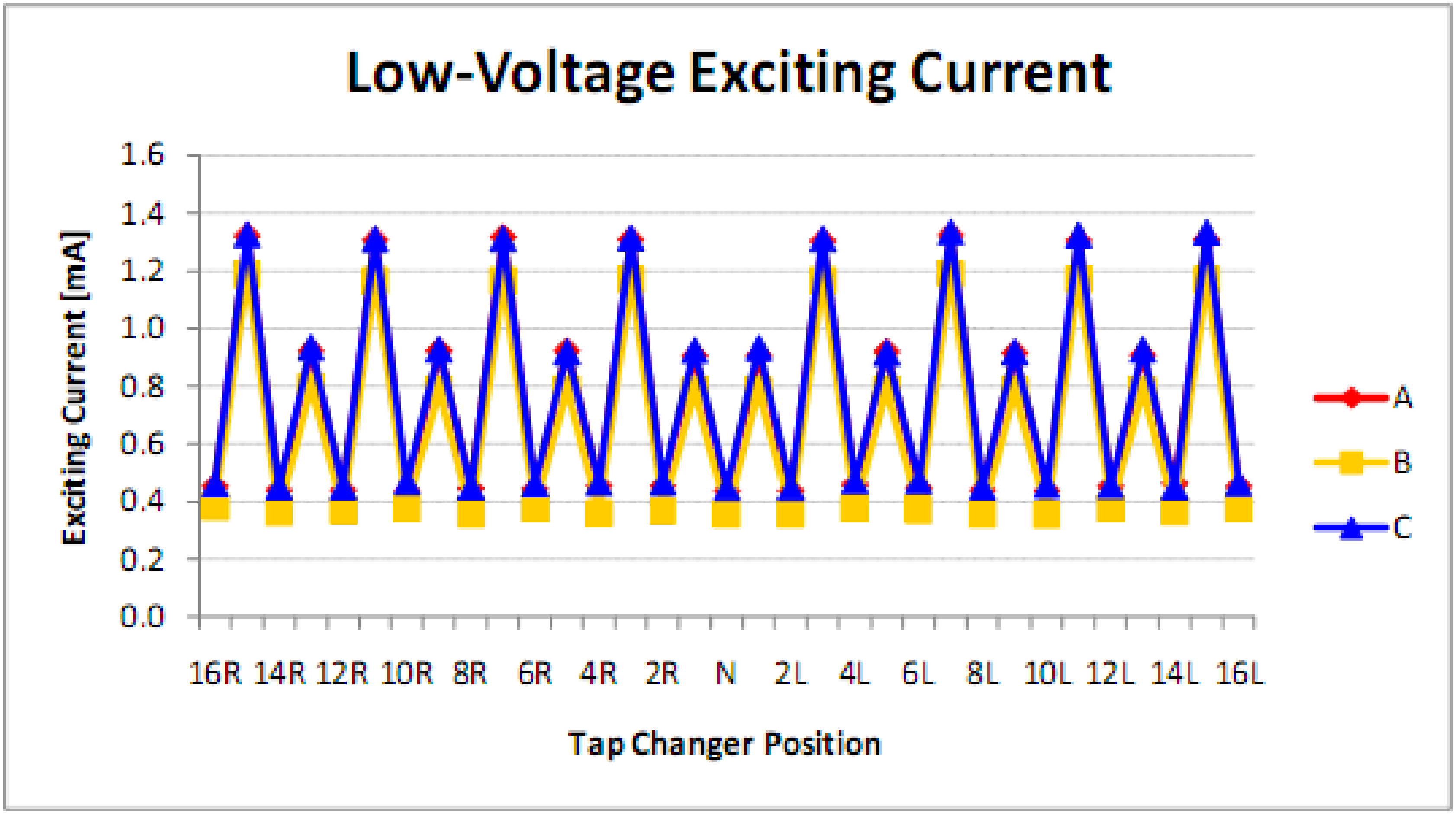
Tap Ratio
8.0000
7.5000
7.0000
6.5000
6.0000
5.5000
5.0000
Ratio
16R 14R 12R 10R 8R 6R 4R 2R N 2L 4L 6L 8L 10L 12L 14L 16L
Tap Changer Position
A
B
C

Turn Ratio



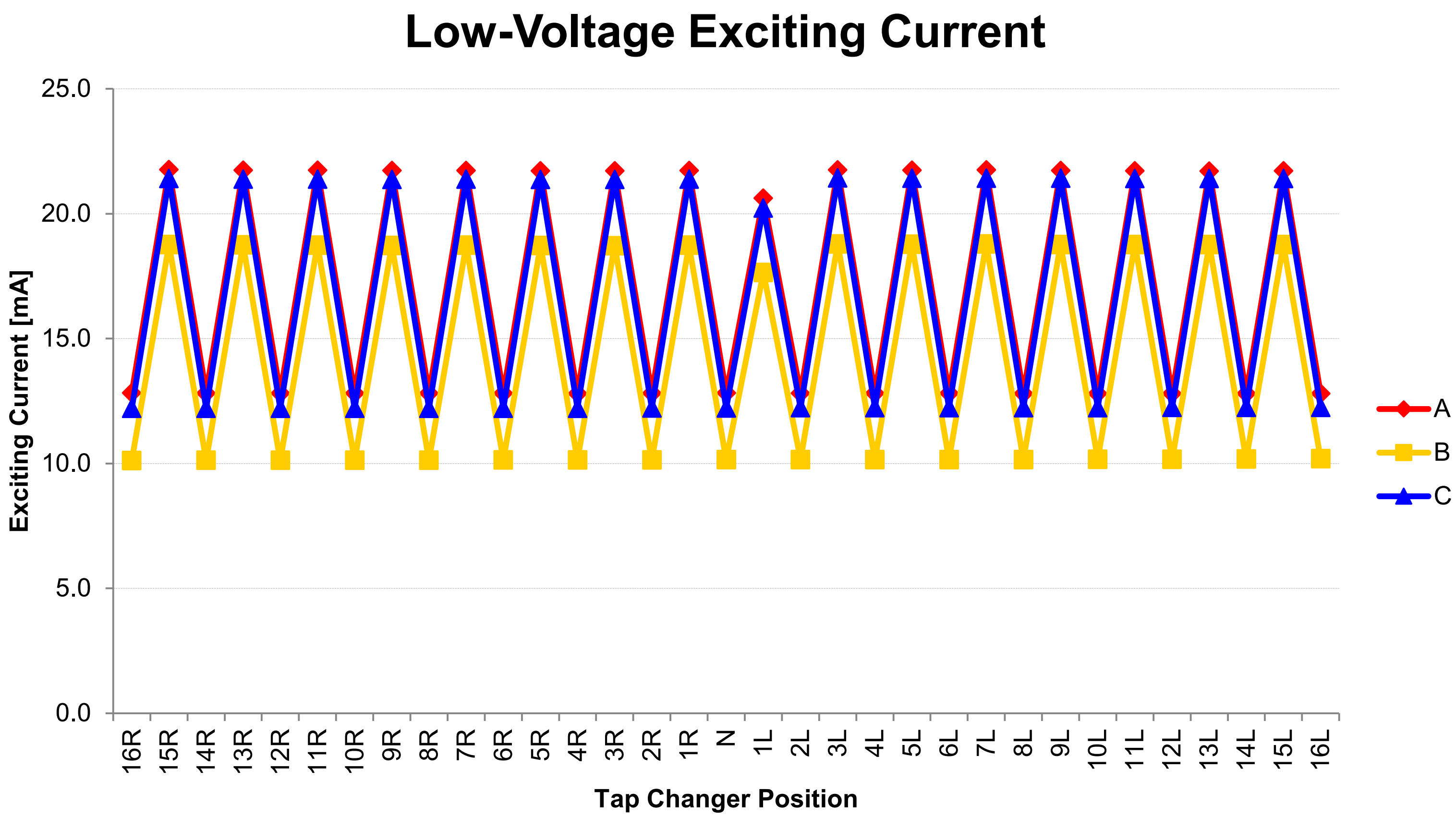
Tap Ratio Deviation
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
Ratio Deviation [%]
16R 14R 12R 10R 8R 6R 4R 2R N 2L 4L 6L 8L 10L 12L 14L 16L
Tap Changer Position
A
B
C

Turn Ratio



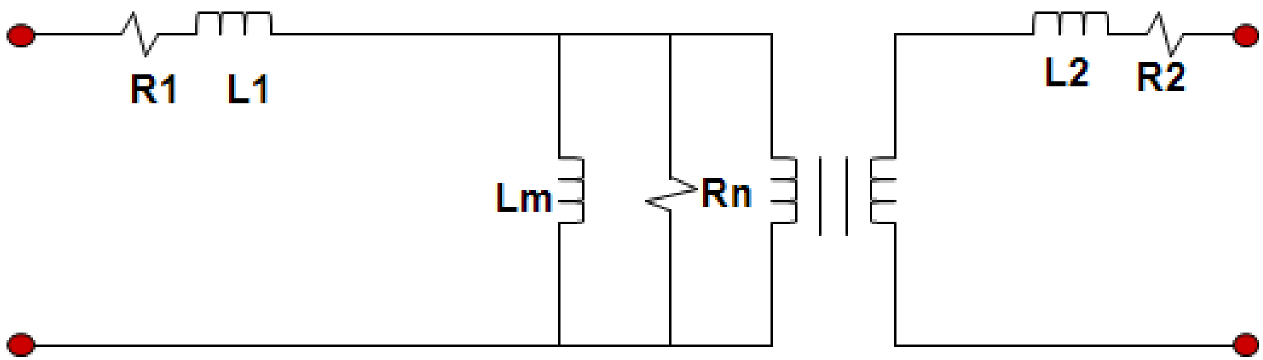
Low-Voltage Exciting Current
Exciting Current [mA]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
16R 14R 12R 10R 8R 6R 4R 2R N 2L 4L 6L 8L 10L 12L 14L 16L
Tap Changer Position
A
B
C

Turn Ratio


Low-Voltage Exciting Current
25.0
20.0
15.0
10.0
5.0
0.0
Exciting Current [mA]
16R 15R 14R 13R 12R 11R 10R 9R 8R 7R 6R 5R 4R 3R 2R 1R N 1L 2L 3L 4L 5L 6L 7L 8L 9L 10L 11L 12L 13L 14L 15L 16L
Tap Changer Position
A
B
C

Transformer Winding Resistance

One Phase Transformer Equivalent Circuit



R1 = Power Loss in HV winding

Rn = Iron Loss in Core

R2 = Power Loss in LV winding

L1= Leakage Inductance of HV Winding

Lm = Core Inductance

L2= Leakage Inductance of LV Winding

Failure Modes

A change greater than the criteria mentioned can be indicative of the following:

1. Shorted Circuited Turns
2. Open Turns
3. Defective DETC or LTC (contacts)
4. A Poor Connection Between Terminals Measured

Winding Resistance

Principle of Winding Resistance Test

1. Inject DC Current from one terminal to the other terminal of a phase

2. Measure the voltage drop across the two terminals' under test once core magnetic circuit has stabilized

3. As long as stable voltage DC source is used, winding inductance Xp is negligible.

$$Vp = Ip * Rp \qquad Rp = Ip / Vp$$

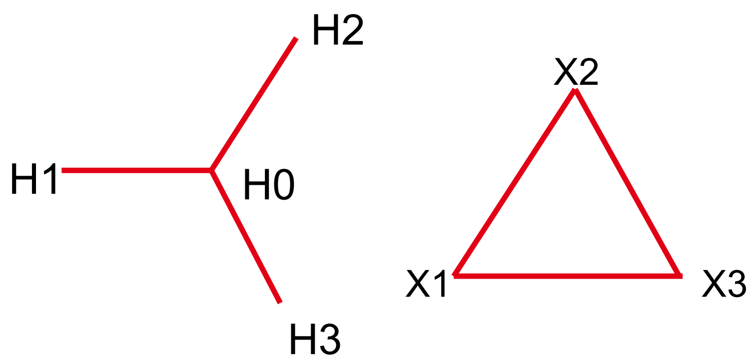
Winding Resistance

Very Important when Performing this test

1. Transformer high voltage and low voltage terminals need to be disconnected and isolated
2. Be aware and use saftey at all time. Make sure the winding is discharged after a test by grounding the terminal.
3. Never inject a DC current higher than 15% of the winding rated current
4. Temperature affects the test results and should be corrected to a common temperature of 75°C or 85°C
5. The temperature of insulated liquid has to be stabilized (top and bottom temperature should not deviate more than 5°C

Winding Resistance Test

Example of how is it performed?

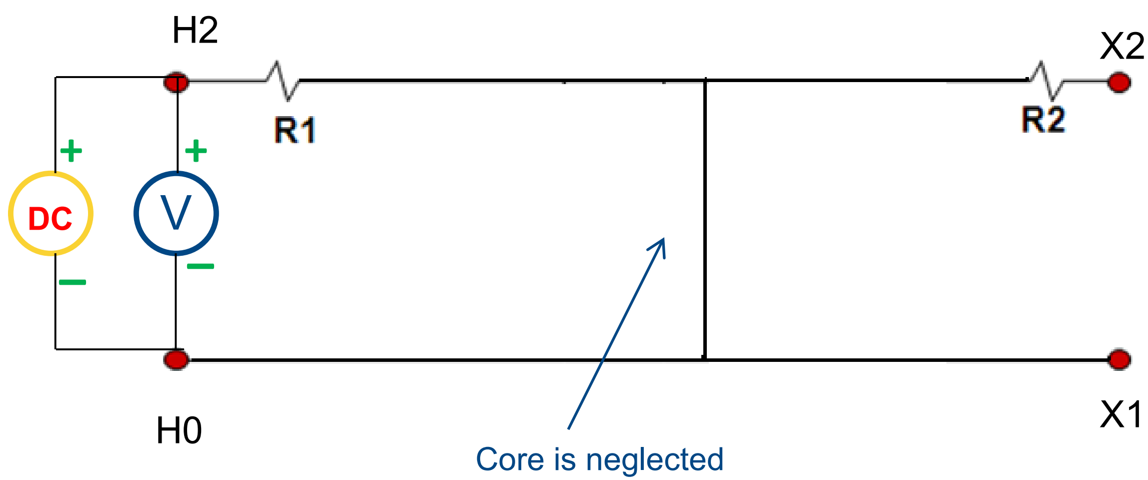


Three Phase Transformer

HV	**230**	**Amps**
LV	**350**	**Amps**

Winding Temperature 35 C

B Phase



Factory Result (75 C)
0.165 Ω

Measurement

Result	Corr.	%Dev
0.148	0.170	3.03

Winding ResistanceTest Procedure

1. By performing DC Winding Resistance test, this will magnetize your core. A magnetized core will affect your Exciting Current and SFRA Test Results.

2. Recommended to perform DC Winding Resistance last.

3. Imporant to let the measurement stabilize. Depending on the size of the transformer could take up to several minutes

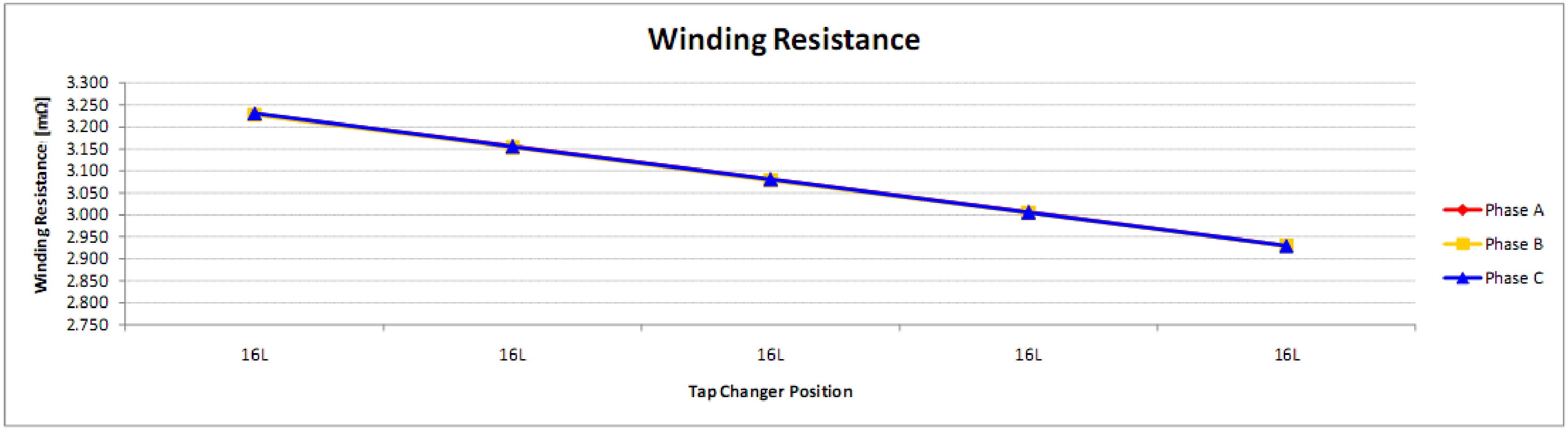
Winding ResistanceTest Procedure

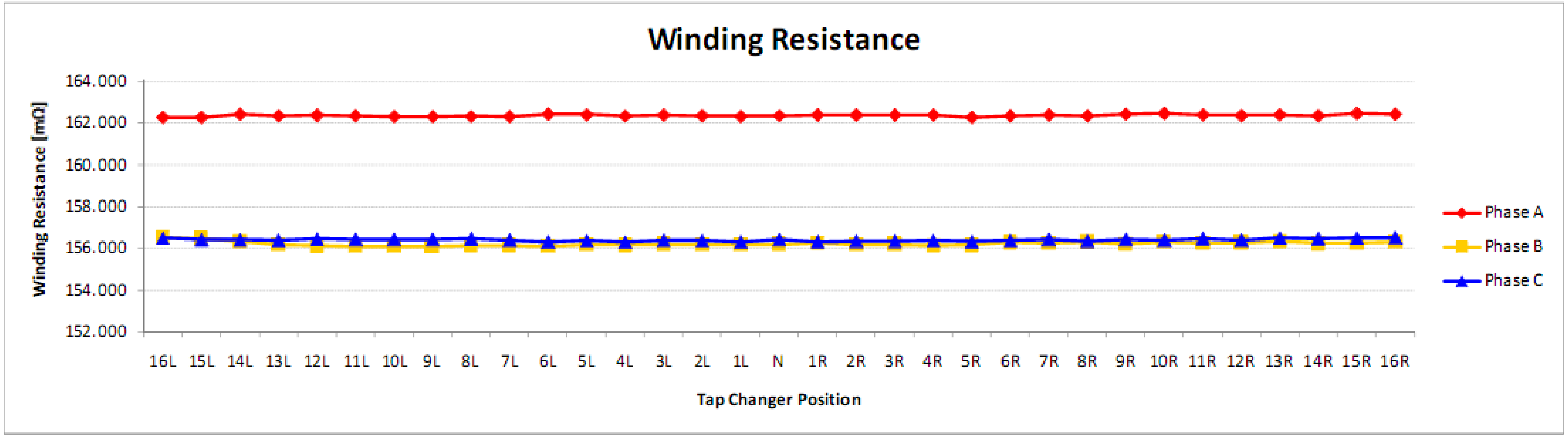
<u>Routine Test</u>

- ⇨Should perform test for phases on "as found" DETC positions
  - ⇨DETC should not be moved unless specified by company or manufacturer

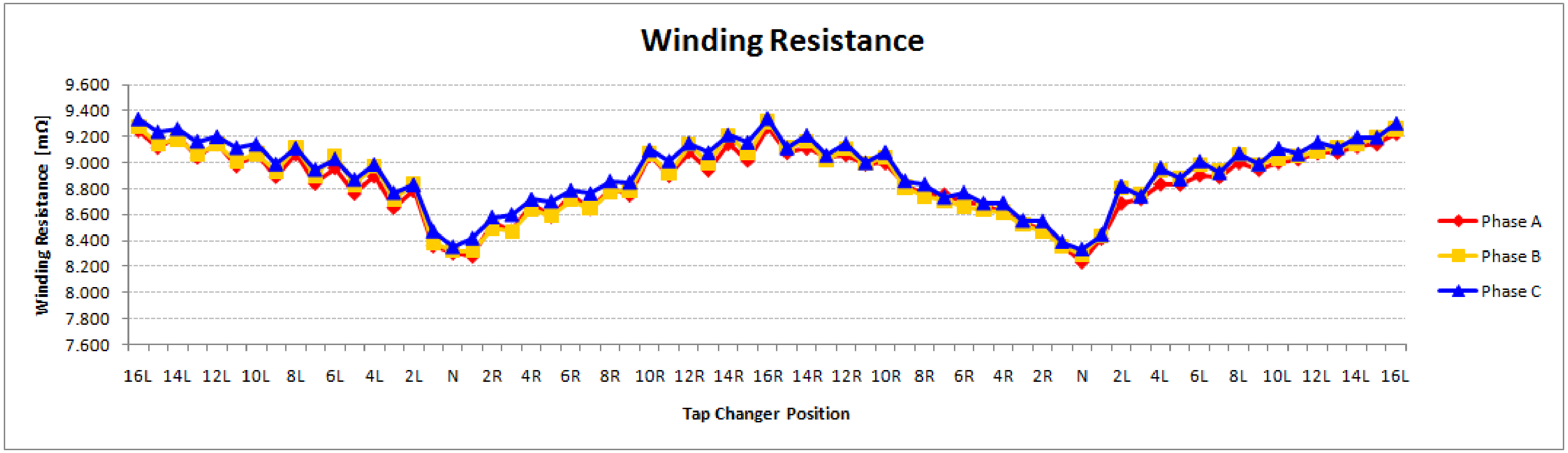
- ⇨Ideally test for phases on all LTC positions
  - ⇨Place DETC in "as found" position

DC Winding Resistance



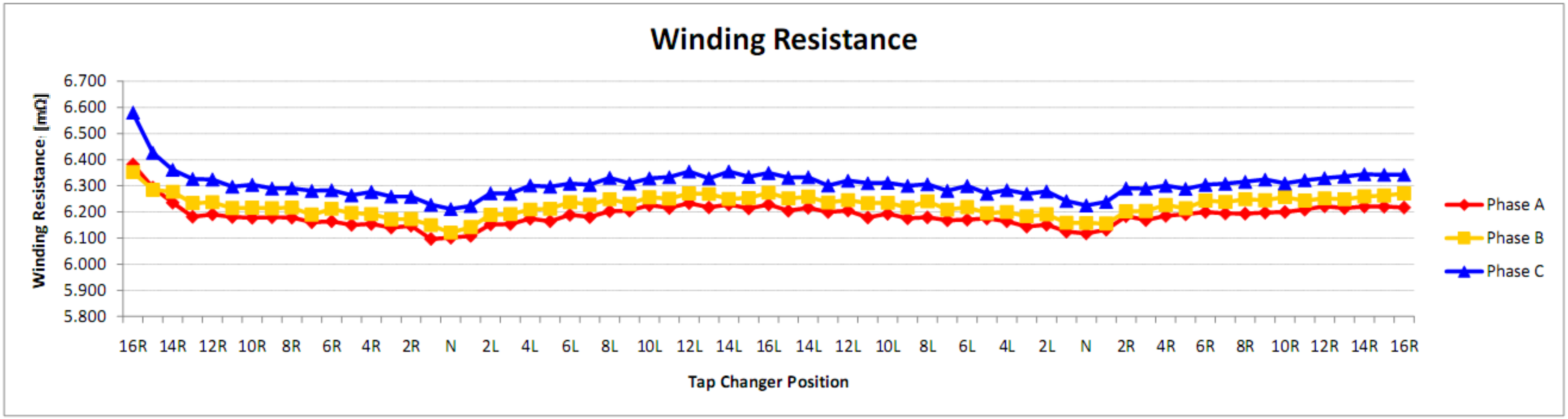


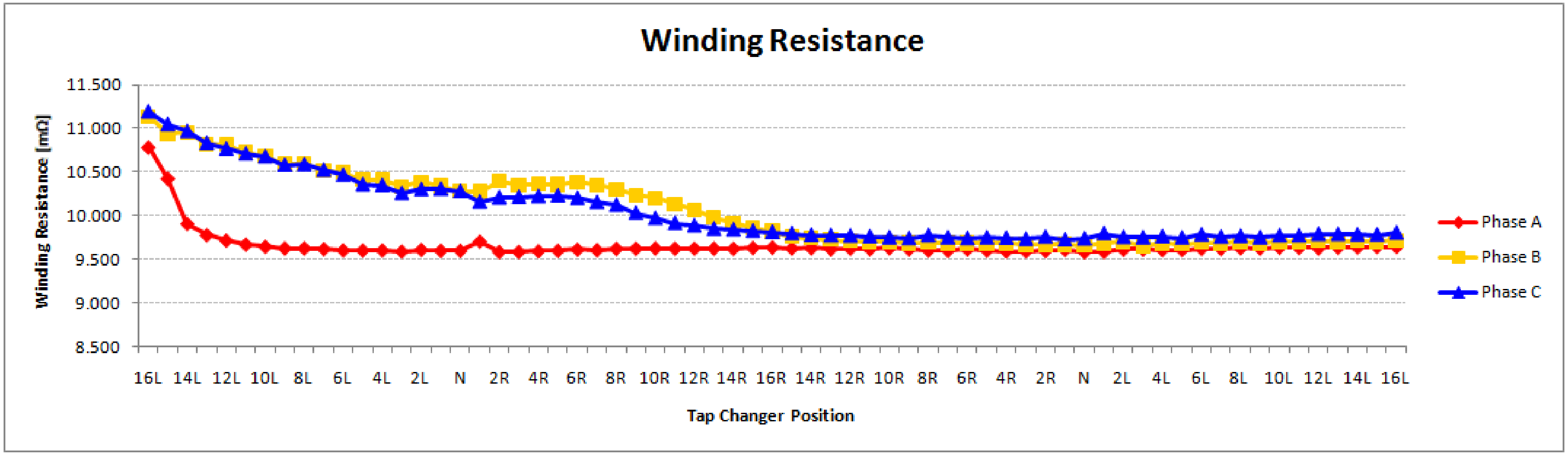
DC Winding Resistance – Normal Pattern; but Unique



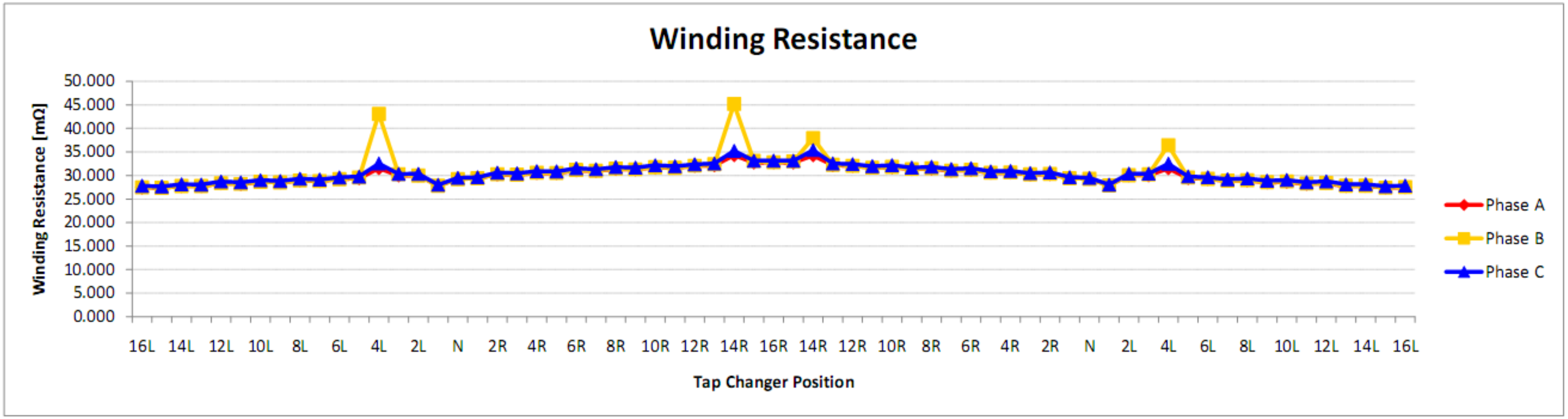
OMICRON

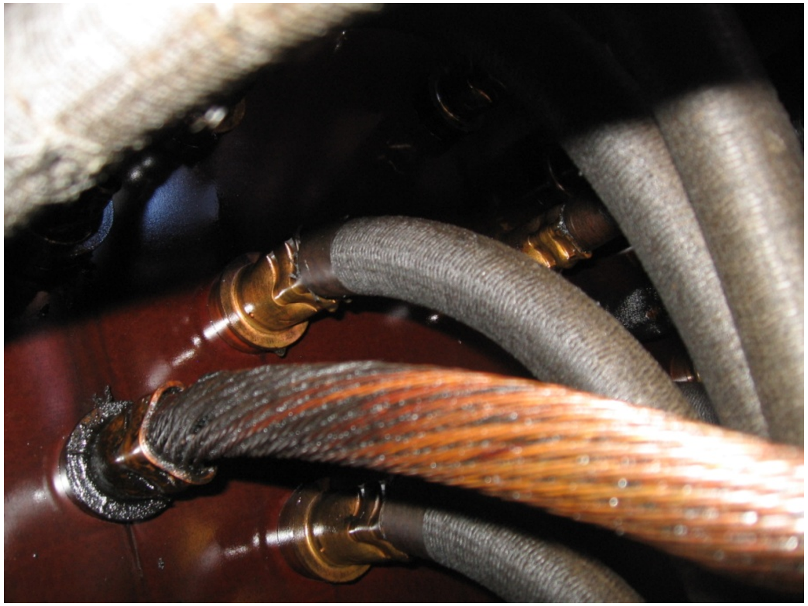
DC Winding Resistance





DC Winding Resistance





Transformer Nameplate

POS	Volts	LTC		
	X1-X2-X3	A	B	9
16R	15180	8	8	M
15R	15095	7	8	
14R	15010	7	7	
13R	14920	6	7	
12R	14835	6	6	
11R	14750	5	6	
10R	14660	5	5	
9R	14575	4	5	
8R	14490	4	4	
7R	14405	3	4	
6R	14320	3	3	
5R	14230	2	3	
4R	14145	2	2	
3R	14060	1	2	
2R	13970	1	1	
1R	13885	0	1	
N	13800	0	0	

N	13800	0	0	
1L	13715	8	0	K
2L	13360	8	8	
3L	13540	7	8	
4L	13455	7	7	
5L	13370	6	7	
6L	13280	6	6	
7L	13195	5	6	
8L	13110	5	5	
9L	13025	4	5	
10L	12940	4	4	
11L	12850	3	4	
12L	12765	3	3	
13L	12680	2	3	
14L	12590	2	2	
15L	12505	1	2	
16L	12420	1	1	

Connection 7 Common to 14R and 4L

Analyzing Results

The winding resistance measurement can be evaluated by the following three methods: (+/-5%)

1. Compare to Factory Results

2. Compare to Previous Results

3. Compare Among Phases

Thank You for Your Attention