North Central REC Engineering Conference

Duluth, Minnesota
March 8, 2006

Transformer 101 Design Issues

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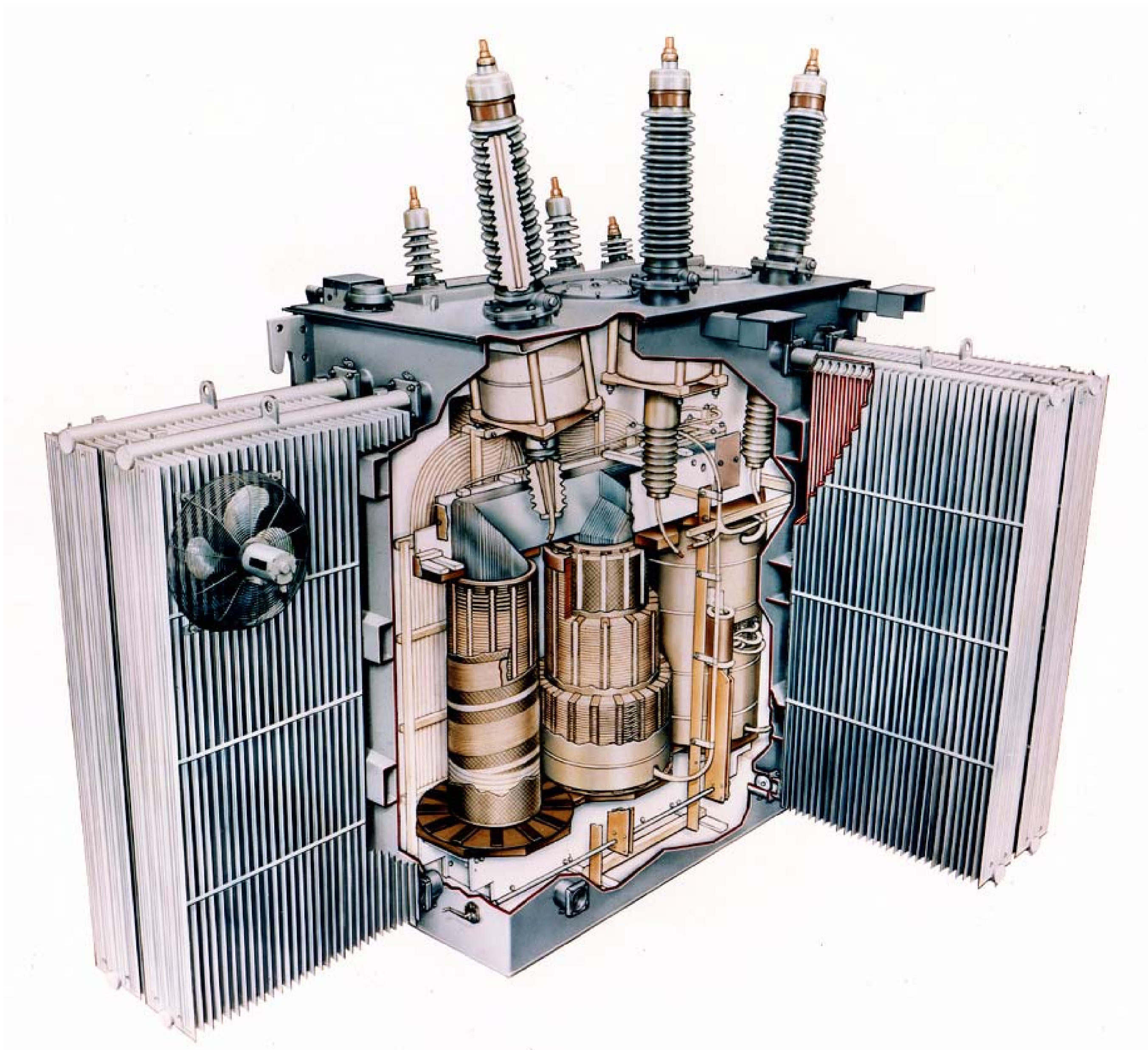

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WAUKESHA ELECTRIC SYSTEMS

- **IEEE/ANSI Standards**
- **Transformer Design Topics**
  - Impedance
  - AMBIENT
  - ALTITUDE
  - OPERATIONAL ISSUES
  - NOMINAL VOLTAGES/OVER EXCITATION
  - ACCESSORIES
  - OIL PRESERVATION SYSTEMS
  - TAP CHANGERS
  - SERIES PARALLEL OPERATION
  - MINIMUM DESIGN BASICS

ANSI/IEEE CURRENT Standards

Key Standards for Power Transformer

IEEE STD C57.12.00-2000 IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers

ANSI STD C57.12.10-1997 Product Standard for Power Transformers

IEEE STD C57.12.90-1999 IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

IEEE C57.19.01-2000 IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings

IEEE STD C57.98-1993 (Reaff 1999) IEEE Guide for Transformer Impulse Tests

IEEE C57.91-1995 IEEE Guide for Loading Mineral-Oil-Immersed Transformers

IEEE PC 57.119 Draft (14.0) - 2001 (Re-circulation) Recommended practice for performing temperature rise tests on oil immersed power transformers at loads beyond nameplate ratings

IEEE C57.12.00-2000
5.Rating Data
<u>5.1 Cooling Classes of Transformers</u>

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400 South Prairie Avenue, Waukesha, Wisconsin 53186

CLASS	ONAN/ONAF/ONAF 3-PHASE	60 HZ		SER. NO	A1234X	
MVA	12/16/20	CONT. TEMP. RISE			55°	C
MVA	13.4/17.9/22.4	CONT. TEMP. RISE			65°	C
HV	46000	VOLTS	BIL	550		KV
LV	12470Y/7200	VOLTS	BIL	150		KV
LV NEUTRAL			BIL	110		KV
IMPEDANCE	15.50% AT 46000-12470	VOLTS	AND	12.0		MVA

Changes Of Cooling Class Designation

Previous Designations	Present Designations
OA	ONAN
FA	ONAF
OA/FA/FA	ONAN/ONAF/ONAF
OA/FA/FOA	ONAN/ONAF/OFAF
OA/FOA*	ONAN/ODAF
OA/FOA*/FOA*	ONAN/ODAF/ODAF
FOA	OFAF
FOW	OFWF
FOA*	ODAF
FOW*	ODWF

Changes Of Cooling Class Designation

First letter: **Internal cooling medium in contact with the windings**

O mineral oil or synthetic insulating liquid with fire point < 300°C

K insulating liquid with fire point > 300°C

L insulating liquid with no measurable fire point

Second letter: **Circulation mechanism for internal cooling medium:**

N natural convection flow through cooling equipment and windings

F forced circulation through cooling equipment (cooling pumps), natural convection flow in windings (non-directed flow)

D forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings

Third letter: **External cooling medium**

A air

W water

Fourth letter: **Circulation mechanism for external cooling medium**

N natural convection

F forced circulation (fans, pumps)

Transformer Design Topics

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Impedance

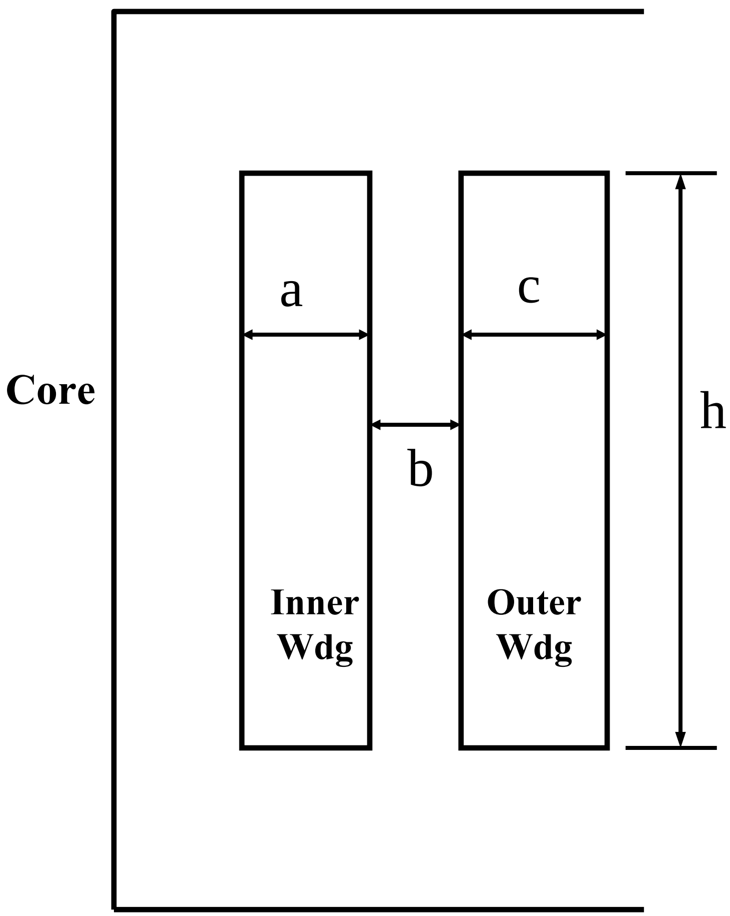
(Leakage Reactance)

IMPEDANCE

ANSI C57.10-1997 Table 10
BILs and percent impedance voltages at self-cooled (ONAN) rating

High Voltage BIL	Without LTC	With LTC
60 – 110	5.5	-
60 – 110 (< 5000 kVA)	6.5	7.0
150	6.5	7.5
200	7.0	7.5
250	7.5	8.0
350	8.0	8.5
450	8.5	9.0
550	9.0	9.5
650	9.5	10.0
750	10.0	10.5

Impedance



Reactance

$$\%IX \propto turns^2 * \left[\frac{\frac{1}{3}a + b + \frac{1}{3}c}{h}\right]$$

Resistance

$$\%IR \propto Winding\ Resistances$$

Impedance

$$\%IZ = \sqrt{\%IX^2 + \%IR^2}$$

Directly Proportional **Frequency & MVA**

Inversely Proportional **Volts/Turn**

Impedance Issues

Systems Standards

Paralleling Operation It should be noted that while parallel operation is not unusual, it is desirable that users advise the manufacturer when paralleling with other transformers is planned and identify the transformers involved.

Low Impedance

- **Raises Secondary Fault Currents**
- **Better Regulation**
- **Increased Short Circuit Withstand**

High Impedance

- **Reduces Secondary fault currents**
- **Poorer regulation**
- **Higher stray losses**
- **Leakage flux related stray losses**
- **Increased cost**

ANSI C57.12-2000

Table 9.2 Tolerances for Impedance

a)	Two-winding transformers	+/- 7.5%
	Duplicate two-winding transformers	+/- 7.5%
b)	Three or more windings or zigzag	+/- 10%
	Duplicate three or more windings or zigzag	+/- 10%
c)	Autotransformers	+/- 10%
	Duplicate autotransformers	+/- 10%

d) Transformers shall be considered suitable for parallel operation when reactances come within the limitations of the foregoing paragraphs, provided that turns ratio and other suitable characteristics are suitable for such operation.

DESIGN TOPICS

- AMBIENT
- ALTITUDE
- NOMINAL VOLTAGES
- OVER EXCITATION
- SERIES PARALLEL OPERATION
- MINIMUM DESIGN BASICS

Ambient

- Maximum of 40º C
- 24 hour average = 30º C
- Minimum -20ºC
- Actual ambient should be used to compute the transformer's load capability
- Transformers surrounded by buildings or walls can result in recirculation of heated air which increases the ambient

High Ambient

•> 40ºC Max or 30ºC average

•Derate transformer rating

•Increase Cooling to compensate

•Reduce Temp Rise

LOW AMBIENT <-20ºC

•Moisture in oil and insulation

•Oil Viscosity

Altitude

The dielectric strength of transformers that depend in whole or in part upon air for insulation decreases as the altitude increases due to the effect of decreased air density. When specified, transformers shall be designed with larger air spacings between terminals using the correction factors of Table 1 to obtain equate air dielectric strength at altitudes above 1000 m (3300 ft).

Altitude (m)	Altitude (ft)	Altitude Correction Factor for Dielectric Strength
1000	3300	1.00
1200	4000	0.98
1500	5000	0.95
1800	6000	0.92
2100	7000	0.89
2400	8000	0.86
2700	9000	0.83
3000	10000	0.80
3600	12000	0.75
4200	14000	0.70
4500	15000	0.67

Normal Operation

- Step Down Operation
- Step-up Operation
  - GSUs
- Reverse Power Flow (Step-up)
- Auto Transformers require additional design consideration.

Generator Step Up Transformers

- **Wye - Delta**
- **Overexcitation**
- **Voltage Regulation considerations**
- **Breaker Protection**

Nominal Voltage

- 67 kV vs 69 kV
- 12.47 vs 13.09 or 13.2 kV
- Transformer supplier assumes that the transmission line voltage is the nominal voltage

Over Excitation Operation

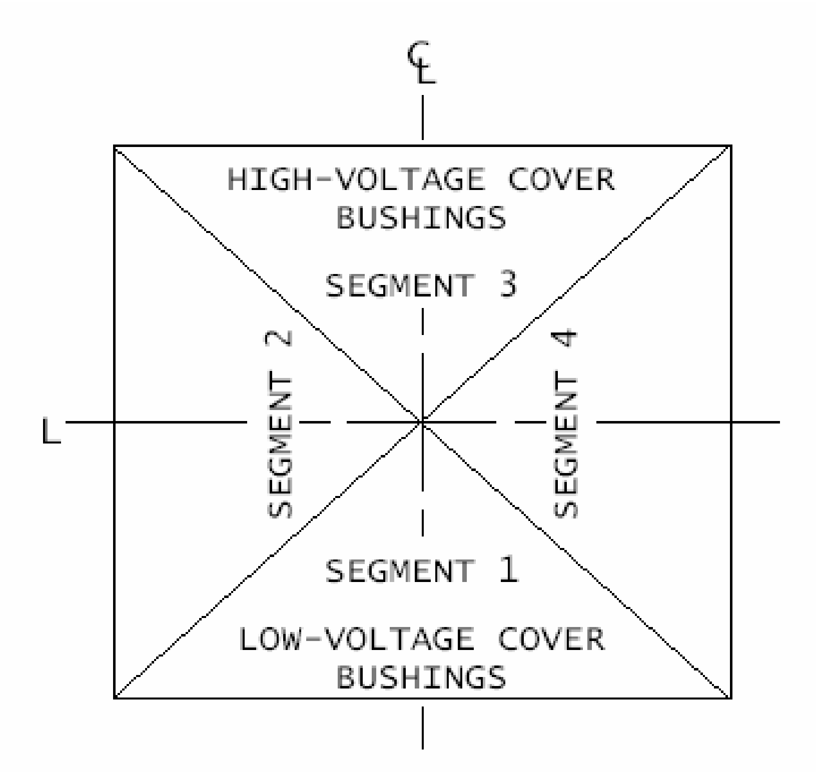
ANSI C57.12.00-2000

4.1.6.1 Capability

Transformers shall be capable of:

- **a) Operating continuously above rated voltage or below rated frequency, at maximum rated kVA for any tap, without exceeding the limits of observable temperature rise in accordance with 5.11.1 when all of the following conditions prevail:**
  - **1) Secondary voltage and volts per hertz do not exceed 105% of rated values.**
  - **2) Load power factor is 80% or higher.**
  - **3) Frequency is at least 95% of rated value.**
- **b) Operating continuously above rated voltage or below rated frequency, on any tap at no load, without exceeding limits of observable temperature rise in accordance with 5.11.1, when neither the voltage nor volts per hertz exceed 110% of rated values.**

Accessories C57.12.10-1997



Accessories	Locations
Tap-changer operating handle	S1, S4
*Liquid-level indicator	S1
*Liquid-temperature indicator	S1
Drain and filter valves	S1
Nameplate	S1
*Pressure-vacuum gauge	S1
Jacking facilities	See Ref 5.3.4
Ground pad(s)	See Ref 5.5
†Load-tap-changing equipment	S1 or S2
†Auxiliary cooling control	S1 or S2 9

*Not furnished for transformers with distribution BIL characteristics 200 kV and below.

†When furnished.

Basic Standard Construction Features

C57.12.00-2000

kVA, ONAN Ratings	750–10 000	12 000–60 000	3750–10 000	12 000–60 000
5.1 Accessories				
5.1.1 Tap-Changer	S	S	S	S
5.1.2 Liquid-Level Indicator	S	S	S	S
5.1.3 Liquid-Temperature Indicator	S	S	S	S
5.1.4 Pressure-Vacuum Gage	S	S	S	S
5.1.5 Drain and Filter Valves (or Conn)	S	S	S	S
5.2 Bushings	S	S	S	S
5.3 Lifting, Moving, and Jacking Facilities	S	S	S	S
5.3.4 Jacking Facilities	S	S	S	S
5.4 Nameplate	S	S	S	S
5.5 Ground Pad(s)	S	S	S	S
5.6 Polarity, Angular Displacement, and Terminal Markings	S	S	S	S
5.7.1 Oil Preservation	S	S	S	S
5.7.2 Pressure-Vacuum Bleeder	S	S	S	S
5.8 Tanks	S	S	S	S
5.9 Auxiliary Cooling Equipment	A	A	A	A
5.9.1 Controls for Auxiliary Cooling Equipment	A	A	A	A
5.9.2 Fans	A	A	A	A
5.9.3 Pumps	–	A	–	A
5.10 Auxiliary Equipment Power Supply	A	A	A	A
6 Load-Tap-Changing Equipment	–	–	S	S
6.1 Load Tap Changer, 6.2 Arcing Tap Switch 6.3 Motor-Drive Mechanism	–	–	S	S
6.4 Position Indicator, 6.5 Operation Counter, 6.6 Automatic Control Equipment				

"S" indicates "standard" "A" indicates "available when specified"

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Core Grounds

- **Standard – Near an access cover**
  Removable for testing
  Captive Hardware

- **External – Brought out through a bushing**

- **Series Transformers**

C57.19.01-2000
IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings

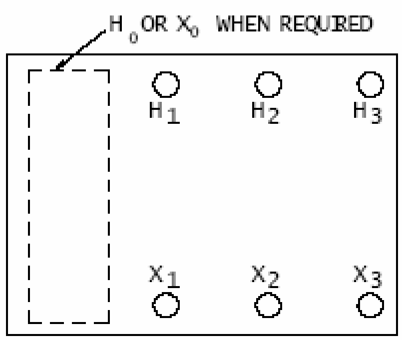
• 200 kV BIL	34.5 kV	400/1200, 2000, 3000, 5000 amp
• 350 kV BIL	69 kV	400/1200, 2000, 3000 amp
• 650 kV BIL	138 kV	800/1200, 2000, 3000 amp
• 900 kV BIL	230 kV	800/1200, 2000, 3000 amp
• 1175 kV BIL	345 kV	800/1200, 2000, 3000 amp
• 1675 kV BIL	500 kV	800/1200, 2000, 3000 amp
• 2050 kV BIL	765 kV	800/1200, 2000 amp

Bushings

The insulation level of line bushings shall be equal to or greater than the insulation level of the windings to which they are connected.

The insulation level of the low-voltage neutral bushing on three-phase transformers having a Y-connected low-voltage winding shall be the same as that of the low-voltage line bushings for windings 15 kV and below. For windings above 15 kV, a 15-kV neutral bushing with 110-kV BIL shall be provided.

Unless otherwise specified, bushings shall be mounted on the cover and located as shown in Figure 2.



Oil Preservation Systems

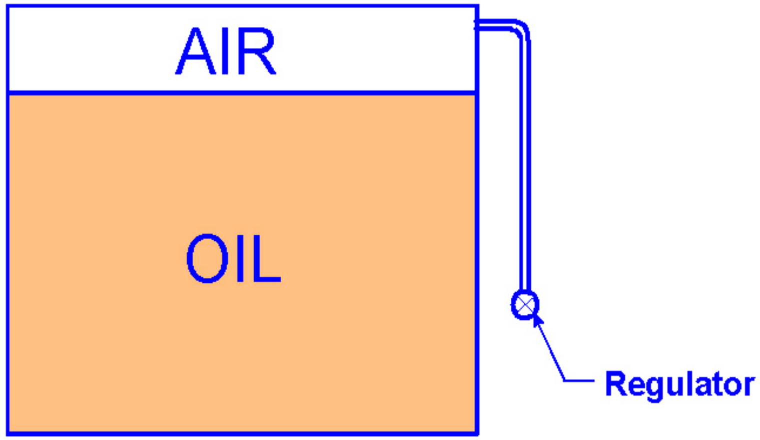
Oil Preservation Systems

- **The goal of an Oil Preservation System is to inhibit the interaction of Oxygen and Moisture with the Insulating Mineral Oil to mitigate their impact on the aging of cellulose insulation system.**
- **Oil Preservation System are necessary to compensate for the operation of the pressure vacuum regulator to expel gas during overpressure and allow intake during vacuum conditions**

Oil Preservation Systems

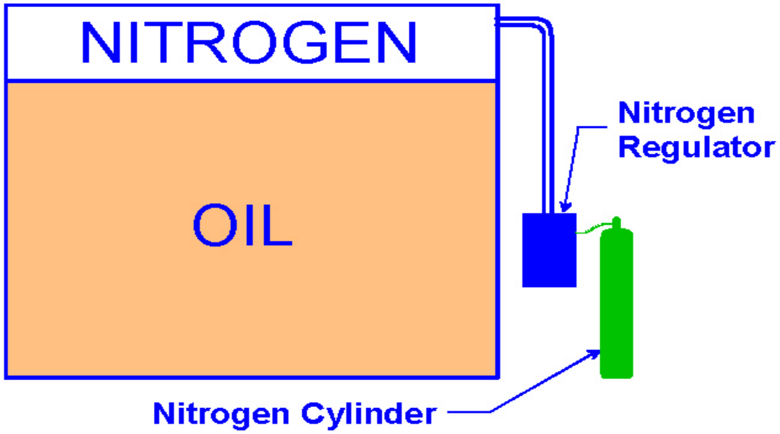
- **Factors**
  - Load Variations
  - Temperature Variations
  - Leaks
  - Maintenance
  - Testing

Oil Preservation Systems
Sealed Tank



- Simplest
- Requires a gas space for expansion of the oil.
- Designed for a max operating pressure of 8 psi with a 125% safety factor(10 PSI)
- Supplied with a pressure relief device as overpressure protection.
- Shipped from the factory with a blanket of Nitrogen
- As the transformers operates, nitrogen is expelled during overpressure(high load and/or high ambient) and air is introduced during vacuum conditions(light load and cold ambient).

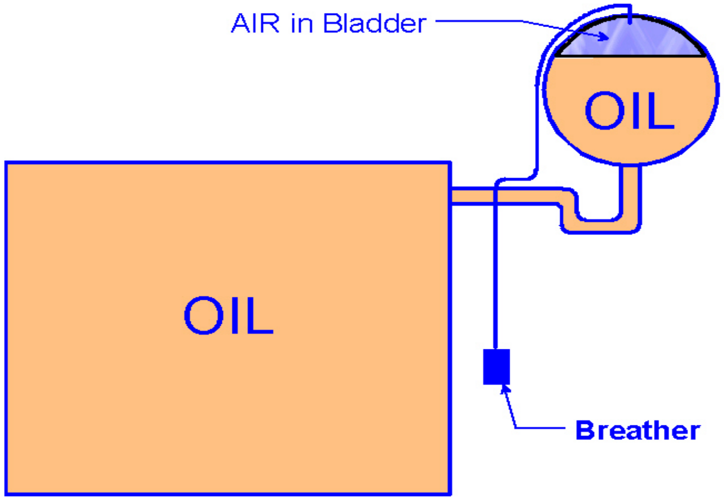
Oil Preservation Systems
Inert Gas Oil Preservation System



- Transformer is supplied with a cylinder of nitrogen and a pressure regulator to automatically maintain a positive pressure of nitrogen in the gas space.
- Normally regulates to +5, -0.5 psi
- Cylinders are supplied with a low pressure alarm to indicate imminent loss of supply.

Oil Preservation Systems

Conservator Oil Preservation System (COPS)



- Expansion space is provided by the conservator
- Requires a bladder to preclude entrance of Oxygen
- Supplied with a Dehydrating Breather to eliminate Moisture
- Requires bleeding off all trapped gas
- Usually supplied with a relay to accumulate gasses (Bucholz or a Gas Accumulation Relay) for fault detection
- Can be used to reduce shipping height, conservator is removed for shipping.

Tap Changers

- **DETCs**
- **Voltage Regulation Methods**
- **Load Tap Changers**
- **LTC Application considerations**
- **IEEE Standard C57.131-1995**

Tap Changers

A device designed to allow changing the winding connections:

- DETC (De-energized)
- LTC (Energized and Under Load)

DETCs

- **De Energized Tap Changers**
- **Typically five positions, 10 % range**
- **Two above and two below nominal @ 2.5%**

DETCs

- **Used to match transformer primary to actual transmission line voltage.**

- **Adjust turns to match design core flux density.**

- **Used to adjust travel of LTC mechanism.**

DETCs

Core performance:

- Core Loss
- Sound Levels

Impedance:

- Inversely proportional to the square of the volts per turn

Voltage Regulation

The voltage regulation is expressed in percentage of the rated secondary voltage at full load

(Normally at the ONAN rating)

Voltage Regulation

Factors Affecting Voltage Regulation:

- Transmission Line variations
- Load Power Factor
- Impedance
- Load variations

Voltage Regulation Calculation per ANSI C57.12.90-1999

14.4.4.1 Exact formulae for the calculation of regulation:

a) when the load is lagging: regulation = $\sqrt{(R + F_p)^2 + (X + q)^2} - 1$

b) when the load is leading: regulation = $\sqrt{(R + F_p)^2 + (X - q)^2} - 1$

Where

F_p is load power factor

q is + $\sqrt{1 - F_p^2}$

R is resistance factor of transformer = (load losses in kilowatts)÷ (rated kilovolt amperes)

X is reactance factor of transformer = + $\sqrt{Z^2 - R^2}$

Z is impedance on a per unit basis

The quantities of F_p, q, R, X and Z are on a per-unit basis, so the results shall Be multiplied by 100 to obtain the regulation in percentage

Voltage Regulation

18/24/30 MVA transformer

Z = 8.0% @ 18 MVA, ;	13.33% @ 30 MVA
I^2R = 60 kW	I^2R = 166.67 kW
R = 0.33%	R = 0.56%
X = 7.99%	X = 13.32%

Calculated Regulation

18 MVA

PF	REG
1.0	0.64%
0.9	4.02%
0.8	5.24%

30 MVA

PF	REG
1.0	1.43%
0.9	6.95%
0.8	8.92%

Voltage Regulation

- **Regulators**
- **Power Factor Correction**
- **Load Tap Changers (LTCs)**

Load Tap Changers

Typical Specifications:

- 33 steps
- +/- 10% (5/8% steps)
- Full Capacity above nominal voltage
- Rated current (reduced capacity) below nominal voltage

Load Tap Changers

- **Operation at lower than rated voltages**

- **Extended tap ranges (+/- 15% or +20/-10%)**

Series Parallel Transformer Connections

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Series Parallel Connections

- **"Two-winding" transformer may consist of more than two actual windings.**
- **Connect windings or sections of windings in series or parallel**
- **Tap out windings or sections of windings**

Ratio of Voltages

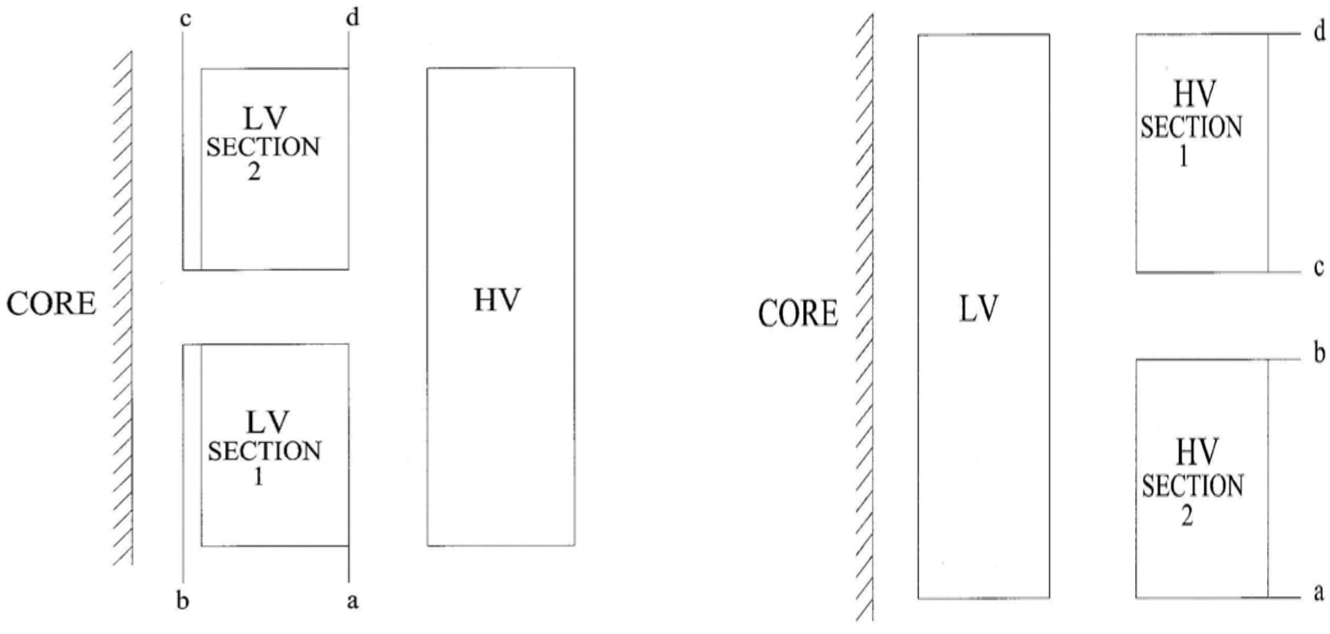
Even Ratio (Whole Number) Applications

- Secondary: ex. *26.4x13.2 kV* (2:1)
- Primary: ex. *138x69 kV* (2:1)

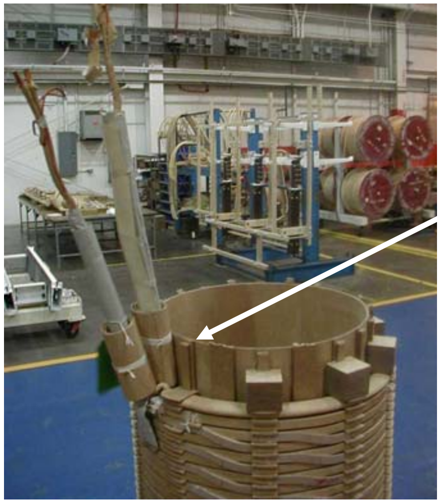
Uneven Ratio Applications

- Primary: ex. *115x69 kV* (1.67:1), *115x46 kV* (2.5:1), *161x69 kV* (2.33:1)
- Secondary: ex. *34.5x13.8kV* (2.5:1)

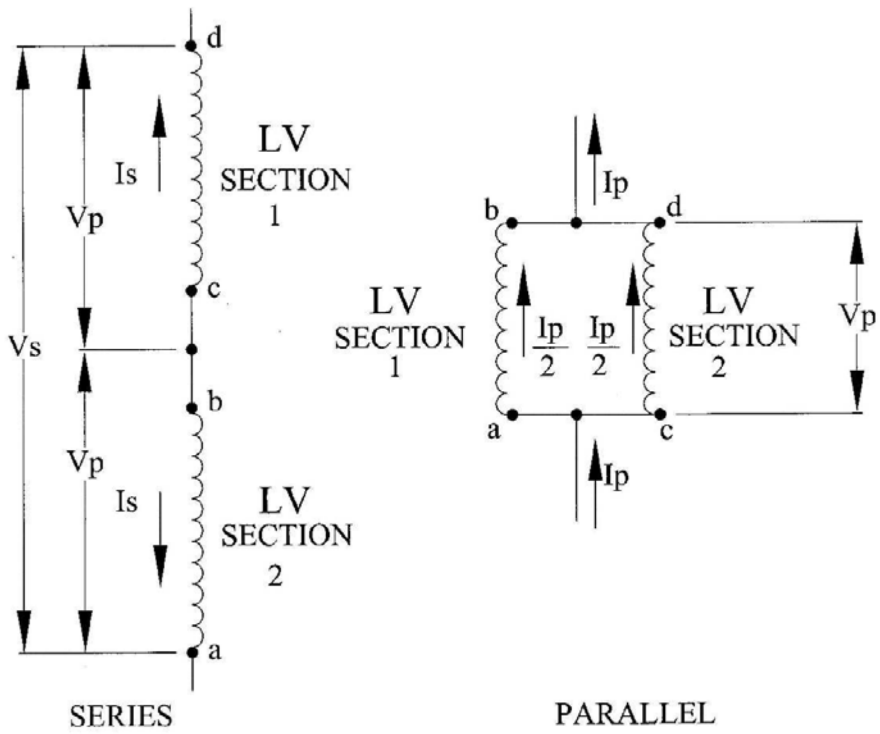
Even Ratio (2:1 shown) Winding Arrangement



Typical LV Winding
Designed with 2:1 Ratio



Connections for 2:1 Ratio



Even Ratio Applications

Performance Characteristics

- **No significant differences in main performance characteristics between two connections**
  - Load losses, impedance, no-load losses, and sound level remain constant
- **Resistance will be different due to windings being connected in series or parallel.**

Primary Winding
De-energized Taps

May not always be practical to obtain ANSI 10% (2±2.5%) range for both connections.

Ex. : *115kV x 69kV*

- If designed with 10% tap range for 115kV connection, or 11.5kV tap section (10% range), 69kV connection will have 11.5kV/2 = 5.75kV tap section, which equates to 8.33% tap range (less than 10% per ANSI)

- If designed for 10% at 69kV connection, 115kV connection will have 12% tap range

Primary Taps - Options

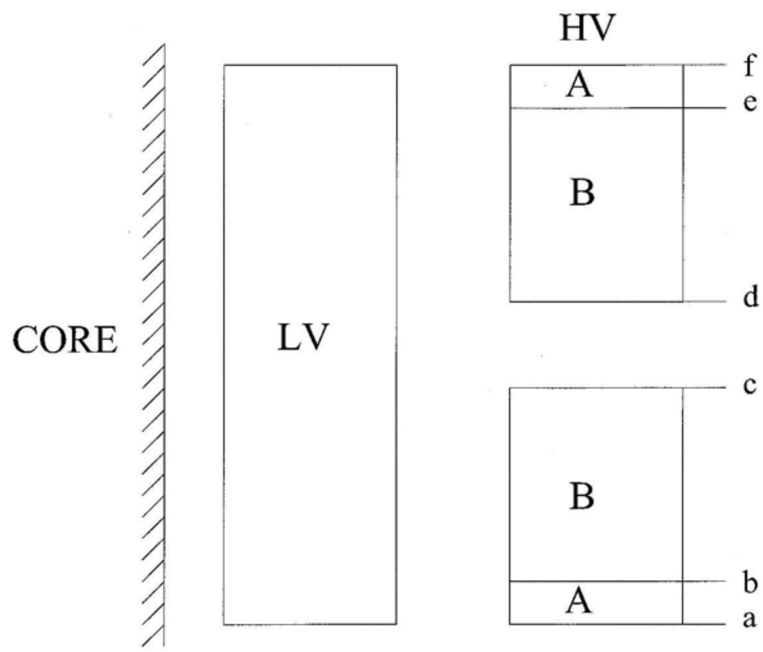
1. 10% range for one connection and accept different range for other connection. Nameplate to reflect actual design voltages.

2. Design somewhere in between (compromise). Nameplate to reflect actual design voltages.

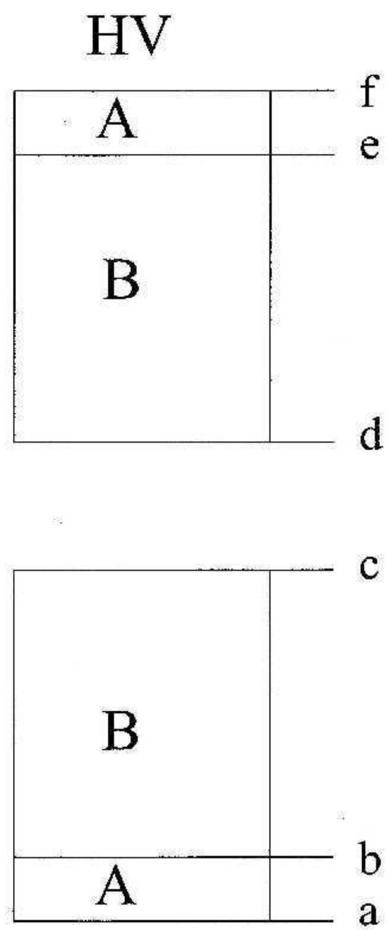
3. Accept greater than ANSI specified 0.5% tolerance for ratio test (not recommended).

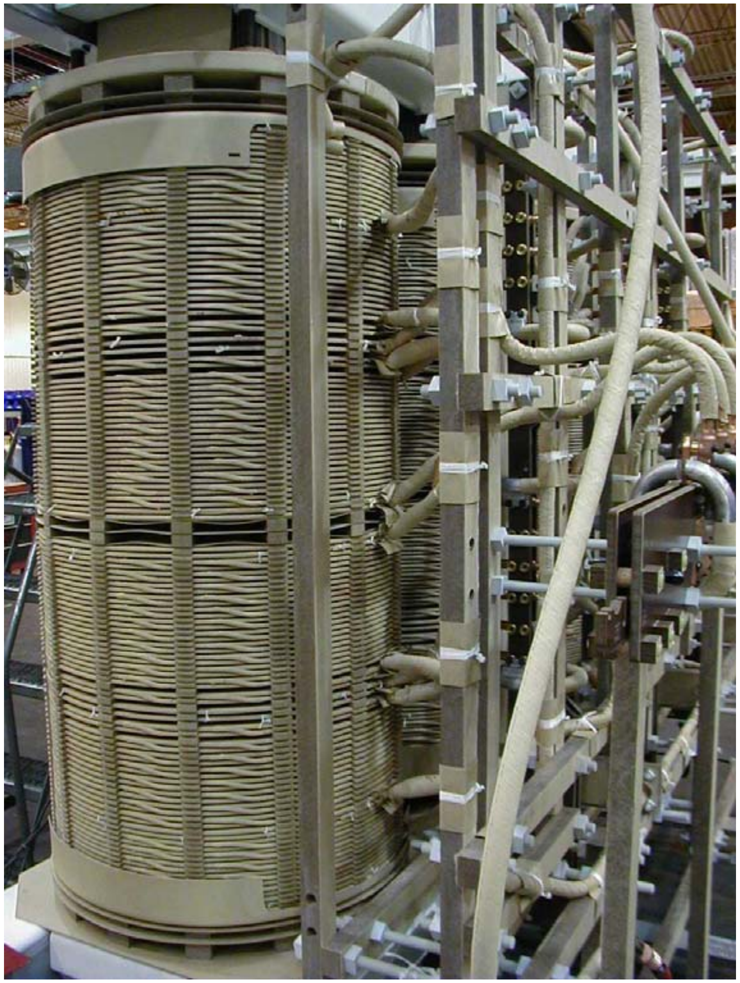
Dual-Voltage Primary

Axial Arrangement & Constant V/T



Sample HV Winding Designed for Uneven Dual-Voltage Ratio





Other Considerations

- No Brazed Joints
- Maximum Fan Speed
- Gasket versus O-Ring
- 3-Phase Auxiliary Power
- Raised Flanges
- Fall Protection
- Galvanized Radiators
- Secondary Air Treminal Chambers
- Busbar for Ground Conductor
- Corner Welds
- Minimum Control Wire Size
- Tap Switch above Coils
- Captive Hardware for internal test connections

Verification

- **Fill In Data Sheets**
- **Verify Special design requirements**
  - **Winding types & Materials**
  - **Losses at ratings other than ONAN**
- **Special test requirements**
- **Special features**
- **Design for Parallel operation**
- **Physical restrictions**

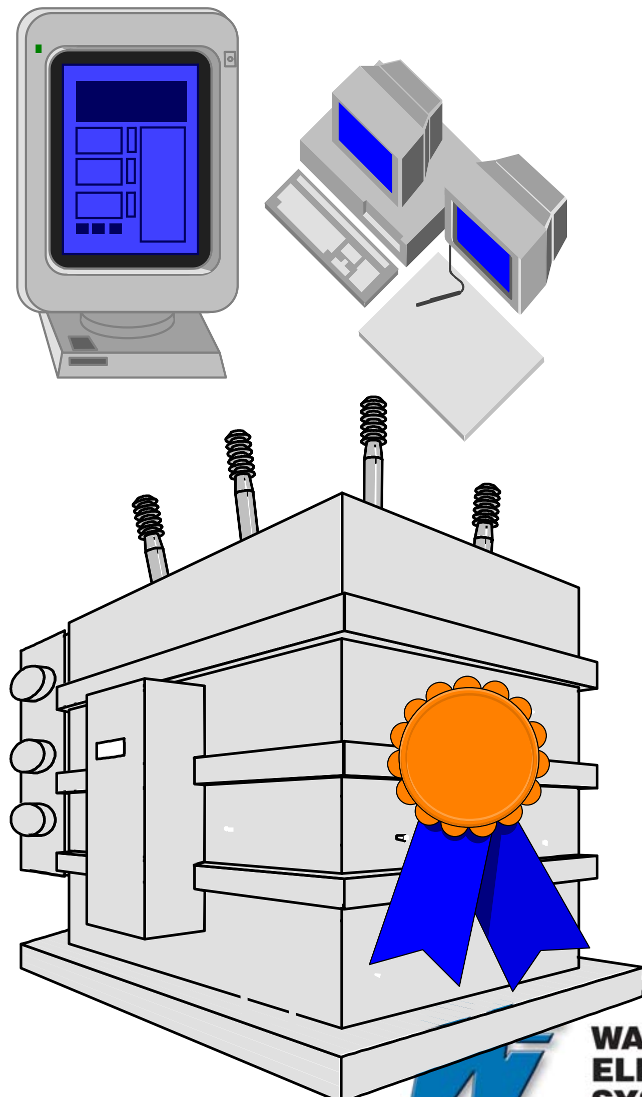
Desired Result

- **Supplier understands and fulfills the specification**

- **Purchaser has no surprises:**
  - **Approval Drawings**
  - **Testing**
  - **Delivery & Installation**

Transformer Design Minimums

- **HV Voltage**
  - Nominal
  - Extremes
- **LV Voltage**
  - Nominal
  - Extremes
- **Rated Current**
- **Fault Current Limits**
- **Regulation**
- **Environmental**
  - Sound Level
  - Ambient Temperature
  - Altitude



Factory Testing

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REASONS FOR TESTING

COMPLIANCE WITH CUSTOMER SPECIFICATIONS

ASSESSMENT OF QUALITY AND RELIABILITY

VERIFICATION OF DESIGN

COMPLIANCE WITH INDUSTRY STANDARDS

IEEE and ANSI STANDARDS

PRECISE COMMUNICATIONS

IDENTIFICATION OF CRITICAL FEATURES

SIMPLER CONTRACTUAL RELATIONSHIP

MINIMUM PERFORMANCE REQUIREMENTS FOR SAFETY

VALUABLE SOURCE OF TECHNICAL INFORMATION

ANSI STANDARDS

ANSI C.57.12.00 General Requirements (What)

- **New Sections For Loss Tolerances**
- **New Requirements For Dielectric Tests**
- **Definition of Thermal Duplicate**

ANSI C.51.12.90 Test Code (How)

- **New Section on Load Loss, No-Load Loss**
- **Wideband PD/RIV Measurement During 1 Hr. Test**
- **Sound Power Level**
- **Loss Test Guide, Impulse Test Guides**

ROUTINE TESTS

BEFORE TANKING

*** CORE INSULATION TESTS**

*** PRE-LEAD ASSEMBLY RATIO TESTS AND ELECTRICAL CENTRE MEASUREMENTS**

*** PRE-VAPOR PHASE RATIO TEST**

*** BUSHING CURRENT TRANSFORMER RATIO AND POLARITY TEST**

ROUTINE TESTS

AFTER TANKING

INSULATION RESISTANCE: CAPACITANCE AND DISSIPATION FACTOR

FINAL TURNS RATIO TESTS

IMPULSE TESTS

APPLIED POTENTIAL TEST

WINDING RESISTANCE MEASUREMENTS

INDUCED VOLTAGE TEST

CORE LOSS AND EXCITING CURRENT MEASUREMENTS

IMPEDIANCE AND LOAD LOSS MEASUREMENTS

WIRING CHECKS AND GAUGE SETTINGS

TRANSFORMER TESTS

DIELECTRIC TESTS	PERFORMANCE TESTS	THERMAL TESTS	OTHER TESTS
1) Lightning Impulse • Full Wave • Chopped Wave • Steep Wave 2) Switching Impulse **LOW (POWER) FREQUNCY** 1) Applied Voltage 2) 10 Induced 3) Induced Voltage 4) Partial Discharge	1) No-Load Loss 2) % Exc. Current 3) Load Loss 4) % Impedance 5) Zero Sequence Impedances 6) Ratio Tests 7) Short Circuit	1) Winding Resistance 2) Heat Run Test • Oil Rise • Wdg. Rise • Hot spot rise 3) Over Load Heat Run 4) Gas In Oil 5) Thermal Scan	*1) Insulation Capacitance and dissipation factor 2) Sound Level Tests 3) 10 kV Exc. Current 4) Megger 5) Core Ground *6) Electrical Center 7) Recurrent Surge 8) Dew Point 9) Core Loss Before Impulse *10) Control Circuit Test *11) Test on Series Transformer 12) LTC Tests *13) Preliminary Ratio Tests *14) Test on Bushing CT *15) Oil Preservation System Tests

*Quality Control Tests

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DIELECTRIC TESTS

BACKGROUND

DIELECTRIC ENVIRONMENT

- 60 HZ (NORMAL, ABNORMAL)
- LIGHTNING IMPULSE
- SWITCHING IMPULSE

TRANSFORMER INSULATION SYSTEM

- MAJOR INSULATION
- MINOR INSULATION
- PHASE TO PHASE INSULATION

DIELECTRIC TESTS

(1) Impulse tests

Lightning impulse
(full wave, chopped wave, front of wave)

Switching impulse

(2) Low (power) frequency dielectric tests

Induced voltage test

Applied voltage test

Single phased induced test

(3) Additional dielectric tests

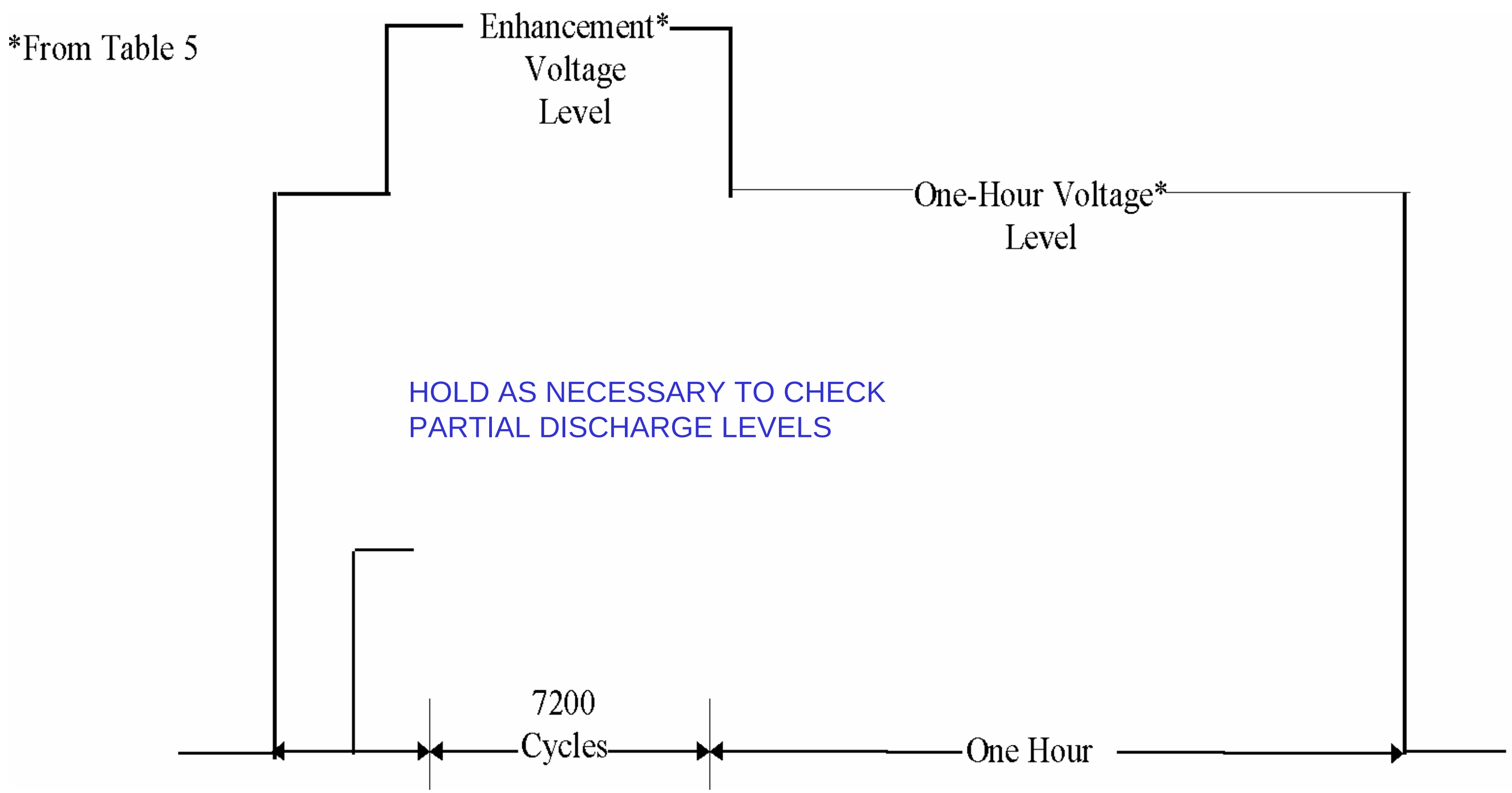
Partial discharge monitoring

1 hour test at 1.5 P.U. voltage

1 Hour Induced Voltage Test Class II Power Transformers

IEEE C57.12-2000 5.110.5.1

With the transformer connected and excited as it will be in service, an induced-voltage test shall be performed as indicated in Figure 2, at voltage levels indicated in Column 5 and Column 6 of Table 6.



Failure Detection

10.8.5 Failure detection

Failure may be indicated by the presence of smoke and bubbles rising in the oil, an audible sound such as a thump, or a sudden increase in test current. Any such indication shall be carefully investigated by observation, by repeating the test, or by other tests to determine whether a failure has occurred.

In terms of interpretation of PD measurements, the results shall be considered acceptable and no further PD tests required under the following conditions:

- **a) The magnitude of the PD level does not exceed 100 ∝V.**
- **b) The increase in PD levels during the 1 h does not exceed 30 ∝V.**
- **c) The PD levels during the 1 h do not exhibit any steadily rising trend, and no sudden, sustained increase in levels occurs during the last 20 min of the tests.**

Judgment should be used on the 5 min readings so that momentary excursions of the radio-influence voltage (RIV) meter caused by cranes or other ambient sources are not recorded. Also, the test may be extended or repeated until acceptable results are obtained.

When no breakdown occurs, and unless very high PDs are sustained for a long time, the test is regarded as nondestructive. A failure to meet the PD acceptance criterion shall, therefore, not warrant immediate rejection, but lead to consultation between purchaser and manufacturer about further investigations.

NO-LOAD LOSSES AND EXCITING CURRENT

- **LOSSES OF UNLOADED TRANSFORMER EXCITED AT RATED VOLTAGE AND RATED FREQUENCY**
- **INCLUDE CORE LOSS, DIELECTRIC LOSS, I R LOSS**
- **CORE LOSS - HYSTERESIS LOSS, EDDY CURRENT LOSS**
- **HYSTERESIS LOSS - MAXIMUM FLUX DENSITY**
- **EDDY CURRENT LOSS - FREQUENCY, TEMPERATURE**
- **AVERAGE VOLTAGE VOLTMETER METHOD**
- **CORRECTION TO SINE WAVE BASIS**

LOAD LOSS AND % IZ

- **LOSSES OF TRANSFORMER DUE TO LOAD CURRENT**
- **INCLUDE I R LOSSES IN WINDINGS**

  STRAY LOSSES IN WINDINGS

  STRAY LOSSES IN STRUCTURAL COMPONENTS

  CIRCULATING CURRENT LOSSES

- **THREE WATTMETER METHOD PREFERRED**
- **P.U. IZ = VOLTAGE FOR RATED AMPS (ONE WDG. SHORTED)**
  RATED VOLTAGE

THERMAL TESTS

MEASUREMENTS OF WINDING RESISTANCES

TEMPERATURE RISE TEST

OVER LOAD HEAT RUNS

GAS IN OIL ANALYSIS

THERMAL SCANNING

TEMPERATURE RISE TESTS

- INSULATION TEMPERATURE DETERMINES "LIFE"
- SIMULATION OF WORST CASE OPERATING CONDITION
- DETERMINATION OF

  TOP OIL RISE
  WINDING RISE (AVERAGE)
  HOT SPOT RISE
- DATE USED IN LOADING (OVER LOADING)

TEST

- DISSIPATE MAXIMUM LOSS - ACHIEVE STEADY STATE MEASURE OIL RISES
- CIRCULATED RATED CURRENT FOR 1 HOUR MEASURE HOT RESISTANCES
- EXTRAPOLATE BACK TO INSTANT OF SHUT DOWN
- CALCULATE WINDING RISES

Additional Tests Performed on New Designs <u>and/or at Customer Request</u>

FRONT CHOPPED IMPULSE TESTS AND SWITCHING SURGE TESTS

HEAT RUNS

SOUND LEVEL TESTS

PD MEASUREMENTS

ZERO SEQUENCE IMPEDANCES

SPECIAL TESTS

OTHER TESTS

TESTS ON CONTROLS

INSULATION RESISTANCE

CAPACITANCE AND DISSIPATION FACTOR

CORE LOSS BEFORE AND AFTER IMPULSE

SINGLE PHASE EXCITING CURRENT AT 10 KV

ELECTRICAL CENTER DETERMINATION

RATED VOLTAGE - RATED CURRENT LTC OPERATION

CORE GROUND MEGGER

DEW POINT AT SHIPMENT

SOUND LEVEL MEASUREMENTS

SPECIAL TESTS

- Sound Test – Especially for low sound units
- Overload Heat Runs
- Time Constant Heat Runs
- Class II testing for all special transformers
    - Series Parallel
    - High or low impedance
- Short Circuit Testing
    - Use Finite Element Analysis in lieu of testing

Test Reporting

C57.12.00-2000

5.9 Total losses

The total losses of a transformer shall be the sum of the no-load losses and the load losses.

The losses of cooling fans, oil pumps, space heaters, and other ancillary equipment are not included in the total losses. When specified, power loss data on such ancillary equipment shall be furnished.

The standard reference temperature for the load losses of power and distribution transformers shall be 85 º C.

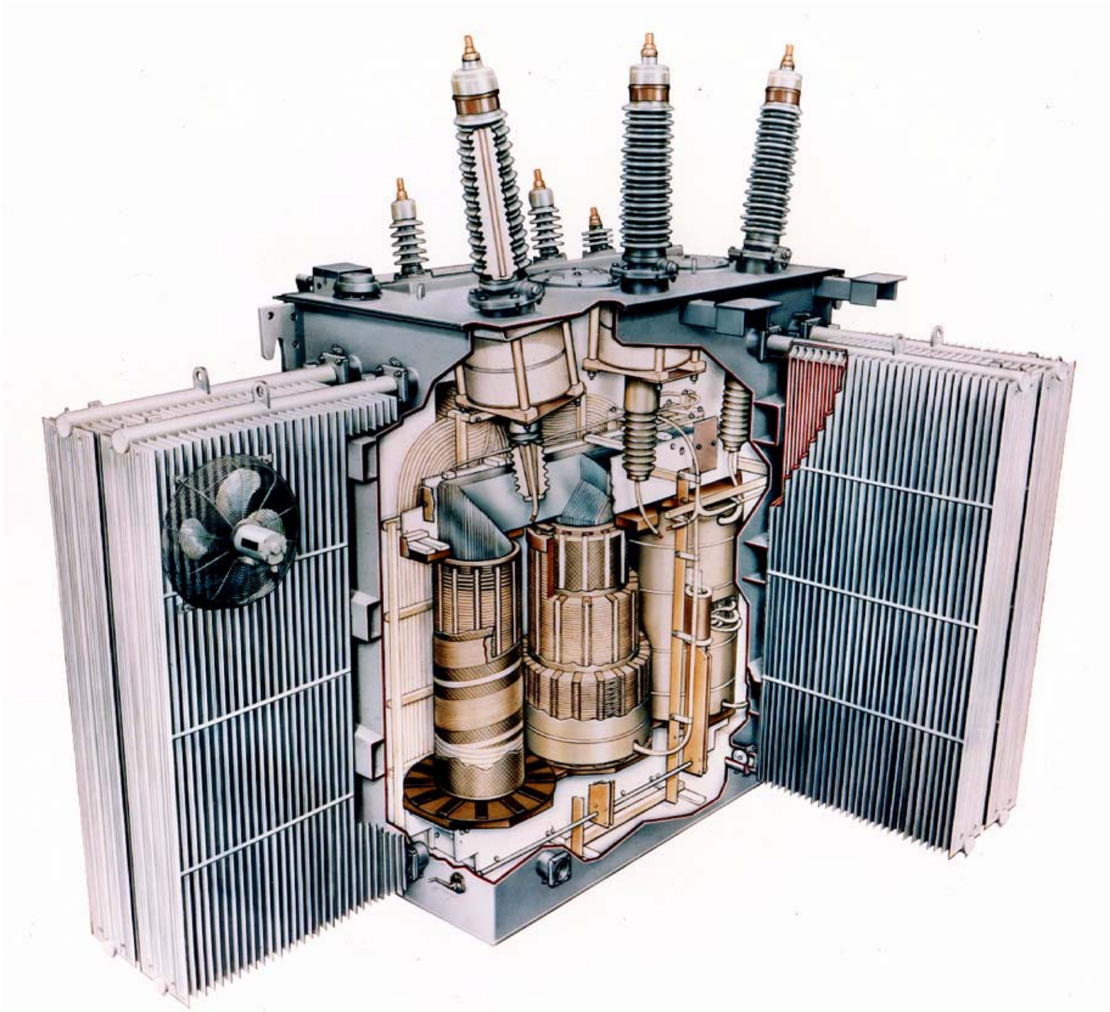
The standard reference temperature for the no-load losses of power and distribution transformers shall be 20 º C.

For Class II transformers, control/auxiliary (cooling) losses shall be measured and recorded. All stages of cooling, pumps, heaters, and all associated control equipment shall be energized, provided these components are integral parts of the transformer.

TRANSFORMER MONITORING

Transformer Failure Modes

Failures due to internal stresses, close in faults, weather, accidents, vandalism:



- **Tank, Radiator leaks**
- **Through Faults**
  - **Winding failures**
  - **Thermal failures**
  - **Tank Failures**
- **Core Damage,**
- **Core grounds**
- **Insulation system**
- **aging process**
- **Tap Changers**
  - **DETCs**
  - **LTCs**

- **Bushings**
- **Surges**
  - **Lightning, switching (external)**
- **Oil Quality**
  - **Moisture**
  - **Oxygen**
- **Thermal**
  - **Fans**
- **Oil Level**

Monitoring - Mechanical Failures

- **Failures due to internal stresses, close in faults, weather, accidents, vandalism:**
  - Tank and Radiator Failure
  - Winding Failures (Buckling, Tipping, Beam bending, Telescoping, etc.)
  - Core Damage
  - Insulation Damage
  - Lead Faults
  - Bushing Mechanical Failure

Transformer Monitoring Electrical Failures

- **Failure initially categorized into areas such as over voltage or partial discharge exceeding the withstand strength of the insulation system**
- **Failures as a result of:**
  - Switching surges
  - Lightning
  - Synchronism issues
- **Typically accompanied by Thermal or Chemical failure**
- **Loss of Insulating oil below critical oil level**

Transformer Monitoring
Thermal

- **Failure due to insulation or conductor destruction as a result of:**
  - Short or long term overloading
  - Faults
  - Undersized leads
  - Contact coking
  - Bad joints
  - Loss of cooling
  - Design issues
  - Low oil levels

Transformer Monitoring Chemical

- **Failure due to**
  - The ingress of water or oxygen
  - Loss of insulating oil
  - Paper degradation due to thermal issues or aging
    - Less obvious, Most overlooked
    - Increases potential of the other three failure modes
    - Paper insulation deteriorates from the effects of moisture, oxygen, and temperature and time.
    - Moisture and oxygen are controlled by the maintenance practices while the rate of thermal degradation is controlled by loading practices.
    - Failure of the oil preservation system.

Transformer Monitoring Failure Mode Analysis

- **FMA provides what, when, and how to monitor**
- **Many tests require transformer to be de-energized**
- **Monitoring provides detection and direction for further prevention testing**
  - Many tests require transformer to be de-energized
  - Current operating practices prevent typical testing procedures due to limited outages
- **ONLINE MONITORING, A VIABLE SOLUTION TO PROVIDE PREDICTION OF TRANSFORMER FAILURES AND ALLOW INTERVENTION BEFORE FAILURE**

Liquid Level

- **Oil Level monitoring**
  - Alarm to allow intervention
  - Trip to provide protection
  - Leak
  - Critical Oil Level trip to prevent dielectric failure
  - Low oil levels resulting from sampling losses, especially in LTCs where oil volumes are significantly smaller
  - Low oil level below radiator headers result in thermal failure

Transformer Monitoring
On Line Chemical Detection

- **Chemical Detection through On Line Gas & Oil Monitors**
- **Most significant**
- **Majority of all utilities use DGA**
  - Manually sample 1-4 times/year
  - Oil quality yearly or less
  - Problems causing failure can go out of control between manual sampling schedule

Transformer Monitoring DGA

- **GE HYDRAN 2**

  www.gepower.com/prod_serv/products/substation_md/en/monitoring_instr_sys/index.htm

  Hydrogen, Acetylene and Carbon Monoxide
  - Provides composite gasses ppm
  - Moisture level sensor available

Morgan Schaffer Calisto

www.morganschaffer.com
- Dissolved hydrogen and moisture
- Stable at low gas concentrations
- Early detection of incipient faults

Transformer Monitoring DGA

Serveron Transformer Monitor

Model TM3

www.serveron.com

- **Newest addition to the Serveron TM Series delivers a cost effective transformer condition identification and alert system.**
- **Offers legitimate identification of the most critical transformer fault types—partial discharge, arcing and thermal faults.**
- **Correlates 3 fault gases (acetylene, ethylene and methane), moisture-in-oil, oil temperature and ambient temperature to transformer load.**
- **The combination of on-line DGA data automatically populating the Duval Triangle provides unprecedented insight into fault diagnosis.**

Transformer Monitoring DGA

Kelman Transfix

Transformer Gas Analyser

www.kelman-usa.com

8 gases + moisture

- Hydrogen (H_2)
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)
- Oxygen (O_2)

Transformer Monitoring
DGA

- **Serveron TRUEGAS Analyzer www.serveron.com**
  - True on line chromatograph
    - Acetylene
    - Hydrogen
    - Methane
    - Ethane
    - Ethylene
    - Carbon Monoxide & Oxygen
    - Built in trending

Accessories – Monitoring – On Line DGA

- **Tree Tech Gas and Moisture Monitor (GMM)**

  www.techsales-nw.com

  - Dissolved hydrogen and moisture
  - Calculations of trends
  - Stores historical values

Transformer Monitoring
Temperature Detection

- **Thermal Detection Equipment**
  - Top Oil
  - Hot Spot
  - LTC Oil Temperature
  - LTC – Main Tank differential

- **Mechanical equipment only provides maximum, duration is also critical**

Luxtron
Fiber-Optic Temperature Systems

www.luxtron.com

- **Provide direct readings of winding temperature hottest-spot**
- **Difficult to position / locate properly**

Direct, Real Time, Accurate Measurement of Hot Spot Temperature, -30 to 200°C

Neoptix
Fiber-Optic Temperature Systems

www.neoptix.com

- **Provide direct readings of winding temperature hottest-spot**
- **Difficult to position / locate properly**

The T/Guard™ System is shown with optional LCD display and eight T2 temperature probes

Dynamic Ratings

www.drmcc.com

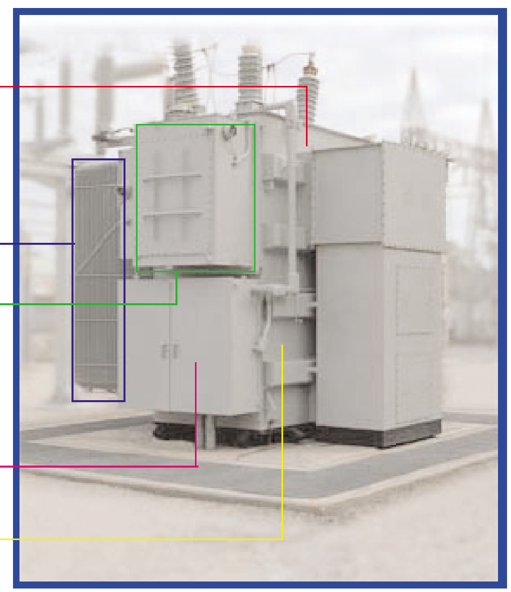
Temperatures:
- Top oil temperature
- Ambient temperature
- Winding hot spot calculation (for each winding
- Direct winding temperature from fiber optic sensors.
- Bottom oil temperature

Cooling System:
- Fan/pump failure
- Fan/pump run hours
- Cooling contactor fail
- Cooling breaker trip
- Cooling switch position

Load Tap Changer:
- Tap Position indication
- Tap counter (per position)
- Time since last through N
- Delta T
- Oil level high/low

Alarm Contacts & Ancillaries:
- Sudden Pressure
- Low/High Oil Level
- Nitrogen Pressure

Core & Coil:
- Dissolved Gas
- Moisture in oil
- Insulation loss of life calculations



energysolutions

… to power your future

WAUKESHA ELECTRIC SYSTEMS

Weschler Transformer Advantage II

www.weschler.com

- **Direct Oil Temperature**
- **Simulated Winding Temperature**
- **Calculated Winding Temperature (CT Models)**
- **LTC Temperature Difference (LTC Models)**
- **Single, Dual and Three Channel Units**
- **Analog & Digital Inputs**
- **Multi-Stage Fan/Pump control**
- **Weatherproof Metal Case**
- **SCADA Ready - DNP3.0 Protocol**

energysolutions

… to power your future

Transformer Monitoring
Temperature Detection

- **Qualitrol Dual Electronic Mechanical**
- **Qualitrol Electronic Temperature Monitors**

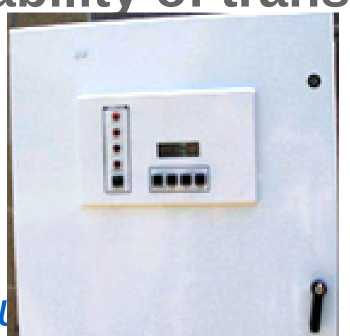
www.qualitrolcorp.com

GE

http://www.gepower.com/prod_serv/products/substation_md/en/monitoring_instr_sys/index.htm

Transformer Condition Assessment

The Transformer-Maintenance Action Planner (T-MAP) monitoring and diagnostic systems provide the information to determine the need for maintenance, extend maintenance cycles and improve the reliability of transformers.



Portable Transformer Monitoring System

The FARADAY Transformer Nursing Unit (TNU) is a dynamic, adaptive, interactive, intelligent and integrating system to monitor and manage the performance of transformers showing signs of distress.

WAUKESHA ELECTRIC SYSTEMS

TRANSFORMER MONITORING

- **DOBLE** **www.doble.com/products/continuous_online_diagnostics.html**
- **SCHWEITZER** **www.selinc.com/sel-701-1.htm**
- **BECKWITH ELECTRIC**
- **ORTO (www.ortodemexico.com)**

Transformer Monitoring Mechanical

- **Sudden Pressure/Fault Pressure RPRR relays**
- **Mechanical Pressure Relief Device**
- **Liquid Level**
- **Pressure Vacuum**
- **Gas Accumulation Relay**
- **Oil Flow monitor**

Transformer Monitoring
Other Considerations

- **Bushings**
- **Acoustic detection of partial discharges**
- **Fan, Pumps operating currents**
- **LTCs**
  - Motor Operating time
  - # of operations
  - Prediction of contact life
  - Position indication
  - Travel limits (16R or 16L)
  - Oil DGA monitoring

Transformer Monitoring Conclusions

- **Use of Electronic and electromechanical monitors reduce need for on site inspection**
- **Monitoring only effective as a predictor, does not replace required maintenance**
- **Only valuable if information is in useable form**
  - Notification of significant indicators
  - User's need to determine what is significant
- **USER needs comfort with reliability,**

Transformer Monitoring Conclusions

- Many systems currently on the market and being developed
- Systems range from simple to complex
- Failure detection rate needs to be evaluated before purchase
- Failures can occur between
- Monitors of no value if data cannot be retrieved easily