Transformer Installation, Assembly & Testing

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Intent

- Provide explanations as to why certain process are important and should be followed
- Describe some examples of what to do and what not to do
- Comments on my personal experiences?
- Provide references that you can study at your leisure
- Answer questions

Format of Presentation

- Ask questions
- Encourage discussion and understanding (especially on topics where there may be more than one way or procedure to install a transformer).
- Please add your experiences.
- Please turn your cell phones <u>**OFF**</u> so we are not distracted by texting, email, etc.


DILBERT
I WOULD LIKE TO THANK EACH OF YOU FOR PLAYING WITH YOUR PHONES AND NOT LISTENING TO A WORD I SAID ALL MEETING.
Dilbert.com DilbertCartoonist@gmail.com
I HOPE KARMA IS A REAL THING AND FROZEN LAVATORY DEBRIS FROM AIR-PLANES KILLS EACH OF YOU.
1-1-14 © 2014 Scott Adams, Inc. /Dist. by Universal Uclick
WHAT WAS HE GOING ON ABOUT?
BEATS ME. I'M NOT MUCH OF A MULTI-TASKER.

Basis of Presentation

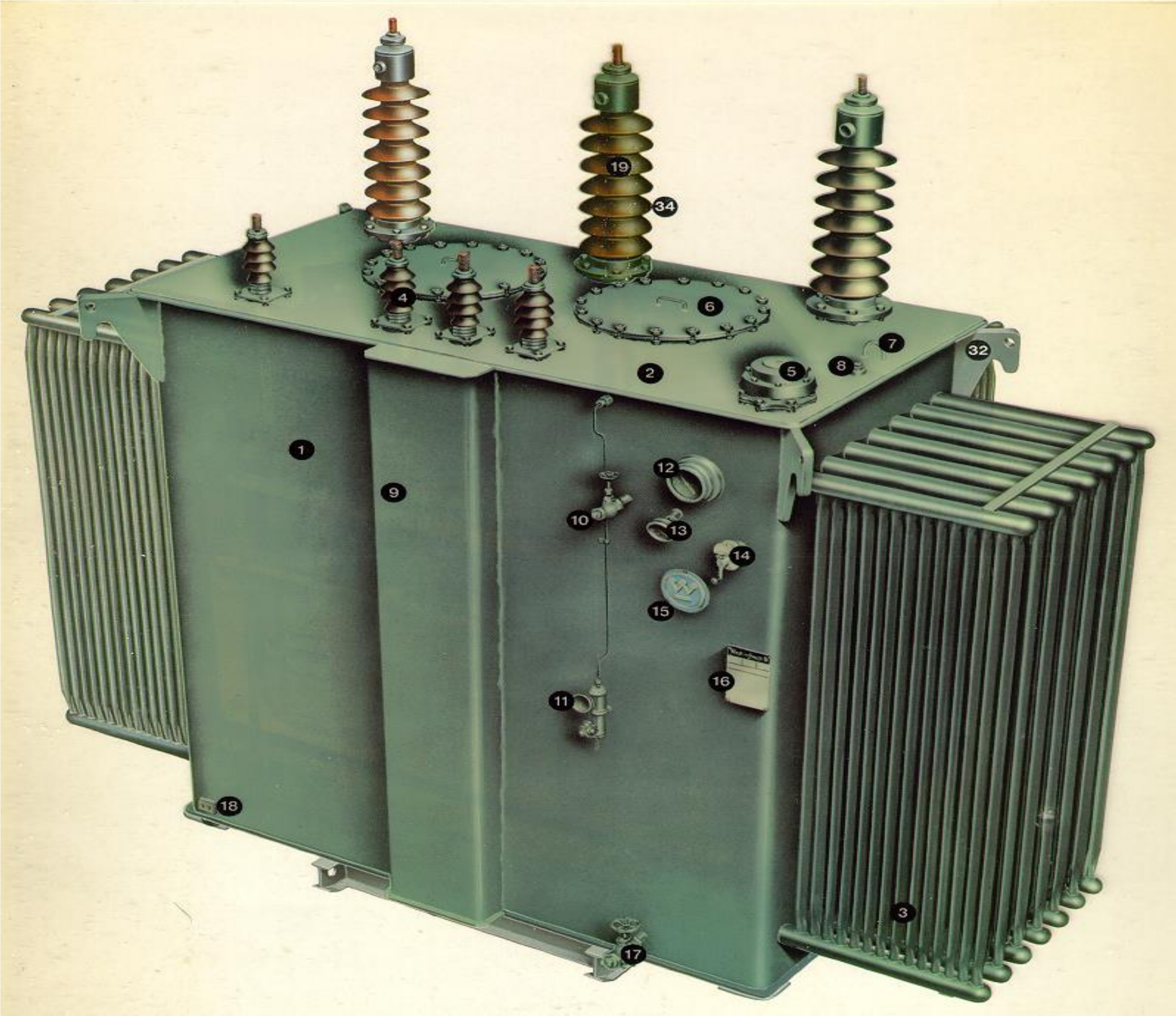
- Industry Accepted Practices;
  - Based on IEEE and other consensus Guides
  - Practical processes that are based on physics, chemistry and logic
  - Based on others' many years experience
- Personal Experience
  - Have personally done this work on transformers from 10 to 750 MVA, 72 to 550 kV for 50 years (proving [to me] processes are possible & practical)

Topics

1. **RECEIVING** a transformer after transport to a substation site
2. **ASSEMBLY** and **PROCESSING** of a transformer at site
3. **TESTING** a transformer to verify its suitability for service
4. Discussion of integrating the transformer into the power system

Importance of Transformer Processes

- The way a transformer is handled and the procedures that are used to receive, assemble, process and test the transformer are of <u>fundamental importance</u> to the long life of the transformer.
- The installation and testing of the transformer verifies its condition at the time it is ready for service as well as forming the baseline or signature tests for all future maintenance and later condition assessment or analysis.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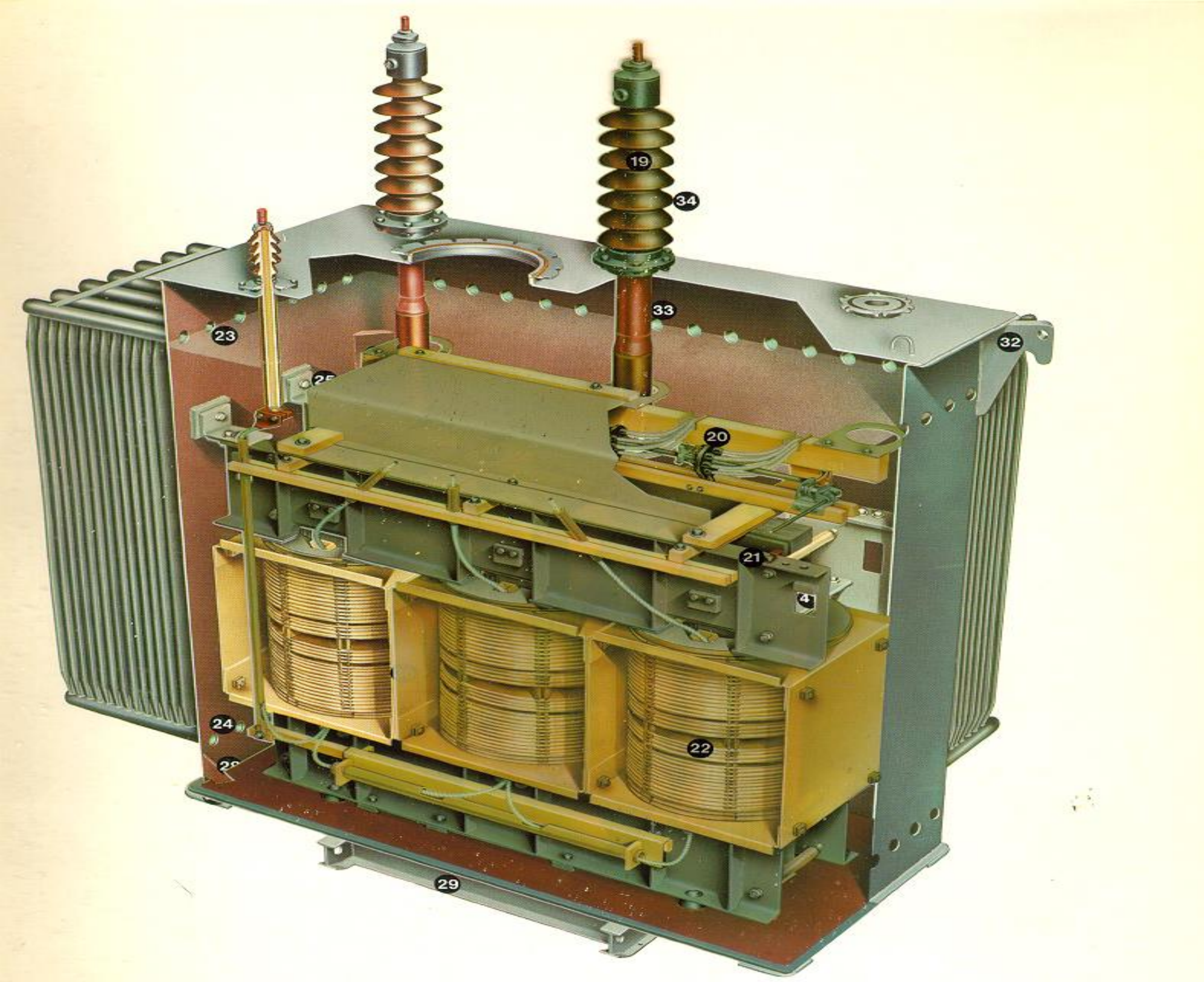
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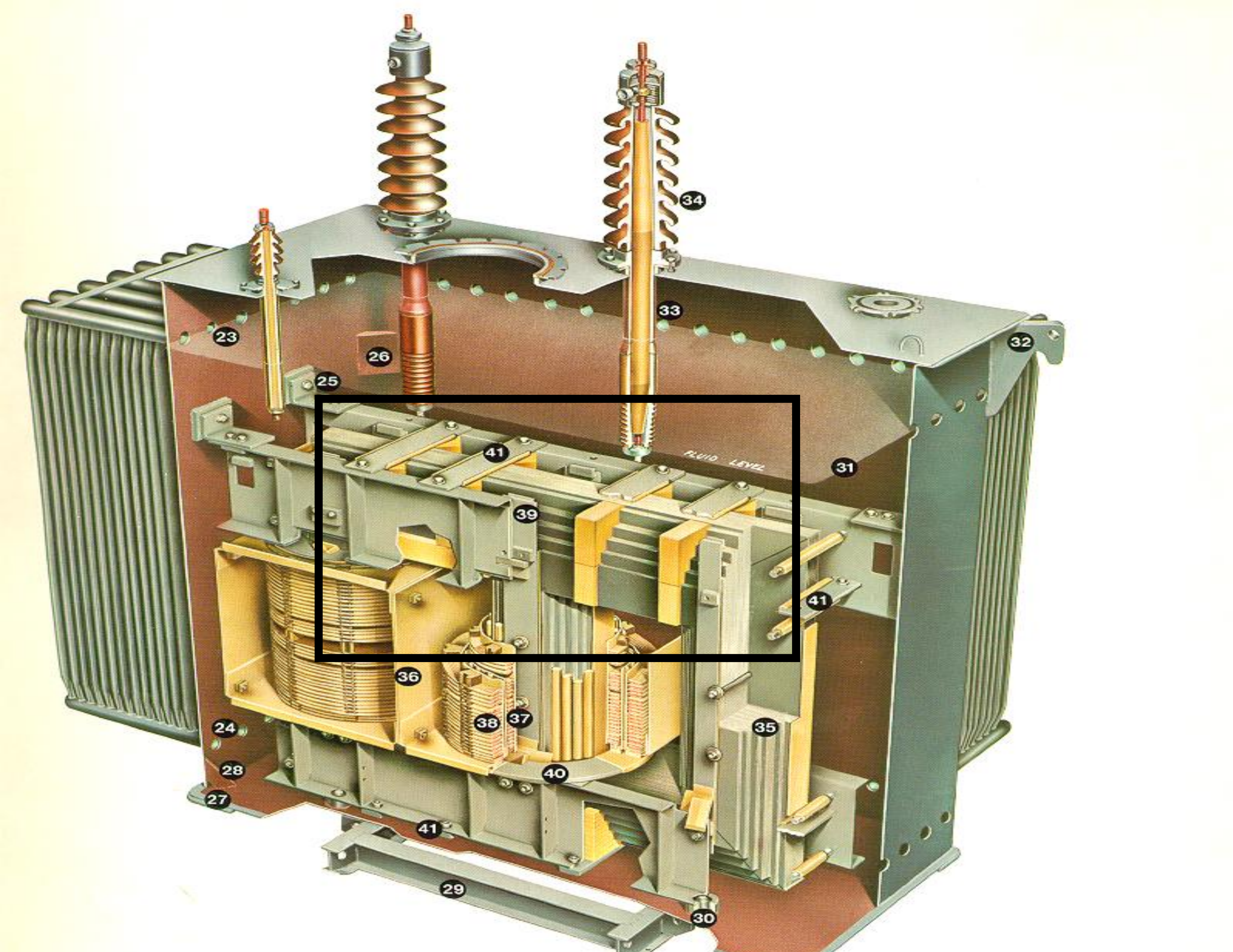
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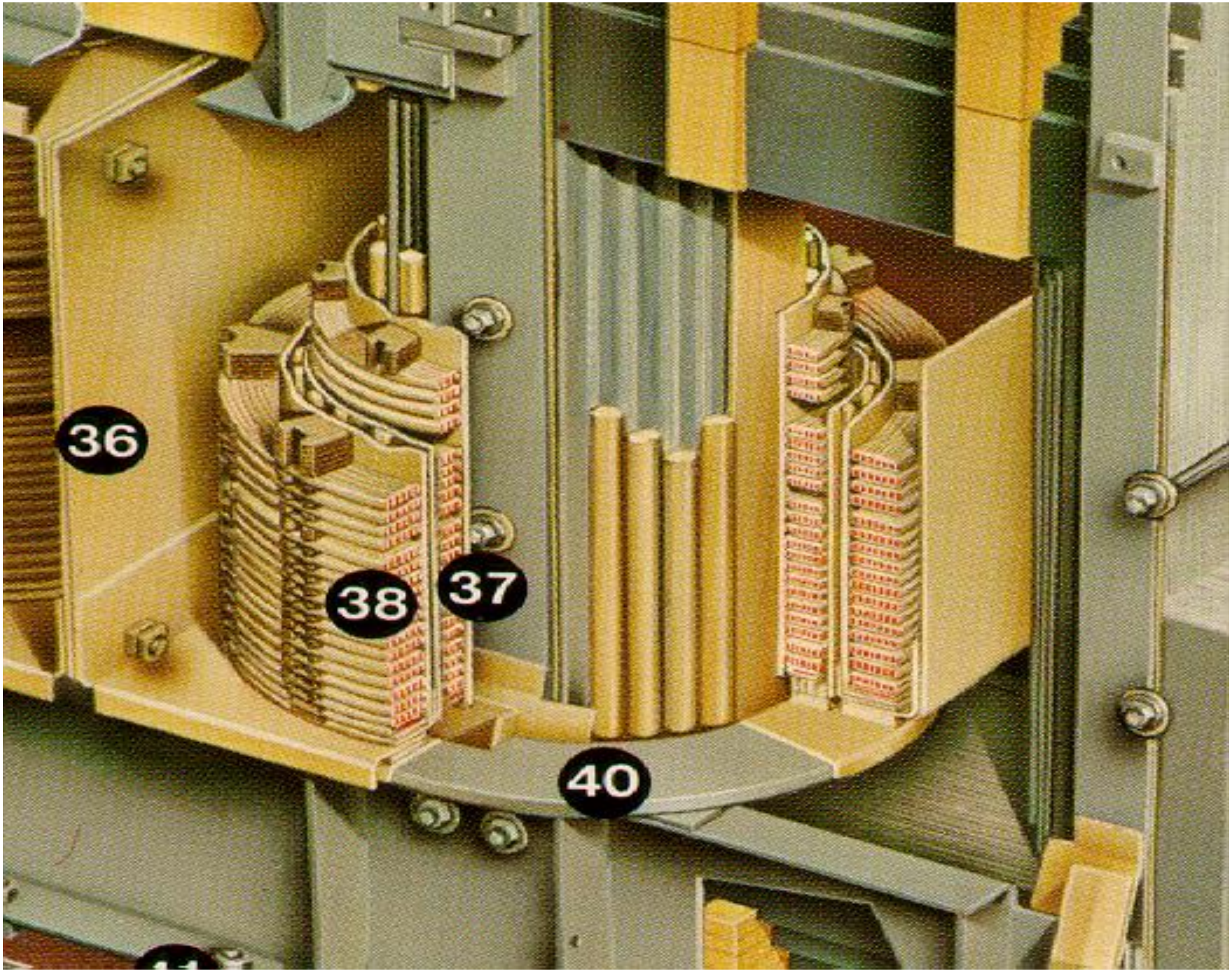
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Transformer Condition Tests

	Diagnostic Test	Winding Turn-to-Turn Ratio	Winding/Bushing Insulation	Winding/Bushing/LTC Continuity	Winding Geometry	Magnetic Circuit Insulation	Magnetic Circuit Integrity
Electrical Test	Winding Ratio	X					
Electrical Test	Winding Resistance			X			
Electrical Test	Magnetizing Current	X				X	
Electrical Test	Capacitance and DF/PF		X				
Electrical Test	Insulation Resistance		X			X	
Electrical Test	Core Ground Test					X	
Electrical Test	Frequency Response Analysis	X			X	X	X
Electrical Test	Leakage Reactance				X		
	Dissolved Gas Analysis	X	X	X		X	X

Industry Standards & Guides

- Presented in the order of when they are used in the transformer assembly and installation process
- Recognize that the transformer assembly and installation process starts much before the transformer ever arrives on site

Reference Standards and Guides
Factory

- CAN/CSA-C88-M90 (Reaffirmed 2009) “Power Transformers and Reactors”
- IEEE Std C57.12.00™-2015 “IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers”
- IEEE Std C57.12.10™-2010 “Standard Requirements for Liquid-Immersed Power Transformers”
- IEEE Std C57.12.70™-2011 “IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers”
- IEEE Std C57.12.90™- 2010 “IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers”

Reference Standards and Guides
Transportation

- "Cargo Securement Rules" Federal Motor Carrier Safety Administration (North American)
- Cargo Securement – Driver's Handbook on Cargo Securement – A Guide to the North American Cargo Securement Standard
- Responsibility of shipper and driver

Reference Standards and Guides
Transportation and Site

- CIGRE 673 (WG A2.42) “Guide on Transformer Transportation”
- IEEE Std C57.150™-2012 “IEEE Guide for the Transportation of Transformers and Reactors Rated 10 000 kVA or Higher”

Reference Standards and Guides
Site

- IEEE Std C57.93™-2007 “IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers”
- CAN/CSA-C50-08 (R2013) “Mineral insulating oil, electrical, for transformers and switches”
- IEEE Std C57.106™-2015 “IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment”
- IEEE Std C57.152™-2013 “IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors”
- IEEE Std C57.149™-2012 “IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers”

Other Standards & Guides of Interest ¼ Accessories

- CAN/CSA C88.1-96 (Reaffirmed 2011) Power Transformer and Reactor Bushings“
- IEEE Std C57.19.01™-2000 “IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings”
- IEEE Std C57.131™-2012 “IEEE Standard Requirements for Load Tap Changers”
- CAN/CSA-C60044-1-07 (R2011) - Instrument Transformers - Part 1: Current Transformers (Includes CSA C13)
- IEEE Std C57.13.1™-2006 “IEEE Guide for Field Testing of Relaying Current Transformers”
- IEEE Std C57.13.3™-2014 “IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases”

Other Standards & Guides of Interest 2/4
Operating Condition

- IEEE Std C57.104™-2008 “IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers”
  - IEEE Std PC57.104™- [2018 November] <u>Unapproved</u> “Draft Guide for the Interpretation of Gases in Oil Immersed Transformers”
- IEEE C57.91™-2011 “IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers and Step Voltage Regulators”

Other Standards & Guides of Interest 3/4 Specialized Transformers

- IEEE std C57.116™-2014- "IEEE Guide for Transformers Directly Connected to Generators“
- IEEE Std C57.21™-2008 “IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA”
- IEC 62032 / IEEE C57.135™-2005 “Guide for the application, specification, and testing of phase-shifting transformers”

Other Standards & Guides of Interest 4/4
IEC

- IEC 60076 (Power transformers Parts 1 through 21)
  - EC 60076-1 ed3.0 General
  - IEC 60076-8 ed1.0 Application guide
- IEC 60214-1 Tap-changers - Part 1: Performance requirements and test methods
- IEC 60137 Insulated bushings for alternating voltages above 1 000 V

Information Required for Installation

- Presented generally in the order that the information is produced.

Customer Information
Specification and Change Orders

- Purchaser’s transformer specification(s) (general and rating/data specifications)
- Purchase order and change orders that may influence technical considerations when installing the transformer (unpriced).

Customer & Factory Information
Design Review

- Explanations, commitments, clarifications and notes from the design review meeting
  - Recommended to be conducted
    - by a transformer expert at the factory
    - in accordance with CIGRE
      - Publication 529 "Guidelines for Conducting Design Reviews for Power Transformers", and
      - Publication 673 "Guide on transformer transportation"

Factory Information – Documentation Related to Receiving

- Transport and handling drawing
- Receiving instructions (in instruction manual?)
- Assembly instructions (in instruction manual?)
- Pre-Transport test results
- Photographs of transformer loaded on carrier
- Detailed packing lists should indicate individual parts in each package/crate
- Final drawings

Factory Information – Testing (Related to Transport & Receiving)

- Core and clamp insulation Megger® tests (with correct Megger® voltage at core ground test terminal)
- Leak test results
- Transport gas pressure and dew point tests
- Shock recorder settings and information and accessories required to interpret results
- FRA tests in
  - Fully assembled and oil filled condition, and/or
  - Transport condition with test bushings

Factory Information – Testing (Related to site testing)

Factory test report

- Winding & bushing insulation resistance, PF (power factor) & capacitance
- Winding ratios
- Polarity
- Winding resistance (demagnetize after)
- Low voltage excitation current
- Single-phase excitation test
- Other

Factory Information – (Required for Installation)

- Factory drawings
- Factory test report(s)
- Instruction manual(s)
- Photographs of assembled or partially assembled transformer (at factory)
- Substation foundation, bus, station service, grounding, protection & control , and SCADA drawings

Transformer Warranty Considerations 1 of 2

- Inspections and receiving
- “Proper” (and sometimes supervised) assembly, processing, & testing of transformer
- Adherence to manufacturer’s or industry protocols for assembly, processing, & testing
- Acceptable test methods and results
- Adequate records

Transformer Warranty Considerations 2 of 2

- Manufacturer, as a condition of warranty, almost always want their representative on site
  - when the transformer arrives. (Megger and impact recorder reading), and
  - during some portions of installation (e.g. installing bushings, internal inspection, etc).
- Owners should always give a manufacturer the option to come to site (even if the manufacturer doesn't require it).

Transformer Installation Records

- Assembly log indicating dates/times and weather conditions, people during entire process
- Records of all inspections and testing (ratio including phase angle and current, Megger®, excitation current and voltage, insulation power factor and capacitance of windings and bushings, FRA, other dielectric tests, oil physical and DGA tests including sampled location(s), functional tests (and methods) on all accessories, etc.)

Transformer Receiving

Transformer Receiving

- Safety
- Be aware of Terms of Transport INCOterms
  - Understand point of transfer of ownership as well as warranty obligations
  - Understand point of transfer of responsibility
- Assess Condition of Transformer

INCOterms 2010

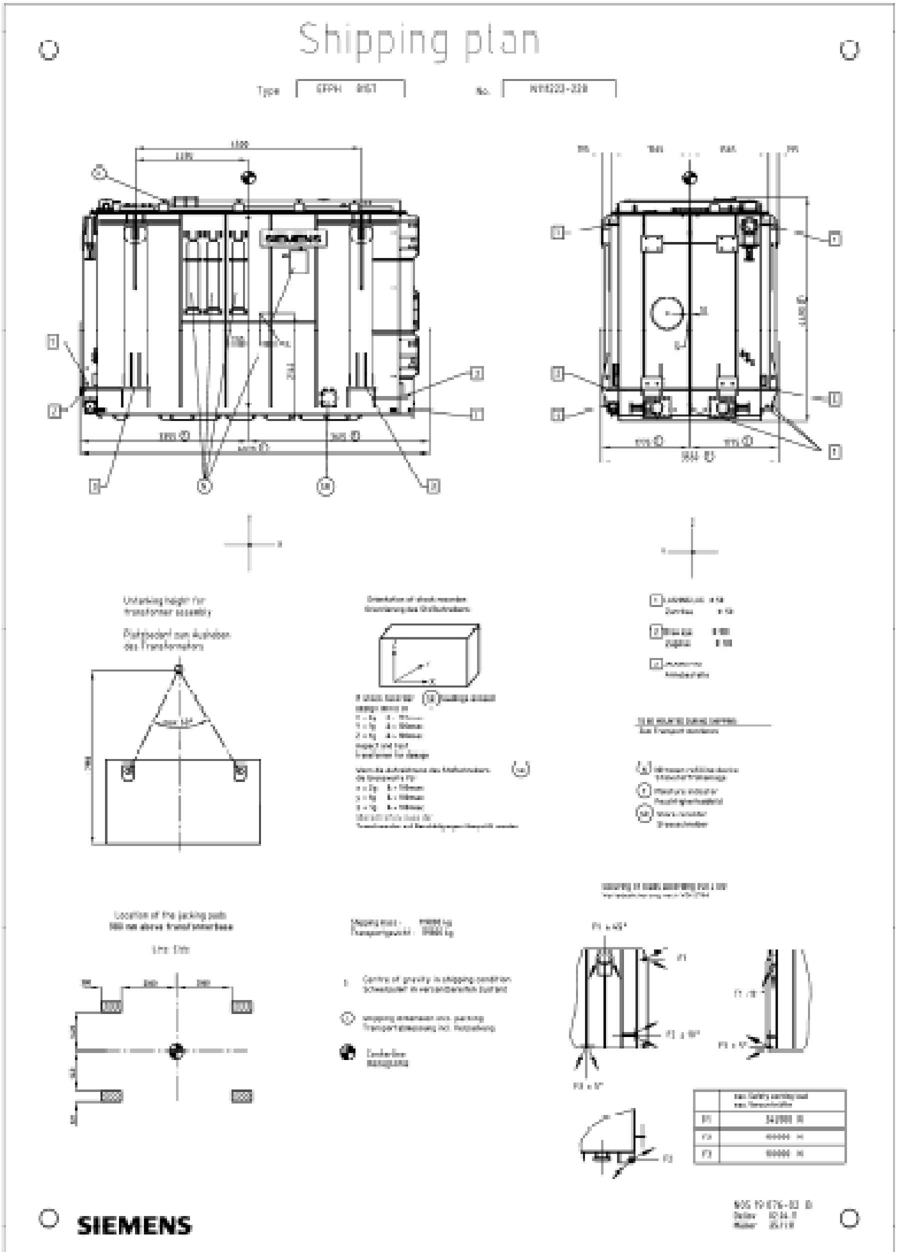
- **RULES FOR ANY MODE OR MODES OF TRANSPORT**
  - ❖ **EXW** EX WORKS
  - **DAT** Delivered At Terminal
  - ✓ **DAP** Delivered At Place
  - **DDP** Delivered Duty Paid
- **RULES FOR SEA AND INLAND WATERWAY TRANSPORT**
  - **FAS** Free Alongside Ship
  - **FOB** Free On Board
  - **CFR** Cost and Freight
  - **CIF** Cost Insurance and Freight

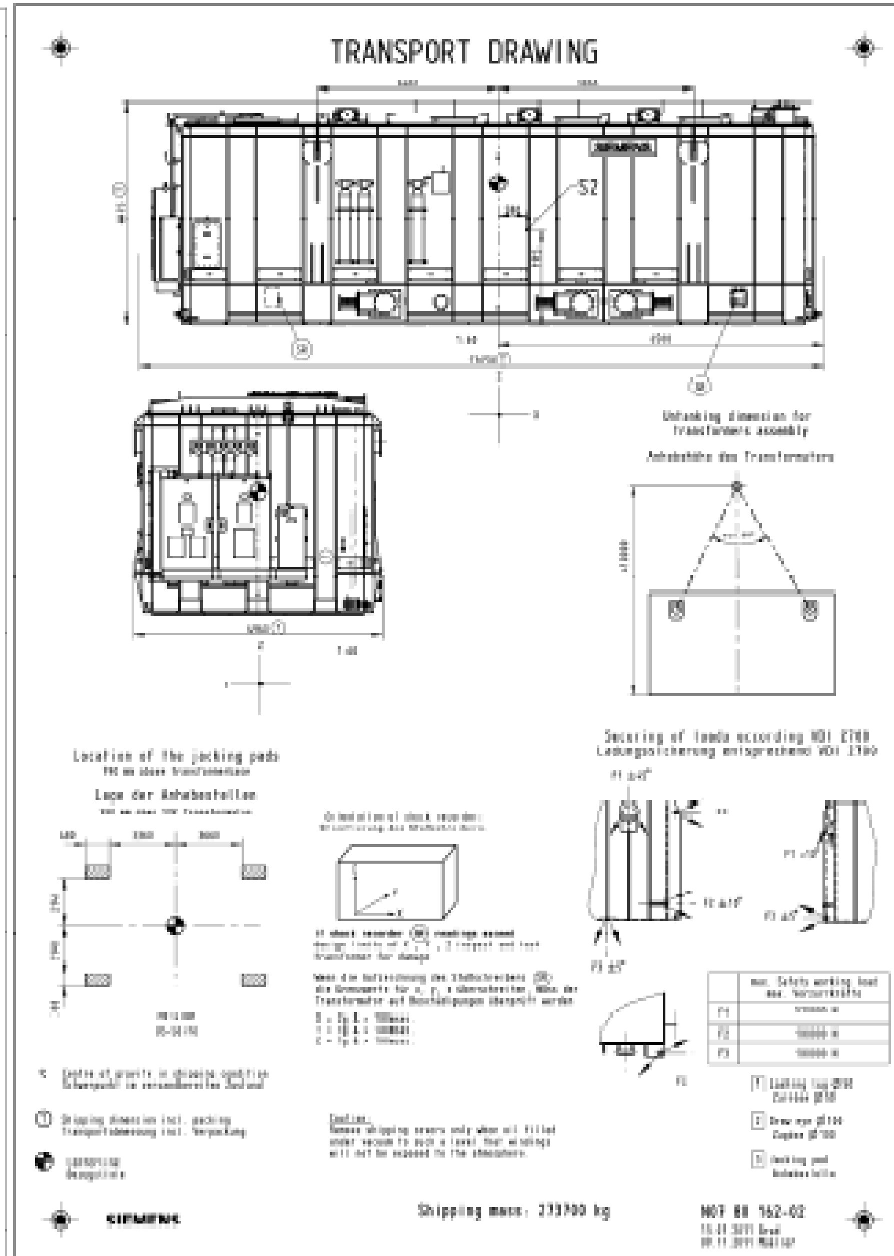
Transformer Receiving - Acceptance

- Assess Condition of Transformer
  - Importance of knowing condition when transformer left the factory to allow comparison.
  - Compare ex-factory condition to as-received conditions to determine change that could be caused by transport or storage.
- Testing and inspection

Transformer Receiving – Safety

- Transport gas could be N_2 or air – test for life compatibility (O_2), absence of combustible gas, absence of CO or CO_2
- Working at height (especially when receiving transformer on transporter). Appropriate fall arrest, falling objects prevention, ladder and electrical safe work practices.
- Confined space entry and extraction.
- Be aware of loose or broken parts, crates, etc.


Shipping plan
SIEMENS


TRANSPORT DRAWING

Transformer - Unloading

- Is foundation in condition to receive transformer? [Size, shape, capacity, flat, level, cured, condition, etc.]
- Use of crane and slings [transport condition vs. fully assembled condition]
- Use of jack and slide [jacking, blocking, slide areas]
- Transport drawing, markings on tank and parts
- Concentrated loading on tank bottom?

Transformer Receiving – Visual Inspection

- Visual inspection for security/tightness of attachments to transporter, movement on transporter, damage caused by securement, collisions with other objects or vibration or impact(s)
- Positive pressure on transport gas gauge
- Absence of shock or vibration recording on shock recorder and confirmation that shock recorder is still functioning
- Visual inspection of accessories to verify arrival in undamaged condition and shipment is complete

Transformer Receiving – Testing

- Visual Inspection
- Transformer transport gas pressure (positive pressure or sustained negative pressure) and dew point (correct for temperature and pressure)
- Core and clamp insulation (with correct voltage of Megger® (also correct for temperature)
- Shock (electronic) recorder assessment (Use CIGRE 673)
- FRA test if other indications of possible damage

Transformer Assembly

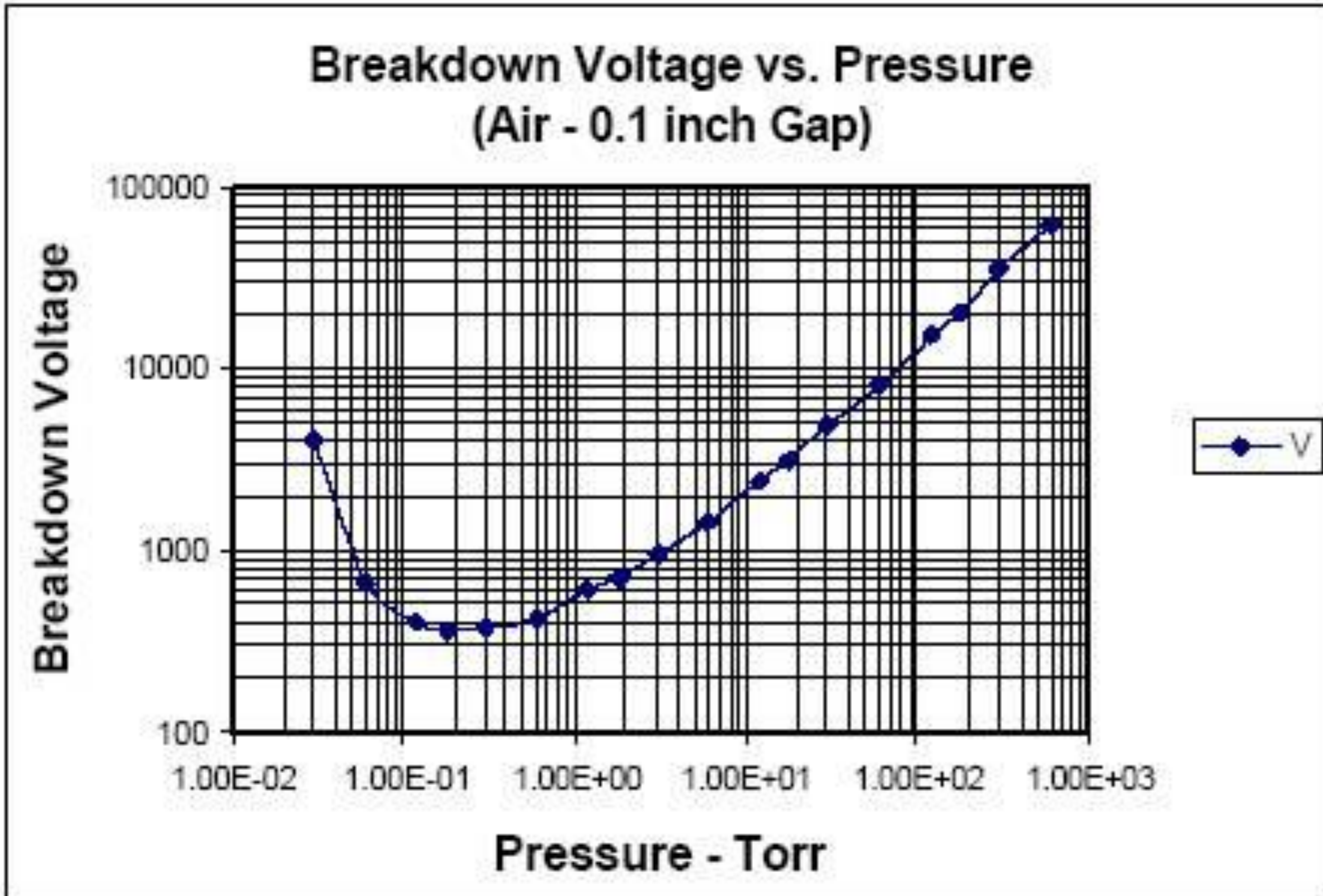
Transformer Safety – People

- Working at height (especially when receiving transformer on transporter). Appropriate fall arrest, falling objects prevention, ladder and electrical safe work practices.
- Confined entry plan and process, extraction?
- Transport gas could be N_2 or air – test for pressure, (before opening manhole), life compatibility O_2, absence of combustible gas and absence of CO or CO_2.

Transformer Safety – Transformer

- Minimize people entry into transformer
- Minimize entry of moisture into transformer
- Maintain dry air environment
- Bond and ground the transformer, all bushings, oil hoses, oil filtering and vacuum equipment.
- Vacuum and oil processing only above **+**10 °C
- Perform leak-down vacuum test prior to vacuum and oil processing
- No electrical testing during vacuum stages

Paschen Curve: Voltage Breakdown vs Pressure



Transformer Assembly

- Cleanliness is very important!
- Ensure parts are “naturally” aligned rather than force fit. (It went together in the factory)
- Importance of care in installing (new) gaskets during assembly. Ensure correct gasket is used to maintain compression ratio for the specific material.
- Use correct torque for each size of bolt.
- Confined entry plan and process

Transformer Assembly – Sequence

- Make sure all components, parts and oil are on site and in good condition.
- Test oil to meet kV, IFT, Neut. No., PF (25 °C & 100 °C) as per IEEE C57.106™ as a minimum before allowing oil to enter the tank or accepting new oil from a tanker
- Ensure safe internal atmosphere and dry (<50 °C) breathable air is available while transformer is open.
- Assemble ladder, conservator, cooling equipment, piping, bushings, cabinets, and some monitoring.

Transformer Assembly - Bushings

- Test cleaned bushings prior to installation (PF, C1, C2)
- Install cleaned bushings with new gaskets, correct torque on current carrying connections, proper procedure for draw lead or draw rod connected bushings.
- Confirm whether the capacitance tap is to be operated in grounded or ungrounded mode.
- Install bushing monitoring devices, if applicable.

Transformer Assembly – Components

- Make sure that piping, conservator tank, cooling equipment, etc. has been shipped in a sealed condition so that no water, dirt, or other foreign material is inside.
- Check that the insides of all accessories are clean.

Transformer Assembly – Conservator

- Make sure conservator tank(s) are clean.
- Check both sides of conservator tank (some conservators are compartmentalized for LTC and main transformer oils).
- Install bladder while conservator on ground. Make sure there is provision to prevent a collapsed bladder from blocking the pipe to the transformer.
- Install piping to main tank (including Buchholz relay) so there is no strain on the GDR.

Transformer Assembly - Cooling

- Install radiators or coolers (and pumps)
- Ensure valves operate correctly
- Ensure all bracing and seismic reinforcing are installed
- Temperature gauge calibration?

Transformer Processing

Why Process Oil & Insulation?

- In factory, cellulose insulation is dried to < 0.5 % water (by weight) to achieve optimum dielectric performance for factory testing. When the active part (core & coils & leads) is removed from vapour-phase process, it starts to regain moisture from air and from oil [water moves relatively easily oil → cellulose but with relative difficulty from cellulose → oil. Moisture in cellulose shortens the life of the insulation.
- Moisture enters transformer during assembly.
- If moisture content of oil is low, less moisture can move into the cellulose insulation.
- Ability of oil to hold dissolved moisture decreases as temperature goes down [saturation must be avoided].

Effect of Moisture on Insulation

- Can cause Failures
  - Lowers dielectric strength of insulation
  - Can generate gas bubbles above certain temperature (>~140 °C)
  - Can initiate partial discharge
- Shortens insulation life

How to Remove Moisture from Transformer?

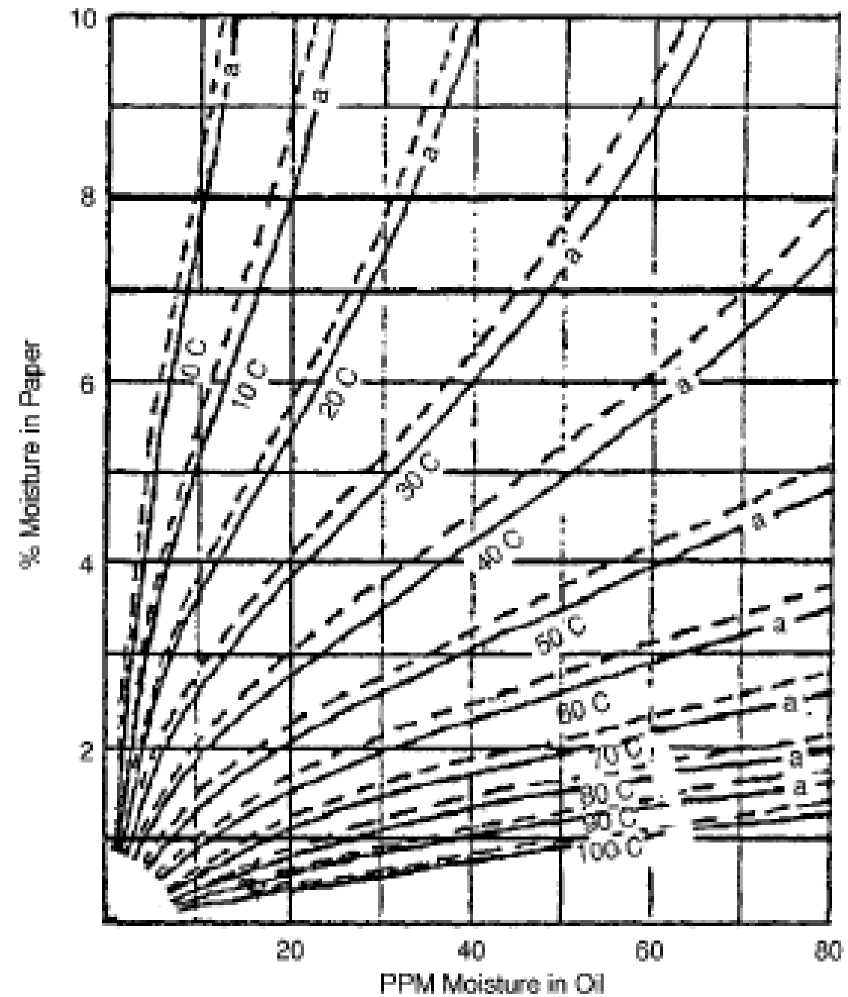
- Easier to keep moisture out than to remove it.
- Easier to move moisture from cellulose to oil at higher temperatures [applied heating or in-service]
- Applying vacuum [lowering absolute pressure] allows the partial pressure of water [lowering boiling point of water] making it move out of cellulose.

Estimating Moisture Content in Insulation

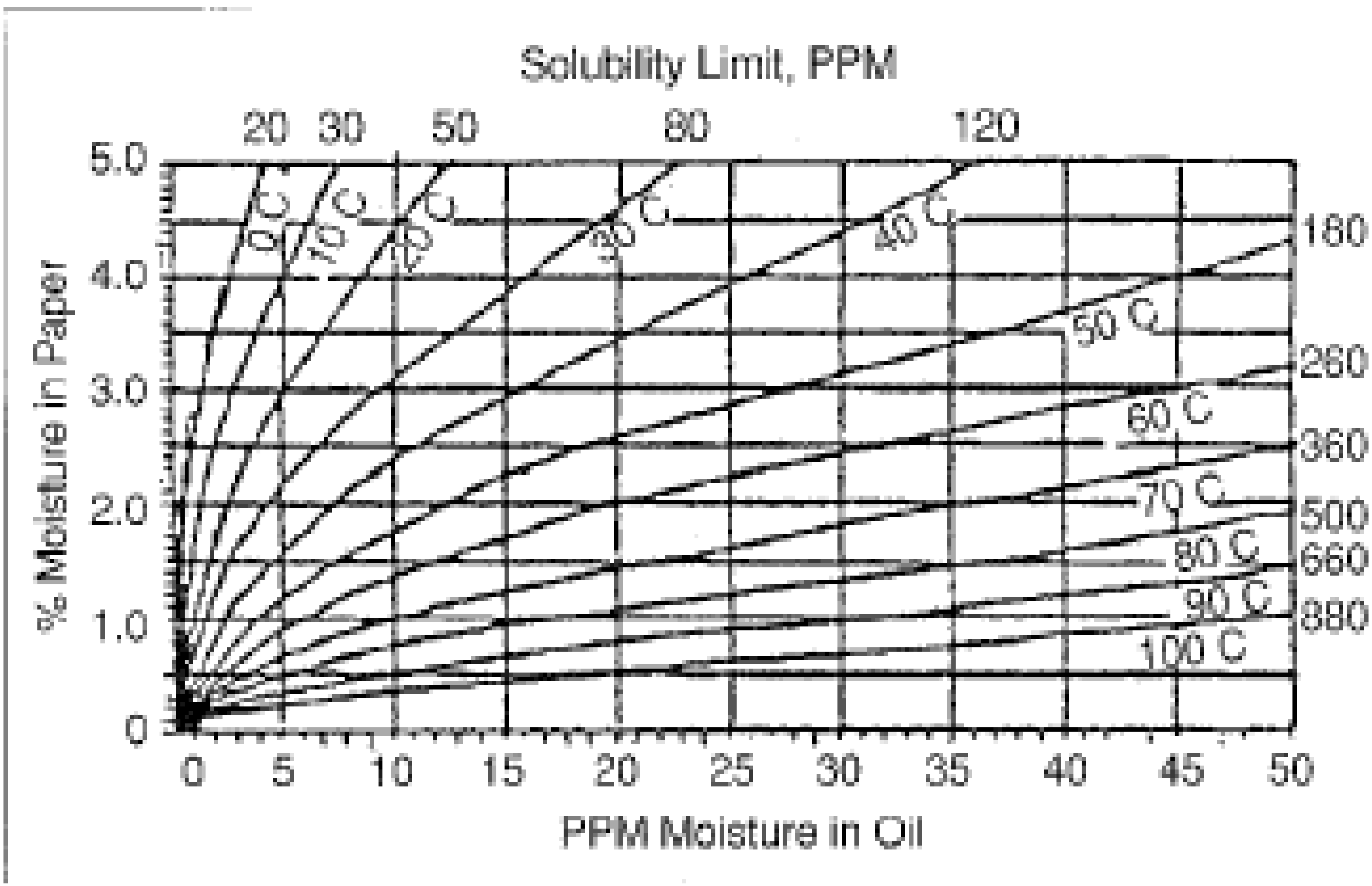
Estimate from moisture in air or in oil

- Difficulty in knowing exact insulation and oil temperature.
- Equilibrium between oil and insulation has time based limitations.
  - Equilibrium is rarely achieved
  - Time constant is different for moisture into or out of paper
  - Moisture unevenly distributed in insulation
- Equilibrium curves dependent on specific oil type/standard.

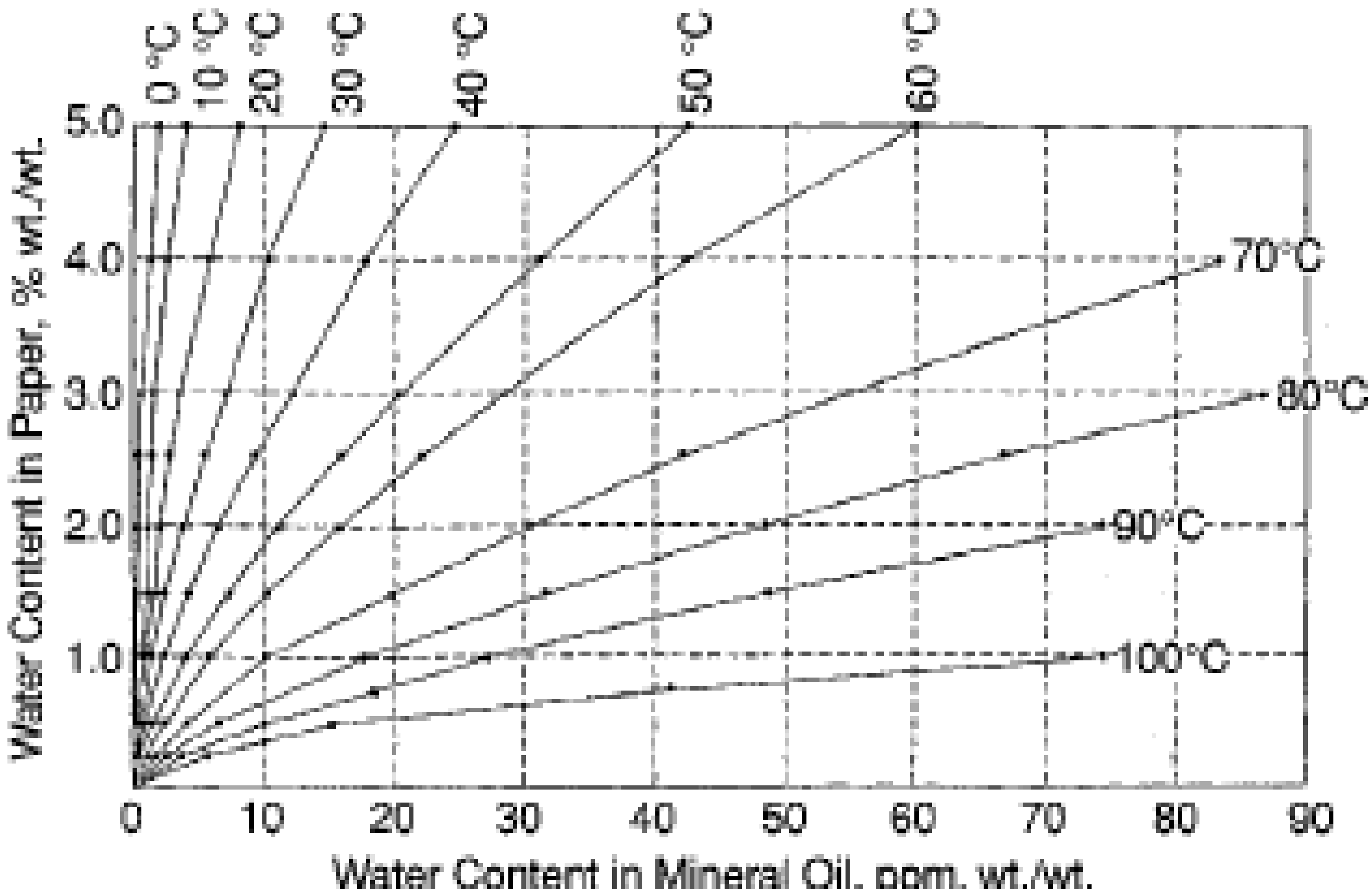
Oommen's Curves for Moisture Equilibrium - Paper-Oil



Oommen curves for Low Moisture Equilibrium – Paper-Oil



Griffin Curves for Water Equilibrium in Cellulose/Mineral Oil Systems



Paper-Oil Moisture References

- T.V. Oommen (Westinghouse, ABB), “**Moisture Equilibrium Charts for Transformer Insulation Drying Practice**”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 10, October 1984
- Y.Du, M. Zahn, B.C. Lesieutre, and A.V. Mamshev (MIT) and S.R. Lindgren (EPRI) “**Moisture Equilibrium in Transformer Paper-Oil Systems**”, IEEE Electrical Insulation Magazine, January/February 1999 – Vol. 15, No. 1
- T.V. Oommen, J. Thompson and B. Ward, “**Moisture Estimation in Transformer Insulation**”, IEEE Transformers Committee Panel Session, March 9, 2004, Sponsored by the Insulating Fluids Subcommittee

Transformer Vacuum Processing

Vacuum Cautions (ref. IEEE C57.93)

a) Ensure the transformer tank and all fittings are suitable for vacuum, including:

1) Conservator tank (tank and bladder, if equipped, have to be *pressure-equalized*)
2) Radiators, pumps, and their valves

If any of these fittings are not designed to withstand vacuum, they need to be removed or valved off.

b) Ensure the LTC is suitable for vacuum or has its pressure *equalized*.

c) Ensure instrumentation is suitable for vacuum (older combustible gas sensor units must not only be isolated but usually removed from the transformer during application of a vacuum).

d) Ensure no additional structure load is to be put on top of the transformer under vacuum (such as people!, lifting, jacking, etc.)

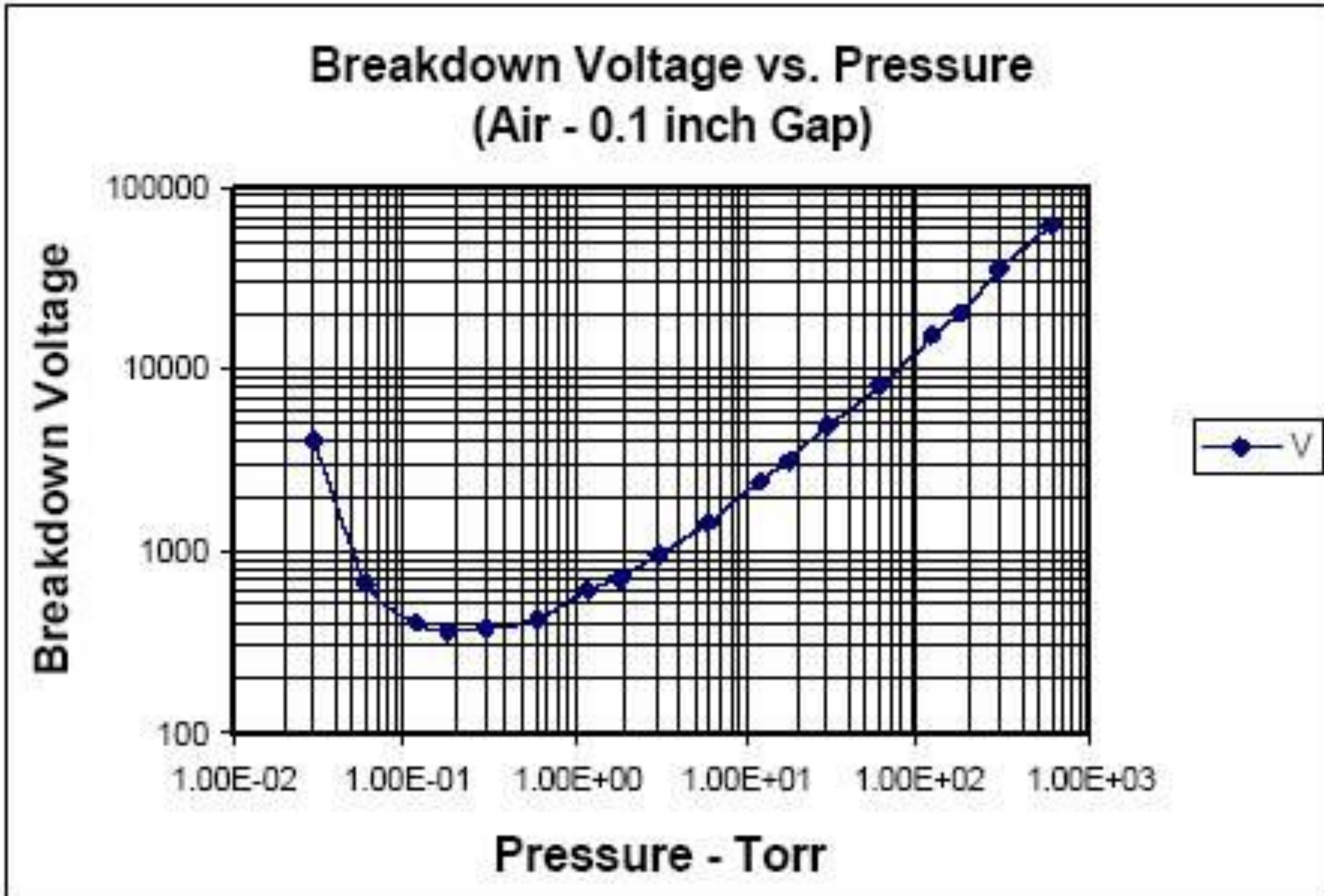
Transformer Vacuum – Sequence

- Install blanking plate on PRD. *
- Pressure test (<5 psi gauge) and monitor.
- Ensure vacuum equalizing piping is installed or valves are open.
- Apply vacuum to about 100 Pa (0.75 Torr) (0.75 mm Hg) to remove surface moisture and perform “leak-down” test.

*Note: PRD is usually removed during vacuum processing. An adapter to use the PRD flange or a separate flange on the cover is used to draw vacuum on the tank.

No electrical testing while under vacuum (10 V PF)

Paschen Curve: Voltage Breakdown vs Pressure



Transformer Vacuum Processing

- Vacuum and oil processing only above +10 °C
- Perform “leak-down” vacuum test prior to vacuum and oil processing IEEE Std C57.106™
- Oil entry into transformer only when oil can be assured of meeting IEEE Std C57.106™ “IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment”

Vacuum Leakage

- NOTE 1— Any air leakage into the transformer tank, while a vacuum is being drawn on the transformer, may seriously contaminate the transformer insulation. Air, when drawn into a vacuum, expands and drops in temperature, consequently releasing moisture. If the core and coils are cold, the moisture released from the air will condense on these parts and will be absorbed into the paper insulation.

Ref: IEEE C57.93 clause 4.8.1 Preparation

Vacuum “Leak Down” Test – Method B

- Two pressure readings; 60 min & 90 min after the vacuum valve on pump is closed, first 60 min allows de-absorption of gasses from insulation.

$$* \text{Leakage} = \frac{V(P90 - P60)(\text{mmHgLiters})}{30 \text{ min (min.)}}$$

- Where V is the volume of oil of the transformer tank in litres.
- Leakage <150 mm Hg litres/minute equivalent to 20 m^3Pa/min
- If leakage rate exceeds 20 m^3Pa/min, corrective action to re-tighten all mounting bolts & fittings and/or application of sealant to suspected fittings is required. If satisfactory, open the main vacuum valve and repeat the evacuation until vacuum condition is stable or below 50 Pa. Repeat the pressure rise recording, extending the recording an additional four readings at five-minute intervals.

Ref: IEEE C57.93 clause 4.8.3

Allowable Vacuum Leak

- Evacuate the transformer to about 100 Pa. Close the main vacuum valve between the transformer tank and the vacuum pumping system.
- New transformers can generally withstand a mass leak rate of 20 m^3Pa per minute
- Note: the larger the transformer the lower pressure rise allowed.

$$\text{micron Hg/h} = \frac{9\,000\,000}{\text{V (oil in liters)}} \qquad \text{Pa/hour} = 1200 \times \frac{1000}{\text{V (in liters)}}$$

Maximum Allowable Moisture

- New 500 kV – less than 0.5% by weight
- New 69 to 230 kV – less than 0.8% by weight

- Ex: 450 MVA, 245-20 kV two-winding transformer weighs ~ 250T
- Core & coils 125T of which 25T is cellulose
- At 2% water, there is 500 kg of water in the insulation. To achieve recommended 0.5% moisture content, 375 kg of water must be removed (hopefully most at the factory!).

When is Insulation Dry?

- Allowable moisture content is dependent on voltage class.
- No direct method to measure moisture.
- Moisture measured by:
  - Gas dew point measurement
  - Monitor moisture in exhaust gas of vacuum pump [weigh ice in trap]
  - **Very Low voltage** (during vacuum processing) measurement of insulation dissipation factor or power factor

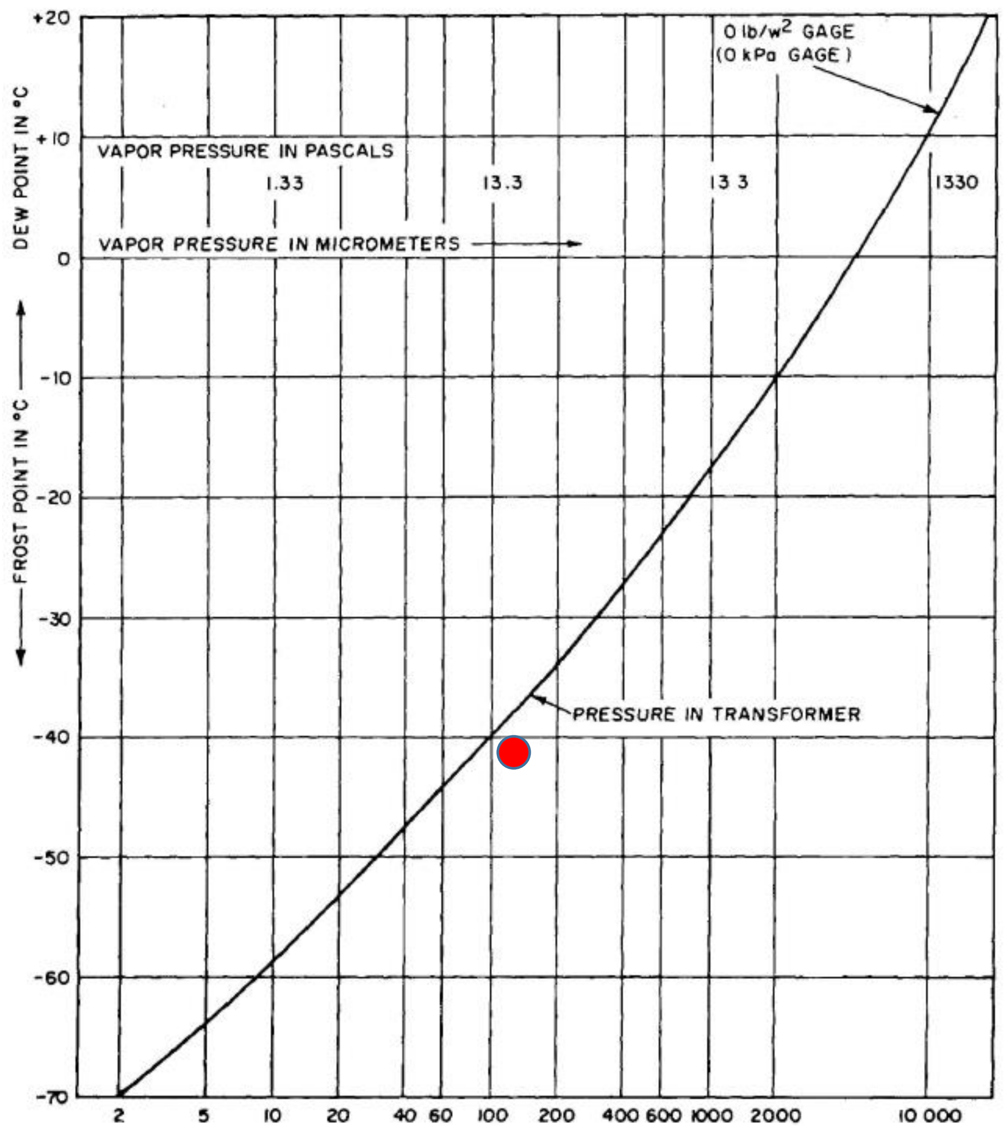
Insulation Dryness Example

Dew point	–40°C (–40°F)
Insulation temperature	20°C (68°F)
Tank gauge pressure	14 kPa (2 lbf/in^2)
Pressure at dew point instrument	0 kPa (0 lbf/in^2)
Atmospheric pressure	101.35 kPa (14.7 lbf/in^2)

- On Figure B.1, read the vapor pressure as 100 μm (13.3 Pa). Correct vapor pressure to tank conditions.
- On Figure B.2, read the moisture content 0.75% of the dry weight of insulation at the junction of 114 μm (15.2 Pa) vapor pressure and the insulation temperature of 20 °C

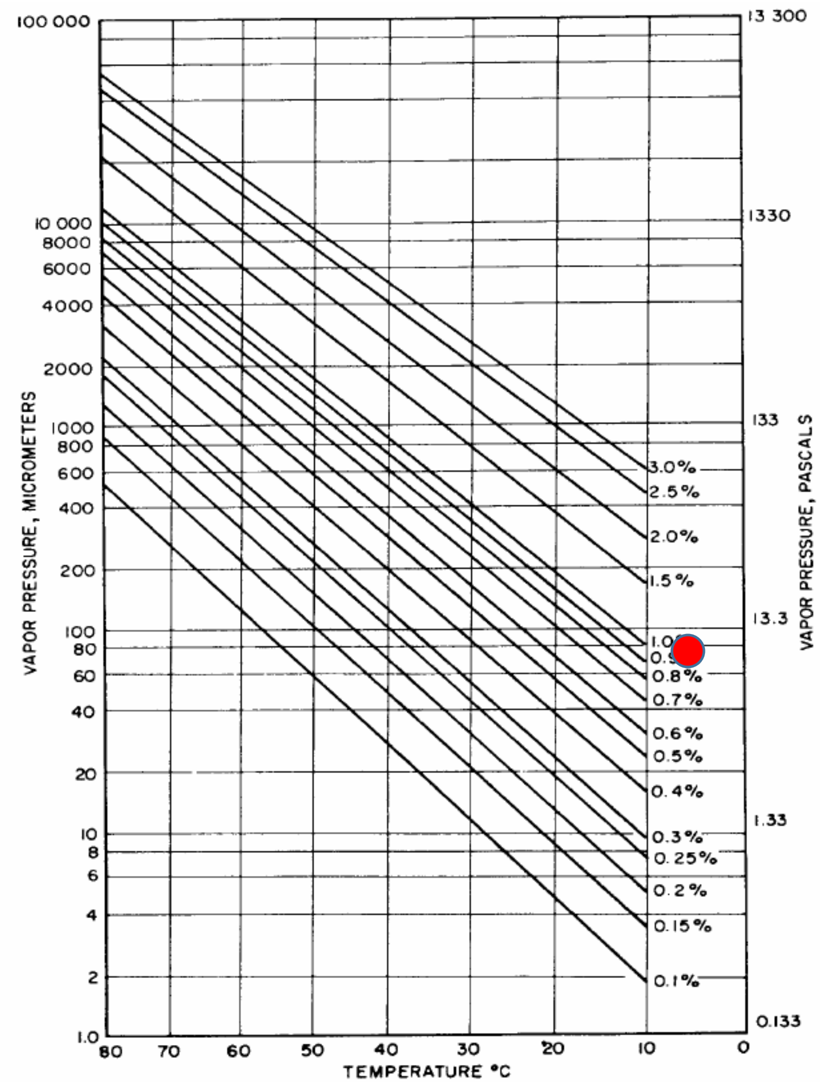
Conversion dew point to vapor pressure

Ref: IEEE C57.93, Figure B.1



Moisture Equilibrium Chart

Ref: IEEE C57.93, Figure B.2



Oil Sampling and Testing

Transformer Oil Sampling - Standards

- ASTM D 923 – 97 “Standard Practices for Sampling Electrical Insulating Liquids”
- ASTM D 2759 – 00 “Standard Practice for Sampling Gas from a Transformer Under Positive Pressure”
- ASTM D117 - 10 ”Standard Guide for Sampling, Test Methods, and Specifications for Electrical Insulating Oils of Petroleum Origin”
- ASTM D 3305 – 94 “Standard Practice for Sampling Small Gas Volume in a Transformer” (This practice is used for sampling gas from a transformer gas space or from a gas-collector relay where the volume of gas available is small and will not permit the use of Practice D 2759.)
- ASTM D 3613 – 98 “Standard Practice for Sampling Insulating Liquids for Gas Analysis and Determination of Water Content”
- IEC 60475 ed2.0 (2011-10) “Method of sampling insulating liquids”

Transformer Oil Sampling - Sensitivity

- Test results for dielectric strength and water content are significantly affected by sampling technique!
- Dissolved gas-in-oil analysis is another test impacted by sampling, sample valve components, contamination or residue, ineffective sample and sampling materials.
- Clean, flush, store/transport
- Sampling method is important!!!

Table 3—Test limits for new mineral insulating oil processed for equipment, 230 kV class and above, prior to energization

Test and method	Value for voltage class	
	≥ 230 kV – < 345 kV	345 kV and above
Dielectric strength, ASTM D1816-97, kV minimum, 1 mm gap[a]: 2 mm gap[a]:	32 55	35 60
Dissipation factor (power factor), ASTM D924-99e1, 25 °C, % maximum: 100 °C, % maximum:	0.05 0.30	0.05 0.30
Interfacial tension, ASTM D971-99a, mN/m minimum:	38	38
Color, ASTM D1500-98, ASTM units maximum:	1.0	0.5
Visual examination, ASTM D1524-94 (1999):	Bright and clear	Bright and clear
Neutralization number (acidity), ASTM D974-02, mg KOH/g maximum:	0.015[b]	0.015[b]
Water content, ASTM D1533-00, mg/kg maximum[d]:	10	10
Total dissolved gas, ASTM D2945-90 (1998):	0.5% or per manufacturer's requirements[c].	0.5% or per manufacturer's requirements[c].

Transformer Acceptance Testing

- Comparison or field tests with factory tests
- Conformance with industry criteria including IEEE Stds C57.93™ and C57.106™
- Customer and/or manufacturer may have acceptance limits for test results and methods
- CSA-C88 Table 9 provides limits for tolerance on factory tests of ratio, impedance (Z1, Z0), excitation current, losses

Transformer Testing - IEEE C57.93 (1/3)

IEEE C57.93 Clause 4.11 Tests after the transformer has been assembled and filled with dielectric liquid

a) Insulation resistance test on each winding to ground and between windings.
b) Insulation power factor or dissipation factor test on each winding to ground and between windings. Capacitance should also be measured on each connection. In addition, core insulation should also be tested.
c) Power factor or dissipation factor test on all bushings equipped with a power factor tap or capacitance tap. Both C1 and C2 insulation should be measured. NOTE—If final bushings are not used in the factory, test results may differ.
d) Check operation of liquid-level and hot-spot temperature indicating and control devices.

Transformer Testing - IEEE C57.93 (2/3)

e) Winding ratio test on each tap. If LTC transformer, check winding ratio on all LTC positions.
f) Check dissolved gas, dielectric strength, power factor, interfacial tension, neutralization number, and water content of the dielectric liquid.
g) Check oxygen content and total combustible gas content of nitrogen gas cushion in sealed tank transformers. A total combustible gas test, where applicable, and a dissolved gas-in-oil test of the dielectric fluid should also be made soon after the transformer is in service at operating temperature to provide a suitable post-energization reference "bench mark."

Transformer Testing - IEEE C57.93 (3/3)

h) Check polarity and excitation current at reduced test voltages.
i) Check resistance, ratio, and polarity of instrument transformers when provided. These tests should be made at the terminal blocks in the control cabinet.
j) Frequency response measurement compared to factory results, if available.
k) Check operation of auxiliary equipment, such as LTCs, liquid-circulating pumps, fans, or liquid or water flow meters in accordance with manufacturer’s instructions.
l) * Check winding resistance of all windings with a Kelvin bridge or another suitable test device and compare with factory test results.

All these tests should be within acceptable limits prior to energization.

Recommended Testing Sequence (1/4)

1) Winding ratio test on each tap. If LTC transformer, check winding ratio on all LTC positions.
2) Insulation resistance test on each winding to ground and between windings. In addition, core & clamp insulation should also be tested (Check maximum allowable kV) .
3) Insulation power factor or dissipation factor test on each winding to ground and between windings. Capacitance should also be measured on each connection. Single phase excitation current at 10 kV
4) Power factor or dissipation factor test on all bushings equipped with a power factor tap or capacitance tap. Both C1 and C2 insulation should be measured.

Recommended Testing Sequence (2/4)

5) Excitation current at 10 kV
6) Check operation of auxiliary equipment, such as LTCs, liquid-circulating pumps, fans, or liquid or water flow meters in accordance with manufacturer's instructions.
7) Check operation of liquid-level and hot-spot temperature indicating and control devices.
8) Check dissolved gas, dielectric strength, power factor, interfacial tension, neutralization number, and water content of the dielectric liquid.
9) Check polarity and excitation current at reduced test voltages.

Recommended Testing Sequence (3/4)

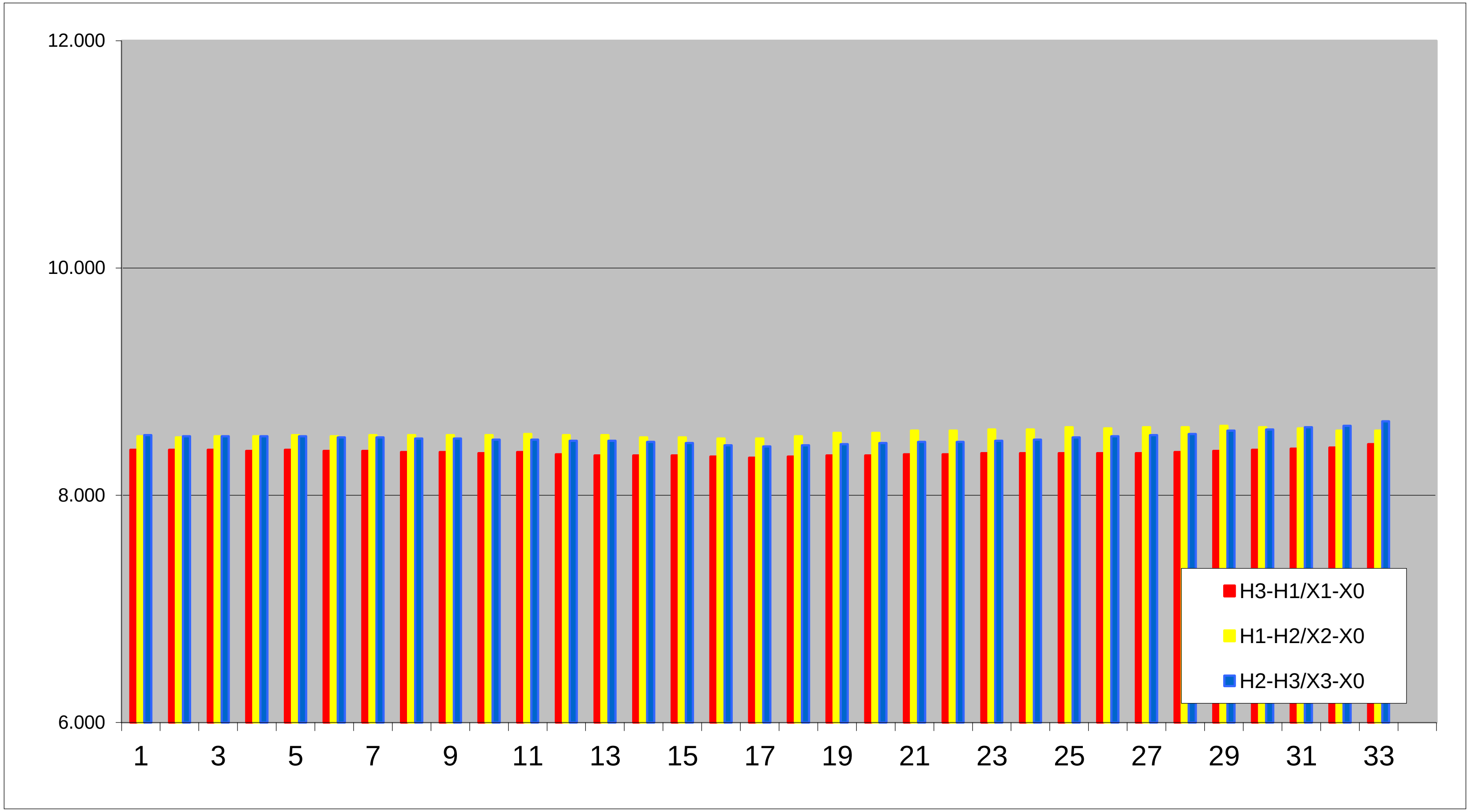
10) Check oxygen content and total combustible gas content of nitrogen gas cushion in sealed tank transformers. A total combustible gas test, where applicable, and a dissolved gas-in-oil test of the dielectric fluid should also be made soon after the transformer is in service at operating temperature to provide a suitable post-energization reference "bench mark."
11) Frequency response measurement compared to factory results, if applicable.
12) Check resistance, ratio, and polarity of instrument transformers when provided. These tests should be made at the terminal blocks in the control cabinet.

Recommended Testing Sequence (4/4)

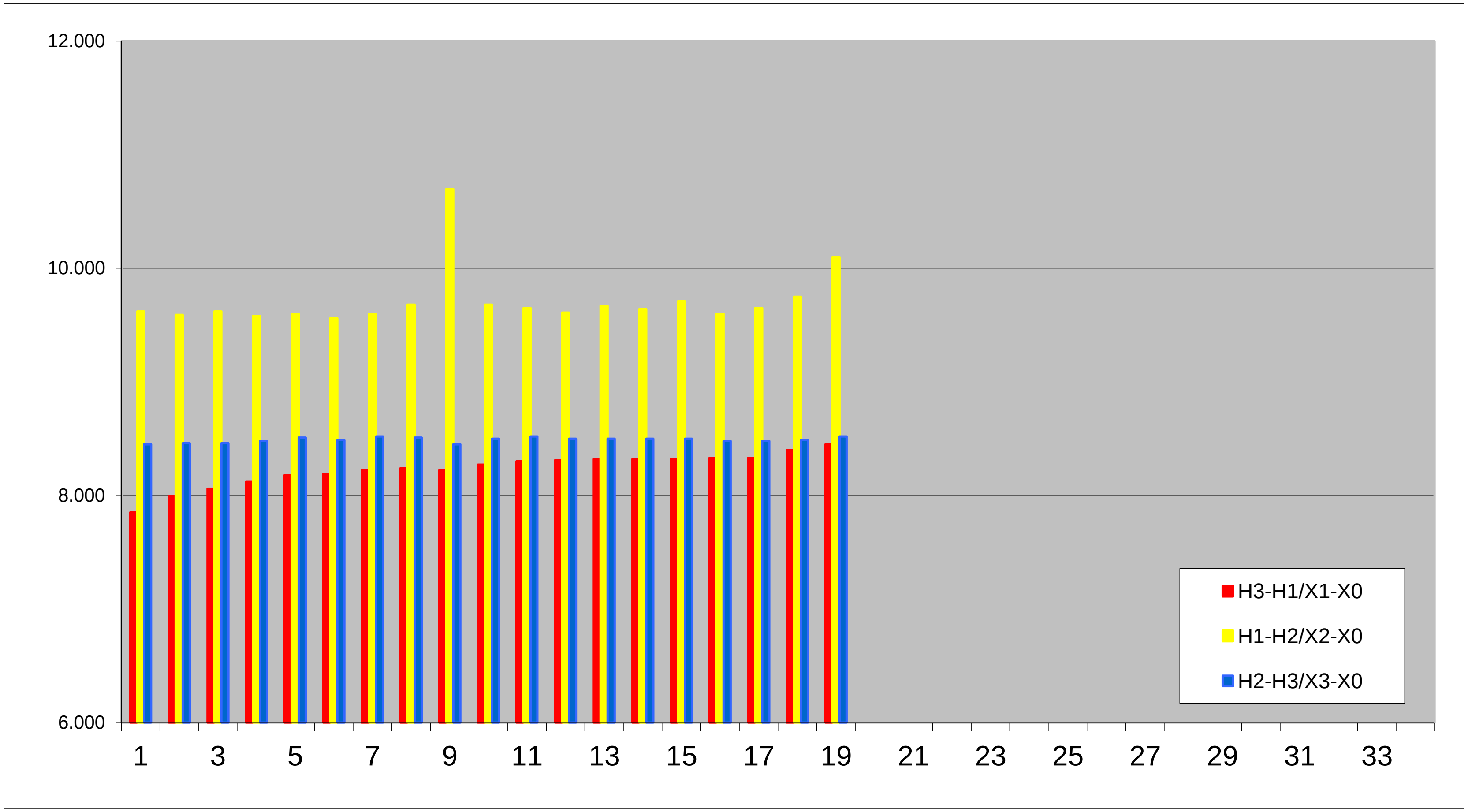
13) Check operation of auxiliary equipment, such as LTCs, pumps, fans, protective devices (GDR, PRD, sudden pressure, etc.) monitoring devices in accordance with manufacturer's instructions.
14) Check winding resistance of all windings with a Kelvin bridge or another suitable test device and compare with factory test results. (demagnetize IEEE Std C57.152™ after or do FRA and excitation current before dc resistance test)
15) Check fiber optic temperature probes if installed

Examples of Unusual Test Results

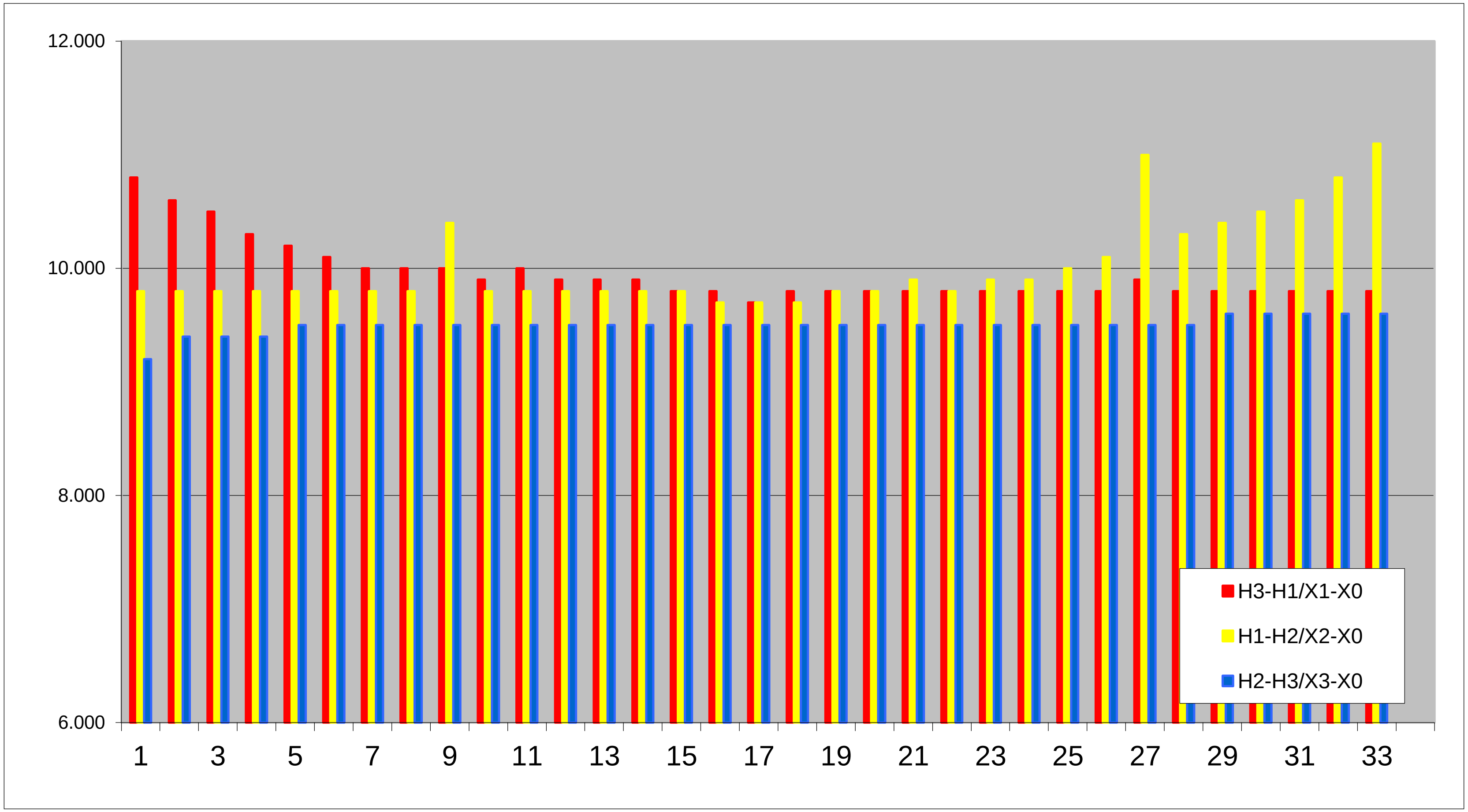
Winding Resistance - Acceptable



Winding Resistance - Unacceptable



Winding Resistance – Full Range



CSA C88 Ratio Tolerance

- Ratio at no-load at the principal tap(s)
- Tolerance ± 0.5% of the rating plate markings

- Example of
  - HV (delta) 260,000 V
  - LV (wye) 25,000/14,434 V
  - LV LTC ±10% IN ±16 STEPS

CSA LTC Tap	IEEE LTC Tap	Typical Nameplate LV	Calc nameplate voltage for ±10% LTC Taps	Calc Ratio	Actual LV	Measured Ratio H1-H3 / X1-X0	Apparent % ratio error
1	-16	22,500	22,500	20.0148	22527.2	20.0390	-0.12%
…							
16	-1	24,844	24,844	18.1264	24829.7	18.1160	0.06%
17	N	25,000	25,000	18.0133	25030.1	18.0350	-0.12%
18	+1	25,156	25,156	17.9016	25246.5	17.9660	-0.36%
19	+2	25,313	25,313	17.7906	25450.2	17.8870	-0.54%
20	+3	25,469	25,469	17.6816	25583.3	17.7610	-0.45%
21	+4	25,625	25,625	17.5740	25655.7	17.5950	-0.12%
22	+5	25,781	25,781	17.4676	25873.0	17.5300	-0.36%
23	+6	25,936	25,156	17.3632	26070.1	17.4530	-0.52%
24	+7	26,094	25,156	17.2581	26207.2	17.3330	-0.43%
25	+8	26,250	25,156	17.1556	26282.8	17.1770	-0.13%
26	+9	26,406	25,156	17.0542	26498.6	17.1140	-0.35%
27	+10	26,563	25,156	16.9534	26701.8	17.0420	-0.52%
28	+11	26,719	25,156	16.8544	26832.5	16.9260	-0.42%
29	+12	26,875	25,156	16.7566	26909.3	16.7780	-0.13%
30	+13	27,031	25,156	16.6599	27126.9	16.7190	-0.35%
31	+14	27,188	25,156	16.5637	27328.1	16.6490	-0.52%
32	+15	27,344	25,156	16.4692	27458.3	16.5380	-0.42%
33	+16	27,500	27,500	16.3758	27532.3	16.3950	-0.12%

exceeds 0.5%

Cause of Ratio Error

- The LV design has 120 turns. Since LTC is 10% of LV it has only 12 turns.
- With 8 steps, ideally 1.5 turns per tap step and 0.75 turns/tap including the bridging position. Practically there can only be full turns per step so the LV winding is designed with turns of 1, 2, 1, 2, 1, 2, 1, 2 turns between steps, which results in 0.5, 0.5, 1, 1, 0.5, 0.5, 1, 1, 0.5, 0.5, 1, 1, 0.5, 0.5, 1, 1 between each tap position. The design is not able to achieve the ideal turns of 0.75 per tap.
- This unequal distribution of turns results in inherent ratio errors. Maximum ratio error for this design was 0.43%, which is less than the allowed ratio error of 0.5%.
- The combination of design ratio error and measurement accuracy resulted in tested ratio error marginally greater than 0.5% in 4 bridging tap positions with the maximum value of 0.54% .

Solution to Ratio Error

CSA C88, table 9 (Tolerances) allows ±0.5% of the rating plate marking .

"On transformers having extensive tap arrangements with few turns between taps, or low-voltage windings with few turns, or both, it may be impossible to arrange turns on all taps or windings such that the voltages as determined by turns ration will be within the 0.5% tolerance from the desired voltages. In these cases, by agreement between the purchaser and the manufacturer, the rating plate may be marked either with the voltages as determined from the actual turns ratios or with the nominal desired voltages, and a greater tolerance permitted."

Consider adding a note on the rating plate to clarify the reason for the listed tap voltage changes.

CSA LTC Tap	IEEE LTC Tap	Typical Nameplate LV	Calc nameplate voltage for ±10% LTC Taps	Calc Ratio	Actual LV	Measured Ratio H1-H3 / X1-X0	Apparent % ratio error	**New** Calc Ratio	**New** Rating Plate LV	**New** % ratio error
1	-16	22,500	22,500	20.0148	22527.2	20.0390	-0.12%	20.0148	22,500	-0.12%
...										
16	-1	24,844	24,844	18.1264	24829.7	18.1160	0.06%	18.1264	24,844	0.06%
17	N	25,000	25,000	18.0133	25030.1	18.0350	-0.12%	18.0133	25,000	-0.12%
18	+1	25,156	25,156	17.9016	25246.5	17.9660	-0.36%	17.9016	25,156	-0.36%
19	+2	25,313	25,313	17.7906	25450.2	17.8870	-0.54%	17.8166	25,276	-0.39%
20	+3	25,469	25,469	17.6816	25583.3	17.7610	-0.45%	17.6816	25,469	-0.45%
21	+4	25,625	25,625	17.5740	25655.7	17.5950	-0.12%	17.5740	25,625	-0.12%
22	+5	25,781	25,781	17.4676	25873.0	17.5300	-0.36%	17.4676	25,781	-0.36%
23	+6	25,936	25,156	17.3632	26070.1	17.4530	-0.52%	17.3874	25,900	-0.38%
24	+7	26,094	25,156	17.2581	26207.2	17.3330	-0.43%	17.2581	26,094	-0.43%
25	+8	26,250	25,156	17.1556	26282.8	17.1770	-0.13%	17.1556	26,250	-0.13%
26	+9	26,406	25,156	17.0542	26498.6	17.1140	-0.35%	17.0542	26,406	-0.35%
27	+10	26,563	25,156	16.9534	26701.8	17.0420	-0.52%	16.9758	26,528	-0.39%
28	+11	26,719	25,156	16.8544	26832.5	16.9260	-0.42%	16.8544	26,719	-0.42%
29	+12	26,875	25,156	16.7566	26909.3	16.7780	-0.13%	16.7566	26,875	-0.13%
30	+13	27,031	25,156	16.6599	27126.9	16.7190	-0.35%	16.6599	27,031	-0.35%
31	+14	27,188	25,156	16.5637	27328.1	16.6490	-0.52%	16.5838	27,155	-0.39%
32	+15	27,344	25,156	16.4692	27458.3	16.5380	-0.42%	16.4692	27,344	-0.42%
33	+16	27,500	27,500	16.3758	27532.3	16.3950	-0.12%	16.3758	27,500	-0.12%

= exceeds 0.5%

= Nameplate voltage changed

I_{ex}, FRA & Leakage Reactance

- These test results are influenced by the condition of the core, particularly after dc resistance testing.
- Always demagnetize the core prior to testing or perform the dc resistance test after these tests:
  - Excitation current
  - Frequency Response Analysis
  - Leakage Reactance

Demagnetize ref. IEEE C57.152-2013, Clause 7.2.11.1.2

Energize ! or ?

Ultimate Failure

- All transformers are a “consumable item’ with deterioration over lifetime so …
- CIGRE 735 Transformer post-mortem analysis
- IEEE Std C57.125™-2015 - IEEE Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors

Integrating Transformer into Electrical System

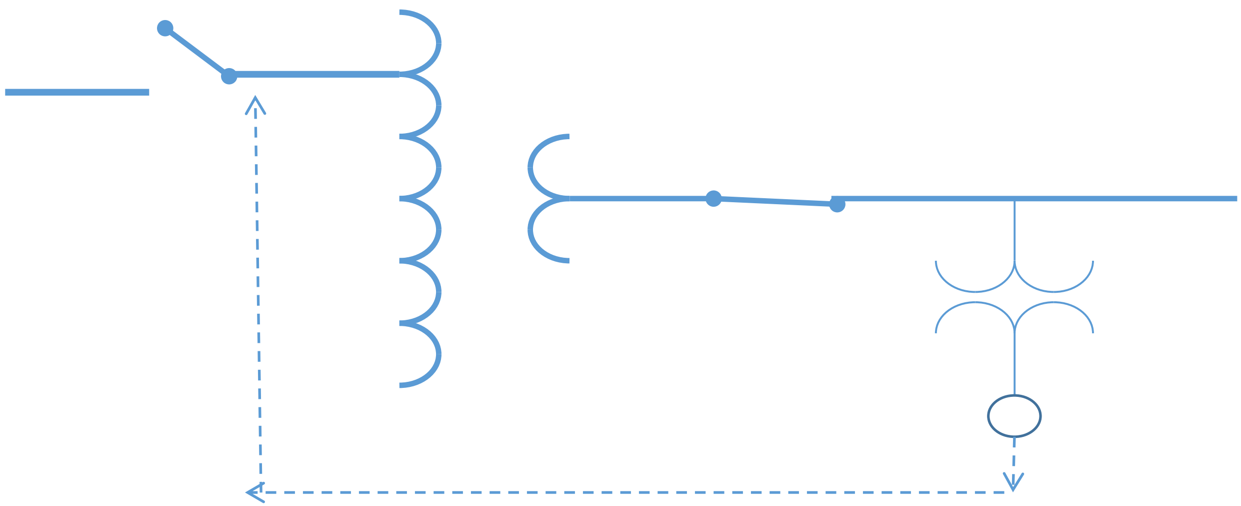
- Check adequacy of station service supply voltage and voltage balance when all cooling equipment, heaters, etc. are operating.
- Check that remote controls of LTC operate in the correct direction with correct tap position indication.
- Check that LTC control voltage reference source is appropriate for all operating configurations (variation in HV or LV system voltage, open or closed circuit breakers, LTC tap range coupled with high %IZ, etc.)
- Check that protection and control inputs are appropriate for protection systems.

LTC Control Integration

- Transformer 260-72 kV
- Specified 235 to 285 kV system range, ±9.6%
- Impedance 11.5 %IZ on base rating (high)
- Resulting high regulation required LTC ±20% in 32 equal steps (±16 x 1.25 %); LTC on HV
- LTC controller set to ±0.5% bandwidth (narrow)
- Control from LV system
- Energized from LV with HV open circuit
- Core over-excited for ~24 hours and permanently damaged (rated 1.75T excited to ~2.0T)

Tap Changer Operation

- System voltage range?
- LTC operating range?
- Source of control signal,
- Control set point & bandwidth?
- Transformer regulation?



Protection & Control

- Differential zone
  - Bushing current transformers are inside bushings
  - Need protection for bushings in a differential zone
- Differential protection with LTC
  - ratio varies over LTC range
  - CT ratio mismatch can be different on HV or LV
- Surge Protection
  - Location of surge protection (protective distance)
  - Ratings of surge protection vs. transformer LIL
- Alarms and Trips (electrical & non-electrical)

Recommended Minimum Energization time at no-load

Voltage class	Energizing period (hours)	Suggested minimum energizing period (hours)
230 kV – 800 kV	24	12
120 – 170 kV	12	8
< 120 kV	8	8

- NOTE 1—In case there is difference between values recommended in Table 5 and the manufacturer recommended time make sure to meet at least the manufacturer’s time.
- NOTE 2—The DGA results with the transformer energized and in no-load condition obtained at the end of the energizing period will be kept for reference and diagnostic purpose if needed. In case there is doubt with certain amount of gas concentration in the results, it will be necessary to proceed also with the analysis of oil samples taken in the beginning of the energizing period for comparison and evaluation.

IEEE (C57.93 Table 5) Note: For some GSU applications this may not be possible. Consult manufacturer.

Preservation of Installation Records

- Form the baseline “fingerprint” for all subsequent maintenance and possible analysis/troubleshooting
- Preserve in “native” electronic format as well as on some “non-deteriorating” format
  - Electronic format for ease of electronic comparison of factory and site installation tests and subsequent maintenance tests
  - “Non-deteriorating” format in case operating system, software or testing instruments change over time

Recommendations

What did we learn?

- Understand the reasons for transformer insulation processing
- Have at least a well-trained supervisor on site
- Assemble the transformer correctly
- Take precautions with accessories during processing (equalizing, vacuum isolation, oil level monitoring)
- Start with proven "good" oil
- Recognize effect of cold temperature ambient during both assembly and processing

Recommendations (1/3)

- Have a comprehensive specification with a method of incorporating problem resolution in future versions of the specification. (Feedback [both directions] from application, design, manufacturing, substation/system engineering, transport, field installation and maintenance)
- Conduct a design review on large transformers

Recommendations (2/3)

- Transportation damage can be significantly reduced with planning and care
- Use electronic shock recorder**s**
- Inspect/test transformer on carrier at time of delivery
- Use very similar test instruments as factory to perform field tests to allow electronic comparison (ex. insulation power factor of windings and bushings, FRA of transformer)
- Comparison tests require factory test reports

Recommendations (3/3)

- Document assembly process and testing
- Use qualified* equipment and persons to assemble and process transformer and oil
- Acceptance testing is based on industry standard criteria and comparison to factory tests
- System integration testing is an important test

* ≡ <u>understand</u> IEEE C57.93, C57.106 & C57.152

Questions ?

Thank you!

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