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Tests are Performed to confirm the integrity of the equipment or a part of it. These are performed:

- At various stages during the manufacturing process
- At final factory acceptance
- As on-site commissioning and acceptance
- As part of routine maintenance and diagnostics
- After system events
- As part of end-of-life determination and de-commissioning

➤ An important part of any equipment’s life cycle
Why all this focus on transformers?

- Average age (North America, typical utility) is 35 – 40 years.
  - On order of book life
  - On order of anticipated design/expected life (whatever that means)
- Condition varies from utility – utility, and from one transformer to another, but many are of marginal condition and getting poorer.
- Replacement programs can’t keep up with escalating age and degrading condition.
- Life extension programs aim to prolong life (age) even further.

"Typical" Transformer Population, Large North American IOU

Number of Units

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Number of Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>175</td>
</tr>
<tr>
<td>11 - 20</td>
<td>125</td>
</tr>
<tr>
<td>21 - 30</td>
<td>100</td>
</tr>
<tr>
<td>31 - 40</td>
<td>400</td>
</tr>
<tr>
<td>41 - 50</td>
<td>375</td>
</tr>
<tr>
<td>51 - 60</td>
<td>350</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>325</td>
</tr>
</tbody>
</table>
Why all this focus on transformers?

• Potential Failure Impacts:
  – Personnel safety
  – Environmental impact
  – Significant collateral damage
  – Long outage times
  – Degrading reliability
  – Long lead times for replacement
  – Significant monetary costs associated with unplanned outages.
1. Overall (Transformer) Power Factor and Capacitance
2. Bushing Power Factor and Capacitance
3. Transformer Turns Ratio
4. DC Winding Resistance
5. Excitation Current
6. Oil Quality
7. Dissolved Gas Analysis
8. Leakage Reactance
9. Sweep Frequency Response Analysis
10. Partial Discharge
11. Visual Inspections
Test Significance

Each test targets a different area/component/accessory of the transformer:

- Core
- Winding
- Insulating fluid
- Solid insulation
- Tap Changer
- Bushings
- Controls
- Tank

→ The main goal is to detect a developing condition (failure) and take corrective action as appropriate.

→ Each test targets a particular potential failure mode/aging/deterioration mechanism
What are the most common failure modes?

Large IOU Failure History, 1988 – 2008 (96 failures)

- Through-Fault: 26%
- Winding: 20%
- Bushing: 15%
- Gassing: 13%
- Leads: 8%
- Lightning: 4%
- Tap Changer: 4%
- Unknown: 5%
- Vandalism: 8%
- Leaking Valve: 20%
- Design Problem: 15%
- Overheating: 13%
What is Power Factor?

• Power factor is a measurement of the efficiency of insulation system.
Basic Power Factor Circuit

\[ I_T = \text{Total Current} \]
\[ I_R = \text{Resistive Current} \]
\[ \theta = \text{Power Factor Angle} \]
\[ I_C = \text{Capacitive Current} \]
\[ E = \text{Applied Voltage} \]
The Term Power Factor Describes:

– The phase angle relationship between the applied voltage across and the total current through a specimen.

– The ratio of the real power to the apparent power.

– The relationship between the total and resistive current

– The efficiency of a power system in terms of real and reactive power flow
Problem Revealed in LV Winding

FPE, 3-φ, 2-winding, Δ-Y transformer
13.8/4.3 kV, 7 MVA

<table>
<thead>
<tr>
<th>Insulation</th>
<th>kV</th>
<th>mA</th>
<th>Watts</th>
<th>% P.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH + CHL</td>
<td>10</td>
<td>28.5</td>
<td>1.45</td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>10</td>
<td>7.05</td>
<td>0.38</td>
<td>0.39</td>
</tr>
<tr>
<td>CHL (UST)</td>
<td>10</td>
<td>21.5</td>
<td>0.95</td>
<td>0.32</td>
</tr>
<tr>
<td>CL + CHL</td>
<td>2</td>
<td>39.5</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>CL</td>
<td>2</td>
<td>17.65</td>
<td>2.85</td>
<td>1.18</td>
</tr>
<tr>
<td>CHL (UST)</td>
<td>2</td>
<td>21.5</td>
<td>3.55</td>
<td>1.2</td>
</tr>
<tr>
<td>CHL</td>
<td></td>
<td>21.85</td>
<td>2.65</td>
<td></td>
</tr>
</tbody>
</table>

Localized moisture/contamination in the L.V. winding

High CL % P.F. & disagreement between HV & LV CHL %P.F.s
Westinghouse, 3-Phase, 345/19 kV, 343 MVA Shell-Form Generator Step-up Transformer

<table>
<thead>
<tr>
<th>Test Date</th>
<th>$C_H$ (%PF)</th>
<th>$C_L$ (%PF)</th>
<th>$C_{HL}$ (%PF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>0.50</td>
<td>0.59</td>
<td>0.47</td>
</tr>
<tr>
<td>1975</td>
<td>1.60</td>
<td>0.57</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Routine Test

Sister unit was tested & did not indicate a similar increase.

Other tests performed:
TTR, DC Winding Resistance, Exciting Current, TCG, DGA, Oil P.F. (No problems indicated)
Results of Internal Inspection:

• Oil pump No. 8 (located in the area of the φ - C H.V. bushing) was severely deteriorated. The outer bearing sleeve, the pump housing, & 1/2 the width of the impeller blade were destroyed.

• 1 other pump was found to have appreciable bearing wear & the remaining 7 pumps had varying, lesser degrees of bearing-wear.

• After clean-up & repair, the unit was returned to service. It failed 4 months later. It is believed that the fault resulted from the magnetic contamination introduced previously.
Dielectric Capacitance

\[ C = \frac{A \varepsilon}{d} \]

- \( C \) = Capacitance
- \( A \) = area of electrodes
- \( \varepsilon \) = Dielectric constant
- \( d \) = Distance between electrodes

All of these variables are Physical Parameters
Changes in Current/Capacitance

• Significance
  – Indicate a physical change
    • Bushings - shorting of capacitive layers
    • Transformers - movement of core/coils
    • Arresters - broken elements

• Suggested Limits
  – ± 5% - Investigate
  – ± 10% - Investigate/remove from service
Significance of Measured Capacitance

Interwinding \((C_{HT})\) capacitance of an autotransformer.

<table>
<thead>
<tr>
<th>Test Date</th>
<th>20°C % PF</th>
<th>Cap (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>0.20</td>
<td>2,650</td>
</tr>
<tr>
<td>1968</td>
<td>0.29</td>
<td>2,756</td>
</tr>
<tr>
<td>1974</td>
<td>0.29</td>
<td>3,710</td>
</tr>
<tr>
<td>1982</td>
<td>0.32</td>
<td>5,100</td>
</tr>
</tbody>
</table>
Capacitance change can indicate movement and/or deformation of transformer windings.

\[ C = \frac{A\varepsilon}{d} \]

What other tests would confirm this?
- Leakage Reactance
- SFRA
Bushing Tests

Fig. 1. Sectional view of Type 07, 115-kv, oil-filled bushing

- Stud for detachable cable conductor
- Core seal gasket
- Breather pipe
- Thermal seal showing section through flow tube
- Heavy spring washers
- Removable plug in hole for inserting oil-sampling tube
- Gasket
- Terminal shield
- Equalizer on one of the concentric Herkolite cylinders
- Treated maple spacing blocks to separate concentric cylinders
- Ground shield
- Support flange
- Gasket
- Support
- Gasket
- Cement joints between porcelains and clamping rings
- Herkolite core insulation
- Copper tube threaded for attaching terminal when tube is used as conductor
- Gasket

Terminal cap
Lifting eyes
Filling hole
Cover
Amber glass oil gage and expansion chamber
Normal oil level
Top washer with sump and drain
Top clamping ring
Top porcelain
Upper intermediate clamping ring
Nameplate
Spring and star washers
Effective ground-sleeve length
Minimum oil level (0.5 in. above end of grounded metal)
Lower intermediate clamping ring
Bottom porcelain
Bottom clamping ring
Drain plug
Bottom washer
Condenser Bushing Components

- Center Conductor
- Sight-Glass
- Liquid or Compound Filler
- Insulating Weather shed
- Main Insulating Core
  - Tap Insulation
  - Tap Electrode
  - Mounting Flange
  - Ground Sleeve
  - Tapped Capacitance-Graded Layer
- Lower Insulator
• Voltage is stressed equally across each condenser layer of $C_1$ insulation
• Relationship between $C_1$ and $C_2$ dependent upon desired voltage at the tap when in service
Typical Condenser Bushing Construction

- Core Wind
- Foil
- C2 Plate
Bushing Tests

- Ungrounded-Specimen Test
  Center Conductor to Tap, $C_1$

- Tap Insulation Test
  Tap to Flange, $C_2$

- Hot Collar Test
  Externally Applied Collar to Center Conductor

- Overall
  Center Conductor to Flange
## Staining of the Lower Insulator

<table>
<thead>
<tr>
<th>Test kV</th>
<th>I (mA)</th>
<th>Watts</th>
<th>20°C %PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.313</td>
<td>-0.007</td>
<td>-0.053</td>
</tr>
</tbody>
</table>

ABB Type O+C 230 kV bushing
Excitation Current & Loss

Magnetic Circuit and Winding Tests

- Exciting Current and Loss
  - Factory Tests at Rated Voltage.
  - Field Tests at the Lesser of Rated Voltage or Highest Capability of the Test Set.

- Simple measurement of single-phase current on one side of the transformer, usually the HV side, with the other side left floating (with the exception of a grounded neutral).

- The tests should be performed at the highest possible test voltage without exceeding the voltage rating of the excited winding.
Excitation Current Tests Can Identify Problems in the Iron Core, Windings, and Tap Changers

<table>
<thead>
<tr>
<th>Core</th>
<th>Windings</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Abnormal core assembly</td>
<td>• Turn-to-turn shorts</td>
</tr>
<tr>
<td></td>
<td>• Turn-to-ground shorts (grounded windings)</td>
</tr>
<tr>
<td></td>
<td>• High resistance turn-to-turn or turn-to-ground shorts</td>
</tr>
</tbody>
</table>

**Tap Changers**

• Mechanical failures
• Auxiliary transformer problems
Excitation current is the current that flows when the winding of the transformer is energized under no-load conditions. It supplies the energy necessary to create the magnetic flux $\Phi$ in the iron core.
When there is a Fault on the Secondary Winding

The primary current increases due to the current through the short-circuited turns.
Excitation Current & Loss

– Examine phase patterns
– Typical pattern is two high similar results on the outer phases and one lower result on the center phase however there are exceptions due to core design, etc.
– Residual magnetism can affect results
  • DC tests can magnetize core
  • Can be a result of being de-energized from the system
– Subsequent tests should be performed at same test voltage and with same connections
A raccoon came into contact with the H3 bushing which took out the bushing and an associated voltage regulator. The bushing was replaced, regulator cleaned up and the equipment was put back into service after a series of tests. Shortly thereafter, the transformer was noted to be running hot.

A DGA and TCG test was performed with very high results. %PF did not show any major changes but the Iex did.
Magnetic Circuit and Winding Tests

- Check for abnormalities due to loose connections, broken strands, and high-contact resistance in tap-changers.

- Interpretation of results is usually based on a comparison of measurements made separately on each phase in the case of a wye-connected winding or between pairs of terminals on a delta-connected winding.

- Comparison may also be made with original data measured in the factory. Agreement to within 5% for any of the above comparisons is usually considered satisfactory.

- It may be necessary to convert the resistance measurements to values corresponding to the reference temperature in the transformer test report.
Transformer Turns Ratio

- Ratio of the number of turns in a higher voltage winding to that in a lower voltage winding
- Factory and Field
  - Low Voltage Method
  - High Voltage Capacitance Reference Method
- Confirm nameplate ratios
- Detect short-circuited turn-to-turn insulation
- Find open-circuited windings
- Find problems with tap changer connections (DETC & LTC)
Mechanical Integrity Diagnostics

- Frequency Response Analysis (FRA)
- Leakage Reactance
- Capacitance
- Excitation Current
- These independent diagnostic methods have their place in ascertaining transformer condition
Frequency Response Testing

Purpose

• Assess Mechanical Condition of Transformers (mechanical distortions)

• Detect Core and Winding Movement
  – Due to large electromagnetic forces from fault currents
  – Winding Shrinkage causing release of clamping pressure
  – Transformer Relocations or Shipping
Test Sequence

• Measures the response $V_{out}$ for a low voltage sign $V_{in}$ that varies in frequency.
  – For two winding three phase transformer 9 tests
    • Open circuit test: one per winding, per phase (6 tests)
    • Short circuit test: one per phase (3 tests)

• The analysis plots the ratio of the transmitted voltage $V_{out}$ waveform to the applied voltage waveform $V_{in}$ in db.

• Low voltage Signal
  – 20hz to 2Mhz

$$dB = 20 \log_{10} \left( \frac{V_{out}}{V_{in}} \right)$$
SFRA - Sweep Frequency Response Analysis

- **Core**: < 2 kHz
- **Clamping structures**: 2 kHz – 20 kHz
- **Main winding**: 20 kHz – 100 kHz
- **Tap leads**: 400 kHz – 2 MHz
- **Tap windings**: 100 kHz – 400 kHz
Case Study: Close-in Fault

- Capacity: 25/33/41 MVA
- Voltage: 112/14.4 kV
- BIL 450KV
- Entered service 1996 (10 years old)

- Transformer saw a number of close in faults, while attempting to isolate a cable problem
- The bus attached to the low side caught fire
- No surge arresters on low side

- Can the transformer be placed back into service?
Overall Capacitance and Power Factor

- **PF Results are acceptable**
- **Capacitance – Unknown because no precious overall results.**

### Overall Test Setup

<table>
<thead>
<tr>
<th>Connections</th>
<th>Inputs</th>
<th>Test Results</th>
<th>Doble eXpert System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>#</strong></td>
<td><strong>HV Lead</strong></td>
<td><strong>Red Measure Lead</strong></td>
<td><strong>Blue Measure Lead</strong></td>
</tr>
<tr>
<td>1</td>
<td>HV Winding</td>
<td>LV Winding</td>
<td>Unused</td>
</tr>
<tr>
<td>2</td>
<td>LV Winding</td>
<td>Unused</td>
<td>CH</td>
</tr>
<tr>
<td>3</td>
<td>Test 1 - Test 2 (calculated)</td>
<td>CHL</td>
<td>CHL</td>
</tr>
<tr>
<td>4</td>
<td>Test 1 - Test 2 (calculated)</td>
<td>CHL</td>
<td>CHL</td>
</tr>
<tr>
<td>5</td>
<td>LV Winding</td>
<td>HV Winding</td>
<td>Unused</td>
</tr>
<tr>
<td>6</td>
<td>LV Winding</td>
<td>HV Winding</td>
<td>Unused</td>
</tr>
<tr>
<td>7</td>
<td>LV Winding</td>
<td>HV Winding</td>
<td>Unused</td>
</tr>
<tr>
<td>8</td>
<td>Test 5 - Test 6 (calculated)</td>
<td>CHL</td>
<td>CHL</td>
</tr>
</tbody>
</table>
Exciting Current Results

Excitation Current Analysis

mA

Tap Position

16L 15L 14L 13L 12L 11L 10L 9L 8L 7L 6L 5L 4L 3L 2L 1L N 1R 2R 3R 4R 5R
### Per Phase Leakage Reactance

#### Leakage Reactance Results

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Test Results</th>
<th>% Reactance</th>
<th>Resistance</th>
<th>% Resistance</th>
<th>Benchmark%</th>
<th>Delta Bench%</th>
<th>Delta Avg.4%</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Voltage</td>
<td>% Reactance</td>
<td>Resistance</td>
<td>% Resistance</td>
<td>Benchmark%</td>
<td>Delta Bench%</td>
<td></td>
</tr>
<tr>
<td>3/N</td>
<td>1.506 A</td>
<td>204.000 V</td>
<td>135.519 Ω</td>
<td>5.057 Ω</td>
<td>9.003%</td>
<td>8.940%</td>
<td>0.704%</td>
<td>3.360%</td>
</tr>
<tr>
<td></td>
<td>1.407 A</td>
<td>223.000 V</td>
<td>148.724 Ω</td>
<td>4.825 Ω</td>
<td>9.880%</td>
<td>8.940%</td>
<td>10.516%</td>
<td>5.054%</td>
</tr>
<tr>
<td></td>
<td>1.499 A</td>
<td>205.000 V</td>
<td>136.451 Ω</td>
<td>5.115 Ω</td>
<td>9.003%</td>
<td>8.540%</td>
<td>1.396%</td>
<td>2.594%</td>
</tr>
</tbody>
</table>

**DTA6 (FRANK)**

**FRANK™'s rating (First Response ANalytics Knowledgebase™)**

<table>
<thead>
<tr>
<th>#</th>
<th>Ratings</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>!</td>
<td>Reactance is high compared to nameplate. The reactance for this phase deviates from delta average. Check shorting configuration to verify that test was performed correctly. This may indicate a change in the mechanical structure of the winding. Contact supervisor or Doble. The initial per phase reactance is not expect to compare with the three phase impedance on the nameplate. This reflects differences in the test setup, though very large variations from the nameplate impedance may represent test setup errors. The delta average is used for evaluation, and they are expected to be within 3% of each other initially. Subsequent results are expected to be within ½ of initial values.</td>
</tr>
<tr>
<td>2</td>
<td>!</td>
<td>Reactance is high compared to nameplate. The reactance for this phase deviates from delta average. Check shorting configuration to verify that test was performed correctly. This may indicate a change in the mechanical structure of the winding. Contact supervisor or Doble.</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>The reactance of this phase compares with the delta average of all three phases.</td>
</tr>
</tbody>
</table>
### Leakage Reactance Results

**Inputs**
- DETC/LTC: 3/N
- Phase: A, B, C

**Test Results**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Current</th>
<th>Voltage</th>
<th>% Reactance</th>
<th>Resistance</th>
<th>% Reactance</th>
<th>Benchmark%</th>
<th>Delta Bench%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.019 A</td>
<td>195.000 V</td>
<td>96.324 Ω</td>
<td>3.411 Ω</td>
<td>9.297%</td>
<td>8.940%</td>
<td>3.989%</td>
</tr>
<tr>
<td>B</td>
<td>2.029 A</td>
<td>187.000 V</td>
<td>91.931 Ω</td>
<td>3.806 Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.025 A</td>
<td>186.000 V</td>
<td>91.625 Ω</td>
<td>3.806 Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Ratings**
- FRANK™'s rating (First Response ANalytics Knowledgebase™)
  - Reactance is within acceptable ranges.
  - The initial three phase equivalent reactance should be within 3-4% of the nameplate impedance, though differences in how tests are performed in the field versus the factory may result in a variation up to 7%, still reflecting apparatus in good condition. Subsequent tests should be within 2% of initial values.
  - A three phase test is not required for this winding configuration.
Open Circuit High Side
Open Circuit Low Side
Short Circuit
0.2 dB delta is significant here!
### Two Years Later

#### Overall Test Setup

<table>
<thead>
<tr>
<th>Connections</th>
<th>Inputs</th>
<th>Test Results</th>
<th>Doble eXpert System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test kV</td>
<td>mA</td>
<td>Watts</td>
</tr>
<tr>
<td>HV Lead</td>
<td>10.000</td>
<td>1.314</td>
<td>1.322</td>
</tr>
<tr>
<td>Red Measure Lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue Measure Lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV Winding</td>
<td>10.000</td>
<td>2.324</td>
<td>2.321</td>
</tr>
<tr>
<td>Unused</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 1 - Test 2 (calculated)</td>
<td>10.000</td>
<td>-1.010</td>
<td>-0.999</td>
</tr>
<tr>
<td>LV Winding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV Winding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unused</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CL + CHL</td>
<td>10.000</td>
<td>4.344</td>
<td>4.321</td>
</tr>
<tr>
<td>Test 5 - Test 6 (calculated)</td>
<td>10.000</td>
<td>-1.010</td>
<td>-1.000</td>
</tr>
</tbody>
</table>
Fluid Tests
Why Measure Gases in Oil?

• Excellent indicators of incipient fault condition - **Most important diagnostic in the industry**

• Can help determine the materials involved

• Severity of the condition - abnormal amounts

• Detect of wide variety of conditions - most important test

• Gas-in-oil analysis complex - not easily simplified for easy analysis in all cases
## Key Gas Analysis

<table>
<thead>
<tr>
<th>Condition</th>
<th>Key Gas</th>
</tr>
</thead>
</table>
| Arcing             | High concentration of hydrogen and acetylene, with minor quantities of methane and ethylene.  
                       | **Key gas - Acetylene**                                                 |
| Corona             | Low-energy electrical discharge creates hydrogen and methane, with lesser quantities of ethane and ethylene.  
                       | **Key gas - Hydrogen**                                                  |
| Overheated Oil     | Includes ethylene and methane, and lesser quantities of hydrogen and ethane.  
                       | **Key gas - Ethylene**                                                  |
| Overheated Cellulose| Carbon dioxide and carbon monoxide are evolved from over-heated cellulose. Hydrocarbon gasses will be formed if the fault involves an oil-impregnated structure.  
                       | **Key gas - Carbon Monoxide**                                           |
### Gases Produced during Overheating

<table>
<thead>
<tr>
<th>Temperature of Overheating</th>
<th>Gas</th>
<th>Chemical Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Temperature (~120°)</td>
<td>Methane</td>
<td>CH4</td>
</tr>
<tr>
<td></td>
<td>Ethane</td>
<td>C2H6</td>
</tr>
<tr>
<td></td>
<td>Ethylene</td>
<td>C2H4</td>
</tr>
<tr>
<td>High Temperature (&gt;350° C)</td>
<td>Acetylene</td>
<td>C2H2</td>
</tr>
</tbody>
</table>
Combustible Gases – Westinghouse 24 years old
Rating 115 kV, 40 MVA

- Hydrogen (H2)
- Methane (CH4)
- Carbon Monox. (CO)
- Ethane (C2H6)
- Ethylene (C2H4)
- Comb Gas
- Acetylene (C2H2)

Date

Concentration, ppm
0 250 500 750 1000 1250 1500 1750 2000 2250 2500
1/1/89 9/28/91 6/24/94 3/20/97 12/15/99 9/10/02 6/6/05
Overheating of Support Structure
Main Clamping Top Beam
• Water content of oil and paper are related and can be described using equilibrium curves
• Dielectric breakdown voltage of the insulation system
• Ability to overload
  – Temperature water vapor bubbles evolve from solid insulation a function of its water content, with 2% water in paper can go up to 140°C without risk of bubbles
  – Aging of the solid insulation directly proportional
• Susceptibility to high relative saturation of water in oil and formation of free water
• Power Factor - Measure of dielectric losses, dielectric heating, indicator soluble polar, ionic or colloidal contaminants or aging byproducts

• Color - Rapid change indicator of accelerated aging of the insulation system

• Interfacial Tension - Detects deterioration of oil in the early stages of aging, affected by the polar contaminants

• Acidity - Aging byproducts, accelerates aging of paper and corrodes metal
Physical Properties and Inhibitor Content

• Viscosity
  – Should not change with aging
  – Important characteristic for cooling
  – Takes gross contamination, aging, or over processing to change significantly

• Relative density
  – Should not change with aging
  – Simple periodic measure
  – Takes gross contamination, aging, or over processing to change significantly

• Inhibitor Content - replenish when handling the oil
Partial Discharge

- PD diagnostics can be used to trend changes in the level and severity of insulation degradation
- Once present – it dominates as it’s own “inherent” stress degradation mechanism
- It’s an early warning signal and precursor to complete insulation failure and breakdown
- Early detection of PD is critical in the prevention of catastrophic failures
Types of PD

Void/Protrusions in solid insulation, cavity in liquids.

Surface discharge

Corona
PD Insulation Model

- The voids capacitance $C_C$ is part of the overall dielectrics capacitance which includes the remaining series capacitance $C_B$ and shunt capacitance $C_A$

- The void has a breakdown voltage $V_S$ that once reached across the void $C_c$ will spark over (PD)
Causes of PD in insulation system:
- Voids in epoxy resins, polymers, paper
- Bubbles in liquids/oils
- Metal deposits, irregularities such as protrusions, contaminants
- Electrodes and insulation surfaces and interfaces

Can arise through:
- Poor design and manufacture
- Damage of equipment e.g. Transport damage
- Poor installation processes – poor workmanship
- General “ageing” or deterioration of materials
PD Measurement on Transformers

- PD
- Tank
- Valve
- Connector
- Sensor
Sensor Application Measuring Impedance

PD Measuring Impedance for Bushing Tap Installation
Acoustics are a valid technique for **locating** PD but it’s the wrong approach for **detecting** PD due to low sensitivity of the AE method and the fact that PD imbedded in the winding will not produce acoustic pressure waves detectable on the tank wall. So no Acoustic Signal does not mean no PD and detection via HF-CT on the star point end will only work for strong PD.
On-Line Testing Methods

- Partial Discharge
  - Acoustic
  - UHF, EMI
  - RIV
- Bushing Monitoring
  - PF/Capacitance (absolute & rate of change)
- Oil
  - DGA
  - Moisture
- Surge Arrester Monitoring
  - Leakage Current
- Complete Substation Monitoring
  - Data from various online monitors
  - Expert System Analysis
Why Monitor Bushings?
• Gradual deterioration over several month span.
• The bushing was one of a type which had several failures around the world recently.
• A sudden variation in leakage current raised an alarm.
• Operations took the bushing off line and replaced it – a tear down indicated they had just hours before catastrophic failure.

Bushing Monitoring – Sudden Increase
• Each test is sensitive to certain types of issues.
• Motivation for testing should always be determined before arbitrarily performing a variety of tests.
• Routine testing should provide owner with a high level of comfort with transformer condition.
• Investigative testing needs to be more focused and thorough.
• Test results should always be scrutinized and taken seriously.
• Planning discussions for contingencies are important in making good decisions
• There are cases where some tests will fail to identify a problem.
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