Guide for Transformer Maintenance

Tutorial of Cigre Working Group A2.34
Convener: Claude Rajotte, Canada
Outline

Introduction

Maintenance strategy
Maintenance process
Component selection and maintenance
Maintenance action catalogue
Major work – transformer repair
Guide for Transformer Maintenance

• Prepared to help transformer users define and apply best practices to transformer maintenance

• Includes transformers rated 69 kV and above, and larger than 25 MVA

• Subjects covered - best practice, checking and testing to evaluate transformer condition, intervals for the various actions, advanced maintenance activities, human and material factors
Transformer Operation and Maintenance Cycle

Guide for Transformer maintenance – Tutorial of Cigre WG A2.34
Outline

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Maintenance Strategy

Importance of Transformer Maintenance

<table>
<thead>
<tr>
<th>Life Used</th>
<th>Possible Impacts of Lack of Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEW</td>
<td>- Data not recorded, commissioning errors missed</td>
</tr>
<tr>
<td></td>
<td>- Failure to detect early life problems within warranty period</td>
</tr>
<tr>
<td>20%</td>
<td>- Oil oxidation begins</td>
</tr>
<tr>
<td>40%</td>
<td>- OLTC contacts wear (medium and heavy loads)</td>
</tr>
<tr>
<td>60%</td>
<td>- Weathering and UV takes affect</td>
</tr>
<tr>
<td>80%</td>
<td>- Trends in condition not observed</td>
</tr>
<tr>
<td>100%</td>
<td>- Corrosion in severe environments</td>
</tr>
<tr>
<td></td>
<td>- Visible affects of weathering and UV</td>
</tr>
<tr>
<td></td>
<td>- Transducers go out of calibration</td>
</tr>
<tr>
<td></td>
<td>- Fan and pump bearing wear</td>
</tr>
<tr>
<td></td>
<td>- Trends in condition not observed</td>
</tr>
<tr>
<td></td>
<td>- Gaskets and seals lose resilience, oil leaks manifest</td>
</tr>
<tr>
<td></td>
<td>- Oil decay products affect paper insulation</td>
</tr>
<tr>
<td></td>
<td>- Weathered paint, edge and spot corrosion</td>
</tr>
<tr>
<td></td>
<td>- Miss opportunity to intercept accelerated ageing</td>
</tr>
<tr>
<td></td>
<td>- Miss benefits of implementing a mid-life intervention</td>
</tr>
<tr>
<td></td>
<td>- Uncertainty on remnant life</td>
</tr>
<tr>
<td></td>
<td>- Oxidation and hydrolysis enters accelerated ageing stage</td>
</tr>
<tr>
<td></td>
<td>- Paper DP drops, sometimes prematurely</td>
</tr>
<tr>
<td></td>
<td>- OLTC and bushing failure rates increase</td>
</tr>
<tr>
<td></td>
<td>- Paint system protection fails</td>
</tr>
<tr>
<td></td>
<td>- Expect sludge if oil has been in poor condition</td>
</tr>
<tr>
<td></td>
<td>- Exposure causes device malfunctions</td>
</tr>
<tr>
<td></td>
<td>- Wiring and cable insulation en-brittle</td>
</tr>
<tr>
<td></td>
<td>- Bad oil leaks need regular topping up</td>
</tr>
<tr>
<td></td>
<td>- Dielectric withstand diminishes (moisture)</td>
</tr>
<tr>
<td></td>
<td>- Expensive failure (often bushing or OLTC)</td>
</tr>
</tbody>
</table>

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The condition begins to deteriorate

The condition change becomes detectable

The condition has deteriorated to the point of failure

To be technically feasible, a condition assessment task should have the ability to:

- **detect initial changes in condition** that are relatively small compared to the deterioration necessary for failure to occur

- have **measurement or inspection intervals** that are smaller than $\Delta T[XY]+\Delta T[YZ]$ to allow *detection before failure occurs*

- have a period of time $\Delta T[YZ]$ that is long enough to be *able to take the preventive action* (ex: transformer outage)
Maintenance Strategy
Survey on Maintenance Practices

KEY FINDINGS

• There were significant differences on the task intervals for "visits".

• Oil test task intervals were generally in accordance with IEC 60422.

• A majority of respondents used Electrical tests on a "Conditional based" criterion only - **CBM**.

• For "Accessories verification", task intervals varied significantly (from 1 to 12 years).

• OLTC task intervals varied between 4 and 12 years.

• Bushing maintenance practices varied significantly between utilities.
Maintenance Strategy
Survey on Maintenance Practices

For **GSU transformers**, it was observed that:

- Visits were made at significantly shorter intervals
- Periodic sampling for dissolved gas analysis (DGA), by the majority, were at intervals of one year or less
- Continuous DGA monitoring was not often applied, probably due to the proximity of a maintenance crew
- A minority of respondents were performing electrical tests periodically

For **Transmission transformers**, it was observed that:

- Generally, the intervals between visits were longer than for GSU users and also varied greatly
- Continuous DGA monitoring was used intensively by 50% of the respondents, particularly on their critical units
- Electrical tests were performed by two thirds of the respondents
Maintenance Strategy
Survey on Maintenance Practices

The survey showed that maintenance practices varied significantly between transformer users.

Factors that can influence maintenance practice and effort:

- Transformer characteristics and specifications
- The quality of the components installed on the transformer
- The required duty of the transformer (load, OLTC operation)
- The transformer environment (temperature, humidity)
- Historical transformer failure rate and failure types
- The level of transformer redundancy and the consequences of unavailability
- The failure mode and its effects on substation safety
- Company culture and focus based on maintenance
- The availability and costs of labour
- The degree of implementation of modern technologies
- The presence of a maintenance optimization program
## Maintenance Strategy

### TBM and TBCM Maintenance Intervals

<table>
<thead>
<tr>
<th>Action</th>
<th>Task Interval</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light</td>
<td>Regular</td>
</tr>
<tr>
<td>Visit</td>
<td>6 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Detailed visual inspection</td>
<td>1 y</td>
<td>3 m</td>
</tr>
<tr>
<td>DGA</td>
<td>2 y</td>
<td>1 y</td>
</tr>
<tr>
<td>Oil tests</td>
<td>6 y</td>
<td>2 y</td>
</tr>
<tr>
<td>Cooling system cleaning</td>
<td>Conditional</td>
<td>Conditional</td>
</tr>
<tr>
<td>Accessories verification</td>
<td>12 y or Cond.</td>
<td>6-8 y</td>
</tr>
<tr>
<td><strong>Electrical basic tests</strong></td>
<td>Conditional</td>
<td>Conditional</td>
</tr>
<tr>
<td>Insulation tests (DF or PF)</td>
<td>Conditional</td>
<td>6-8 y</td>
</tr>
<tr>
<td>OLTC internal inspection</td>
<td>12 y</td>
<td>6-8 y</td>
</tr>
</tbody>
</table>

Survey showed many tasks were performed conditionally - **CBM**
Maintenance Strategy
TBM and TBCM Maintenance Intervals

The intensity of these maintenance task intervals:

**Light**
- Transformer equipped with components known to be very reliable
- Low load and low number of tap-changer operations
- Transformer does not operate in a harsh environment
- Advanced technology that requires less maintenance
- Low consequences from unexpected failure

**Intensive**
- Components that are known to require frequent attention
- High load, high number of OLTC operations
- Transformer operates in a harsh environment
- Older transformer technologies
- High consequences from unexpected failure

**Regular**
- Any situation between these two
Maintenance Strategy
Condition Based Maintenance – Oil Test Results

Limit Values Exceeded

- Oil Test Affected
  - Breakdown Voltage
    - Particles (carbon - OLTC leak)
    - Oil Filtration
    - Repair Leaks
  - Water Content
    - Water Ingress
    - Paper Ageing
  - Dissipation/Power Factor and Interfacial Tension
    - Polar Particles (carbon - OLTC leak)
  - Acidity
    - Oil Ageing
    - Transformer Drying
    - Stop Water Ingress (Gaskets, hermetic oil seals)
  - Inhibitor Content or other Oil Additive Content
    - Additive being Consumed
    - Maintain Additive Content

Possible Cause
On-line Monitoring
Data, measurements or samples (oil) are collected while the transformer is energized and in service. If these are performed at discrete intervals (in ‘visits’) then they provide only ‘snapshots’ of the transformer’s condition.

Continuous On-line Monitoring
Data, measurements or samples are collected in a continuum by transducers, sometimes at discrete sampling rates, while the transformer is energized and in service. This captures real time data to provide trends in transformer condition.
Modern continuous on-line monitoring adds an intelligent electronic device (IED) to the monitoring transducer(s). These devices have a measurement mechanism, that together with internal signal and data processing capabilities, can be described as ‘smart sensors’ or ‘smart systems’ capable of providing multiple measurement and control functions.
Maintenance Strategy
Continuous DGA On-Line Monitoring

- This is the most commonly used on-line monitoring technology for transformers because:
  - It is a very good indicator for most transformer incipient faults
  - Early detection of incipient faults often avoids major failure

- DGA sensor technologies include fuel cell, chromatography, semiconductor, photo-acoustic spectroscopy, thermal conductivity

- Depending on the technology chosen, these systems can provide:
  - A single measurement of one specific gas
  - A single measurement of a composition of several gases with specific proportions and sensitivities
  - Multiple measurements of different gases

- Gas-in-oil monitors often include a built-in moisture sensor
Maintenance Strategy
Other On-Line Monitoring Technologies

• Systems with models or algorithms that calculate winding hot spot temperatures, rate of ageing of paper insulation, moisture content in paper or barriers, and effectiveness of cooling systems

• Monitors condenser bushings by measuring leakage current through their capacitance taps

• OLTC monitoring including mechanical conditions of the drive system, contact wear, temperature differential, dissolved gas analysis, tap position tracking/counting

• Partial discharge detection using electrical, acoustical, or UHF signals
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Major work – transformer repair
Maintenance Process

Planning → Organization → Execution → Recording

Optimization

Guide for Transformer maintenance – Tutorial of Cigre WG A2.34
Maintenance Process
Maintenance Planning – Maintenance Guidelines

A guideline would include:

• General information about the transformer (type, power, voltage)

• Types of maintenance work to be done with relevant triggering points (time interval, event, condition, result of diagnostics) and operational status (energized, de-energized, or both de-energized and disconnected)

• Qualifications and skills required to perform individual maintenance works

• List of tasks related to individual maintenance works and the associated time required

• Excerpt from, or reference to manufacturer’s manual giving detailed information (work steps, sequence, tools, material, safety aspects)

• Maintenance report forms

• Source of information for maintenance data collection and reporting – based on standard report forms
Maintenance Planning – Computer Aided Maintenance Management Systems (MMS)

There are different computer aided tools for maintenance planning used by different utilities. All have this similar structure:

- Equipment Inventory
- Computerized Maintenance Guidelines
- Task lists and Operations
- Maintenance plan
- Maintenance schedules
- Work orders
- Outage Planning
- Maintenance task tracking
Maintenance Process

Planning → Organization → Execution → Recording

Optimization
Level 1:

Actions to be taken on certain transformer components, and generally described in a maintenance manual issued by the manufacturer.

Examples: control operations, check of oil levels, exchange of consumable materials
Level 2:

Actions performed with **basic** written procedures and/or supporting equipment or devices, which are simple to use or to assemble, being part of the transformer or external to it.

*Examples: replacement / exchange of accessories or parts, routine checks.*
Level 3:

Actions performed with complex written procedures or the use of special supporting equipment. Personnel are trained in using complex tools or processes.

*Examples: exchange of an original part or component, complex setting or re-setting*
Level 4:

Actions performed requiring personnel trained in special techniques or technologies and utilization of special tools, and/or supporting equipment.

Examples: modifications and upgrading activities, changes in functions, changes in the way of operation and use.
Level 5:

Actions needing *specialist* technical knowledge and with the support of industrial processes, industrial equipment or devices.

*Examples: complete inspections or revisions which require detailed dismantling of the equipment, its reconstruction, replacement of obsolete or worn parts or components.*
Maintenance Process

Planning → Organization → Execution → Recording

Optimization
Maintenance Execution

Safety

Some safety aspects that have to be considered when working on a transformer:

• ground all bushings to avoid induction
• use working at height safety measures
• beware all bushings and leads when testing
• beware opening pressurized access covers
• identify and isolate cubicle auxiliary supplies
• deactivate springs whilst working on OLTC
• treat all tanks as confined spaces
• beware of nitrogen gas filling
• vent explosive gases accumulated by OLTCs or faults
• perform a risk assessment on the need to deactivate the fire extinguishing system
Maintenance Process

Planning ➔ Organization ➔ Execution ➔ Recording

Optimization
Maintenance Recording
Corrective Maintenance Tracking

Data recorded for corrective maintenance should contain:
• Unique identification of the transformer and its properties and location
• Transformer location details
• Time of maintenance action
• Environmental conditions on site during maintenance action: 
  Temperature, wind, rain, storm, humidity
• Components, parts and material used and the parts replaced
• Photographs: The ‘as found’ and ‘return to service’ condition, providing a reference for future work
• Tests results taken before a return to service
• Problem description: Failure, symptoms and circumstances
• Problem cause: Data on what was causal to the failure or malfunction (in some cases the root-cause may not be obvious and requires more detailed diagnosis and investigation)
• Remedy / Action: A report of the remedial action taken
Maintenance Process

Planning → Organization → Execution → Recording

Optimization
A combination of TBM, TBCM, CBM and OLCM is often used to maintain large complex assets such as power transformers.

**Reliability Centred Maintenance:** The extent of maintenance to be performed is proportional to the level of risk associated with the transformer

\[
\text{Risk} = \text{likelihood of failure} \times \text{failure consequence}
\]

The *likelihood of failure* can be represented by the "Health Index" of the unit (obsolescence, service history, technical condition)

*Failure consequence* can also be mitigated by various control measures (protection upgrade, contingency plan, fire wall, oil containment)
Outline

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Maintenance process

Component selection and maintenance

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Component Selection and Maintenance

Transformer maintenance effort is strongly related to component selection.

- Bushings
- Oil preservation systems
- Cooling systems
- Gaskets
- Gauges, indicators and relays
- Control cabinets
- Current transformers
- On-load tap changers
- De-energized tap changers
- Surge arresters
- Transformer active part
- Sensing and monitoring devices

This is because transformer components vary in quality, initial cost, maintainability, technology, reliability, life expectancy and potential for its failure and the consequences.
## Component Selection and Maintenance

### Bushings

#### Oil Impregnated Paper (OIP) Bushings

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Very long history with relatively good performances</td>
<td>- Vulnerable to insulating oil leaks and water ingress if the gasket/sealing system is compromised</td>
</tr>
<tr>
<td>- Very low partial discharge – can be used at any voltage level</td>
<td>- Higher risk of bushing explosion and resultant transformer fire</td>
</tr>
<tr>
<td>- Relatively low cost</td>
<td>- Positioning angle during transportation, handling and storage</td>
</tr>
<tr>
<td>- Minimal handling and storage requirements</td>
<td></td>
</tr>
<tr>
<td>- DGA diagnostics are possible</td>
<td></td>
</tr>
</tbody>
</table>

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## Resin Impregnated Paper (RIP) Bushings

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Non-flammable core</td>
<td>- Relatively higher costs</td>
</tr>
<tr>
<td>- Bushing failure is less likely to release main tank oil</td>
<td>- Constraints on handling and storage</td>
</tr>
<tr>
<td>- The core is less likely to be affected by water ingress</td>
<td>- The oil end of the body must be protected from moisture during storage</td>
</tr>
<tr>
<td>- Very low partial discharge levels – can be used at any voltage level</td>
<td>- Oil end of the bushing is susceptible to transport damage</td>
</tr>
<tr>
<td>- No constraints on the attitude of the bushing during transportation, handling and storage</td>
<td></td>
</tr>
</tbody>
</table>
## Component Selection and Maintenance

### Bushings

**Porcelain Insulators**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- No ageing</td>
<td>- Could create exploding projectiles if the bushing fails</td>
</tr>
<tr>
<td>- Long history of good reliability</td>
<td>- Relatively fragile in the event of shock or heavy force</td>
</tr>
<tr>
<td></td>
<td>- Makes the bushing relatively heavy</td>
</tr>
</tbody>
</table>

**Composite Insulators**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Relatively lightweight</td>
<td>- Less field experience compare to porcelain</td>
</tr>
<tr>
<td>- Lower risk of projectiles in the event of a bushing failure</td>
<td>- Long term reliability is not known, early examples have suffered from surface deterioration</td>
</tr>
<tr>
<td>- High seismic withstand capability</td>
<td></td>
</tr>
<tr>
<td>- Better hydrophobicity in polluted conditions</td>
<td></td>
</tr>
</tbody>
</table>
Component Selection and Maintenance
Bushings

Types of Bushing Connections

<table>
<thead>
<tr>
<th>Draw Lead</th>
<th>Solid Conductor</th>
<th>Bottom Connected</th>
<th>Draw Rod</th>
</tr>
</thead>
</table>

Black denotes the current path
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Introduction
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Component selection and maintenance
**Maintenance action catalogue**
Major work – transformer repair
# Maintenance Action Catalogue

## Electrical Tests and DGA Diagnostic Matrix

<table>
<thead>
<tr>
<th>Type of Problem</th>
<th>Diagnostic Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Circuit Integrity</td>
<td>Winding Ratio</td>
</tr>
<tr>
<td>Magnetic Circuit Insulation</td>
<td>Winding Resistance</td>
</tr>
<tr>
<td>Winding Geometry</td>
<td>Magnetisation current</td>
</tr>
<tr>
<td>Winding/Bushing/OLTC Continuity</td>
<td>Capacitance and DF/PF</td>
</tr>
<tr>
<td>Winding/Bushing Insulation</td>
<td>Leakage Reactance</td>
</tr>
<tr>
<td>Winding Turn to Turn Insulation</td>
<td>Insulation Resistance</td>
</tr>
<tr>
<td></td>
<td>Core Ground Test</td>
</tr>
<tr>
<td></td>
<td>Frequency Response of Stray Losses</td>
</tr>
<tr>
<td>Advanced Electrical</td>
<td>Frequency Response Analysis</td>
</tr>
<tr>
<td></td>
<td>Frequency Response Analysts</td>
</tr>
<tr>
<td></td>
<td>Polarisation/Depolarisation</td>
</tr>
<tr>
<td></td>
<td>Frequency Domain Spectroscopy</td>
</tr>
<tr>
<td></td>
<td>Recovery Voltage Method</td>
</tr>
<tr>
<td></td>
<td>Electrical Detection of PD</td>
</tr>
<tr>
<td></td>
<td>Acoustical Detection of PD</td>
</tr>
<tr>
<td></td>
<td>UHF Detection of PD</td>
</tr>
<tr>
<td>Basic Electrical</td>
<td>Dissolved Gas Analysis</td>
</tr>
<tr>
<td></td>
<td>Dissolved Gas Analysis</td>
</tr>
</tbody>
</table>

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## Electrical Test Example – Winding Resistance

<table>
<thead>
<tr>
<th>Detectable failures</th>
<th>Contact problems on the tap selector, contact problems on the diverter switch, <strong>broken conductors</strong>, broken parallel strands, <strong>shorted winding</strong> disks, shorted winding layers, poor bushing connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indication</td>
<td><strong>High internal temperatures</strong>, normally indicated by the <strong>DGA</strong></td>
</tr>
<tr>
<td>Test method</td>
<td>A constant current source is used to feed a <strong>DC current into the winding</strong>. The <strong>test current</strong> and the <strong>voltage across the winding</strong> are <strong>measured</strong> and the <strong>resistance value is calculated</strong>. The accuracy of the equipment should guarantee that differences of 1% or even lower can be detected. Since the winding resistances are small, the test set should be connected in 4-wire technology. A relatively high no-load voltage enables a quick saturation of the core and a fast reaching of the stationary final value. It is recommended to measure the resistance for all taps of the OLTC. The resistance values should be corrected to 75°C according to IEC 60076 Part 1</td>
</tr>
<tr>
<td>Reference</td>
<td><strong>Test report</strong> of the manufacturer, <strong>fingerprint</strong> measurements</td>
</tr>
<tr>
<td>Interpretation</td>
<td>The measured winding resistance should <strong>not differ more than about 1%</strong> compared to the factory test report, if the winding temperature at measurement conditions is corrected to the factory conditions. <strong>Difference between phases usually less than 2-3%</strong>; Comparison between HV and LV resistance is usually in the order of the square of the winding ratio, when losses are balanced between HV and LV</td>
</tr>
<tr>
<td>Comments</td>
<td>In comparison to the LV winding, the resistance of the HV winding is much higher. Therefore identification of contact problems can be less sensitive on the HV side than the LV side. If the LV windings have very low resistance values, in the order of a few mΩ, it can be helpful to use the HV winding of the same limb in serial connection to get faster stabilization of the measurement current. The time needed to get stable readings can be in the order of tens of minutes for very low resistance values</td>
</tr>
</tbody>
</table>
Maintenance Action Catalogue  
Dissolved Gas Analysis

• One of the most useful and widely applied diagnostic tools
• Gases commonly measured: Hydrogen (H2), Methane (CH4), Ethane (C2H6), Ethylene (C2H4), Acetylene (C2H2), Carbon Monoxide (CO), Carbon Dioxide (CO2), Oxygen (O2) and Nitrogen (N2)
• No consensus about the absolute maximum level acceptable for each gas
• Considers both gassing rates and absolute values of the different gases
• Algorithms are used to:
  - Identify significant gases because they exceed a limit value
  - Evaluate gassing rates by comparing with previous gas concentrations
  - Assign weightings to each gas (because each gas is not produced by the same amount of energy)
There are several methods used to interpret DGA results. Commonly, gas ratios are used to match the DGA gas profile to the generation source in the transformer (incipient faults), and identify the level of energy (temperature) required to produce them.

Depending on the DGA profile (ratios), the gassing may be associated with:

- Thermal faults of low temperature
- Thermal faults of medium temperature
- Thermal faults of high temperature
- Discharges of low energy
- Discharges of high energy
- Partial discharge activity
Tests for in-service oils:

- GROUP 1: Minimum monitoring to ensure the oil is suitable for continued use - *colour*, *water content*, *breakdown voltage*, *interfacial tension*, *acidity*, *dissipation/power factor* and *resistivity*

- GROUP 2: Additional tests that obtain specific information about the quality of the oil and also used to assist in the evaluation of the oil for continued use – *particle count*, *oxidation stability*, *sediment and sludge*

- GROUP 3: Tests used to determine the suitability of the oil for use in the transformer and the oil’s environmental compliance – *corrosive sulphur and PCB*
# Maintenance Action Catalogue

Relation between Transformer Problems and Main Parameters of the Oil

<table>
<thead>
<tr>
<th>OIL PARAMETER</th>
<th>OVERHEATING</th>
<th>PARTIAL DISCHARGE</th>
<th>DAMAGE TO HERMETIC SEAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In Core</td>
<td>Connection</td>
<td>Winding / Cooling Problem</td>
</tr>
<tr>
<td>Acidity / IFT</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>1,2</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Colour</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>1,2</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Water Content</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5,6</td>
</tr>
<tr>
<td>Breakdown Voltage</td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>3,12</td>
<td></td>
<td>4,6,12</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>1,2</td>
<td>1,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Gas Content</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>1,10</td>
<td>1,10</td>
<td>1,10</td>
</tr>
</tbody>
</table>

| LEGEND                  | In 1- Oil Destruction | 5- Paper Ageing | 9- Water, Sediment, Emulsion |
|                        | 2- Oil Ageing         | 6- Water Production | 10- Gas Production |
|                        | 3- Oil Carbonization  | 7- Dissolved Air  | 11- Bubble |
|                        | 4- Paper Destruction  | 8- Free Water     | 12- Particles |

Guide for Transformer maintenance – Tutorial of Cigre WG A2.34 46
### Maintenance Action Catalogue
Diagnostic Capabilities of Different OLTC Tests

<table>
<thead>
<tr>
<th>VIBRO-AcouSTIC</th>
<th>OLTC TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td></td>
</tr>
<tr>
<td>Reactor</td>
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<tr>
<td>Resistor</td>
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<table>
<thead>
<tr>
<th>MOTOR TORQUE</th>
<th>OLTC TYPE</th>
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<tr>
<th>DISSOLVED GAS ANALYSIS</th>
<th>OLTC TYPE</th>
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<td>Vacuum</td>
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<tr>
<td>Reactor</td>
<td></td>
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<td>Resistor</td>
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<table>
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<tr>
<th>IR THERMOGRAPHY</th>
<th>OLTC TYPE</th>
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<tr>
<td>In-Tank</td>
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<tr>
<td>Compartment</td>
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<table>
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<tr>
<th>DYNAMIC RESISTANCE</th>
<th>OLTC TYPE</th>
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<tbody>
<tr>
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#### PROBLEMS

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<tr>
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<tr>
<td>Linkage/Gears</td>
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<tr>
<td>Timing/Sequence</td>
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<tr>
<td>Control/Relays</td>
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<tr>
<td>Motor</td>
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<td>G</td>
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<tr>
<td>Brake</td>
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<tr>
<td>Lubrication</td>
<td></td>
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<tr>
<td>Contacts alignment</td>
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<td>G</td>
<td>G</td>
<td>G</td>
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<tr>
<td>Arcing</td>
<td></td>
<td>M</td>
<td>G</td>
<td>E</td>
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<tr>
<td>Overheating/Coking</td>
<td>G</td>
<td>L</td>
<td>M</td>
<td>E</td>
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<tr>
<td>Contact wear</td>
<td>M</td>
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<td>E</td>
<td>M</td>
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<tr>
<td>Transition</td>
<td>E</td>
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</tr>
</tbody>
</table>

L-Low
M-Moderate
G-Good
E-Excellent
Maintenance Action Catalogue

Maintenance Inspection Tasks

• Thermography
• Main tank and conservator
• Cooling system
• Accessories
• Transformer cabinets
• On-Load Tapchanger
• Buchholz relay operation
Maintenance Action Catalogue
Insulation Drying

The moisture in a transformer is generated by several sources:

• Remaining moisture in insulation during manufacturing
• Humid air from outside during transportation and/or assembling in substation
• Humid air from outside through the breather (non sealed)
• Moisture ingress through gaskets
• Chemical decomposition of cellulose
• Moisture absorption due to exposure during maintenance
• Topping-up of oil level made with humid oil (non dried)
Maintenance Action Catalogue
Risks of Not Drying Insulation

- Accelerated ageing of the transformer insulation
  
  A 1% increase in the moisture content of paper has the same effect as an increase in operating temperature of 8°C (doubling the rate of depolymerisation)

- Moisture in the oil combined with particles reduces the breakdown voltage of the oil and increases the risk of static electrification, partial discharge activity and tracking

- High water content in cellulose increases the risk of bubbling during sudden overload or thermal stress, and the risk of dielectric breakdown

Reference: CIGRE Brochure #349 Moisture Equilibrium and Moisture Migration within Transformer Insulation System

Guide for Transformer maintenance – Tutorial of Cigre WG A2.34
Maintenance Action Catalogue
Drying Techniques

- On-line oil dryers - molecular sieve
- Hot oil circulation
- Hot oil + vacuum / hot oil + vacuum + hot oil spray / hot oil + vacuum + cold trap
- Low frequency heating (LFH) / LFH + hot oil spray
- Vapour phase

The typical time needed to dry a transformer from initial moisture in the solid insulation of 3% to remaining moisture of 1%:

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Hot oil + Vacuum (24 h / day)</th>
<th>LFH + Oil Spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 MVA / 70 kV</td>
<td>8 days</td>
<td>4 days</td>
</tr>
<tr>
<td>400 MVA / 400 kV</td>
<td>20-30 days</td>
<td>9 days</td>
</tr>
</tbody>
</table>
• Reclamation is defined by the IEC as “a process that eliminates or reduces soluble and insoluble polar contaminants from the oil by chemical and physical processing”.

• The contaminants in question are mostly oxidation products predominately in the oil but also on the solid insulation.

• Chemical and physical processing is typically a combination of treatment with a sorbent material and filtering.

• Oil reclamation scenarios: on-site on-line, on site off-line, tank to tank, large scale reclaiming
Oil reclamation treatment is recommended because:

- An increase in oil acidity accelerates paper ageing
- Timely treatment, before advanced degradation, is important if the oil quality is to be maintained.

3 oil treatments used for corrosive sulphur problems:

- Adding metal passivator
- Removal of corrosive sulphur
- Oil exchange

Reference: CIGRE Brochure #378
Copper Sulphide in Transformer Insulation
Work that requires oil to be partially or completely removed from the transformer may be regarded as invasive.

Invasive work requires certain precautions to be taken because the transformer insulation is very sensitive to moisture, trapped air or gas bubbles, and particulate contaminants.

Contaminants may easily be introduced either from airborne dust and humidity, or directly from people, tools and materials entering the transformer.
Planning the Work
Evaluation of the amount of oil required to carry out, if the work required to access into the tank, proper confined space training, plans and permit, plan to reduce the exposure time to minimum, evaluate the ability of the tank to withstand vacuum

Draining the Transformer
Use of dry air to during oil draining, apply a positive pressure if the tank is left empty, avoid any loss of oil into the environment

Access to the Transformer
Extreme cleanliness, continuous flow of dry air entering the tank, suitable safety precautions need to be taken, gaskets replacement, cleaning cloths and boots, be aware of the compatibility of solvents, paints, glues and other chemicals, tools should be tethered and an inventory be kept

Refilling the Transformer
Vacuum filled (if the transformer was originally vacuum filled), air leaks elimination, remove any free water on the tank, use dry oil and use a reconditioning plan, limit the oil flow velocity, winding connected to earth, apply a standing time following oil filling
Outline

Introduction
Maintenance strategy
Maintenance process
Component selection and maintenance
Maintenance action catalogue

Major work – transformer repair
Major Work – Transformer Repair

Definition

On-site repair is invasive work, performed in-situ, where it is necessary to partly or completely drain oil and remove the main covers in order to repair or upgrade the transformer.

The level of expertise and the need for high voltage tests may vary, depending on the complexity of the work.

Repairs are categorized as follows:

- **Minor repairs** such as replacement of bushings or tap changers, repair of connections

- **Major repairs** such as exchange of windings, repair of the core, modifications or upgrades
Major Work – Transformer Repair

Advantages of On-site Repair

On-site repair might have advantages over factory repair:

• Transportation difficult or impossible:  
  *disused railway, axle load limits,*  
  *changed road alignment, bridges,*  
  *roundabouts*

• High transportation costs

• High transportation risks: *poor road conditions,*  
  *heavily aged insulation*

• Reduced down-time by avoiding transportation:  
  *avoid higher losses in the network due to changes in optimum power flow,*  
  *loss of energy sales,*  
  *loss of water in a hydro plant,*  
  *penalty in case of non delivery of energy; time saving 1 - 3 months*
Major Work – Transformer Repair Process

- The process of on-site major repair can with appropriate resources and planning effectively emulate a workshop repair. Some adaptations are needed due to site conditions.

- A detailed plan for each activity will allow adequate time for the equipment and material to arrive at the proper phase of the repair. Planning should be updated daily by the site supervisor and reviewed periodically. Site personnel require regular contact with their service centre or factory for logistical, administrative and technical support.

- On-site repair requires excellent logistics, competent planning as well as the flexibility to adapt to the unforeseen (inherent to most repair situations) in order to minimize delays to the schedule.
Major Work – Transformer Repair Testing

Site testing extends the repair time and represents significant costs. However, these tests will reduce future risk of unexpected failure.

In defining the scope of site testing, the following aspects should be considered:

- Type of repair and scope of work (*replacing bushings, winding replacement*)
- Possible consequences of a failure
- Stress from the network (*lightning, short-circuit, overload*)
- Urgency and loss of production due to downtime
- Repair/refurbishment versus replacement
**Suggested categories of on-site testing:**

<table>
<thead>
<tr>
<th>Transformer Category</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Category 1           | - Nominal Voltage < 72.5 kV  
- Units with no critical loss of production in case of failure, or with good redundancy or a spare unit  
- Limited risk of fire in case of failure (collateral damages)  
- Repair of connections, replacement of bushing or OLTC  
- No expected overload. Good protection system. Low risk of short-circuit on the network  
- Urgency to put the units back in service to meet operation constraints  
- No availability of testing equipment |
| Category 2           | - Nominal Voltage >=72.5kV and < 170 kV  
- Repair involving work on the active part |
| Category 3           | - Nominal Voltage >=170kV and <= 300 kV  
- Transformers with severe consequences in case of failure and/or significant loss of production - generation or industrial applications  
- Transformer with no spare unit |
| Category 4           | - Nominal Voltage > 300 kV  
- Repair that incorporates a new winding design  
- Upgrade with new design to reach higher MVA / Voltage.  
- Transformers with high lightning exposure |
<table>
<thead>
<tr>
<th>Category</th>
<th>Recommended tests</th>
</tr>
</thead>
</table>
| Category 1 | - Low voltage tests: winding resistance, ratio, insulation resistance of windings & core, power factor  
- Functional tests and checks on indicators, control circuits, relays and OLTC  
- Dielectric Response (DR) and Frequency Response Analysis (FRA) as a fingerprint  
- Continuous increase of voltage whenever possible (GSU) without any load: 20%–100% Un  
- Connection to the network with no load at 100% Un for 12 hours with monitoring of gas (preferably on-line or off-line after one hour and then every 3 hours). In any case, the results of DGA should be analyzed before putting the transformer back under load  
- Incremental load rise (whenever possible)  
- Monthly follow-up of DGA over a 6 month period |
| Category 2 | - Same tests as for Category 1  
- Induced voltage tests with partial discharge (PD) measurement according to IEC 60076-3 or IEEE C57.12.00 standard |
| Category 3 | - Same tests as for Category 2  
- In case of delta connected HV windings, separate source AC withstand voltage test (applied voltage test) at 80% of the nominal voltage test according to IEC 60076-3 or IEEE C57.12.00 standard |
| Category 4 | - Same tests as for Category 3  
- Lightning impulse test, switching impulse test and chopped impulse test may be performed; nevertheless, the added value of these has to be evaluated (costs involved, availability of test equipments) |
Major Work – Transformer Repair Economics

Factors to consider:
- Costs of material and labour
- Core and winding losses
- Transportation
- Outage time
- Reliability and Tests

Case Examples:
- Problematic transportation
- Problematic outage time
- Repair of a faulted unit with core repair and windings replacement
Major Work – Transformer Repair

Environmental Considerations

![Life Cycle Inventory Analysis (LCI) Diagram]

- Material Extraction
- Assembly
- Transport
- Operating
- Deposit
- Recycle

IN (Raw material, Fuel etc.)

OUT (CO₂, SOₓ, etc.)

Classification & Characterization

Life Cycle Impact Assessment (LCIA)

- Global Warming
- Air Pollution
- Human Toxicity
- Resource Consumption
- etc.

Grouping & Weighting

Damage Value

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