WPO-112-1
Factors to Consider in Risk Assessment & Life Extension of Power Transformers
Ed teNyenhuis – ABB TRES Canada
Abstract - Much attention is rightly focused on reliability risks from the aging fleet of power transformers and on the enormous cost in both dollars and time to replace them. But many factors beyond age place a transformer at risk of failure. This workshop considers the main contributing factors, their likelihood of impact on a particular unit and steps that can be taken to extend their life within a limited budget.
Your safety is important to us
Please be aware of these emergency procedures

- In the event of an emergency please dial ext. 55555 from any house phone. Do not dial 9-1-1.
- In the event of an alarm, please proceed carefully to the nearest exit. Emergency exits are clearly marked throughout the hotel and convention center.
- Use the stairwells to evacuate the building and do not attempt to use the elevators.
- Hotel associates will be located throughout the public space to assist in directing guests toward the closest exit.
- Any guest requiring assistance during an evacuation should dial “0” from any house phone and notify the operator of their location.
- Do not re-enter the building until advised by hotel personnel or an “all clear” announcement is made.
Your safety is important to us
Convention Center exits in case of an emergency

Know your surroundings:
- Identify the meeting room your workshop is being held in
- Locate the nearest exit
Agenda

- Failure Statistics
- Risk of failure
- Life Extension
- Case Study / Examples
- Q & A
Transformer Failure Rate
Some statistics

- Industry failure rate has been around 2 to 2.5%
  - Higher for units with LTC’s
  - Higher for increasing kV
- Source of the failures
  - 43% winding insulation
  - 16% load tap changers
  - 19% bushings
  - 22% other
  - (Reference = Doble)
- Average age in the industry is close to 40 years
Overall Risk Assessment

Input Data

Rules

R₁

R₂

Rₙ

Risk Categories

- Mechanical Risk
- Thermal Risk
- Dielectric Risk
- Accessory Risk
- Miscellaneous Risk

Weights:

Wₘₐₛₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐ$_{MRF}$

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Wₜₜₜₜₜₜₜₜₜₜₜₜₜₜₜₜₜ$_{MBSRF}$

Total Risk of Failure
High Level Transformer Risk of Failure

Stresses Acting on Power Transformers

Mechanical Stresses

- Forces between conductors, leads and windings due to overcurrents or fault currents caused by short circuits and inrush currents

Thermal Stresses

- Due to local overheating, overload currents and leakage fluxes when loading above nameplate ratings; malfunction of cooling equipment

Dielectric Stresses

- Due to system overvoltages, transient impulse conditions or switching transients
Mechanical Risk Aspect

- Winding failure due to through fault is common type of failures
  - Can be the result of a single throughfault or the cumulative effect of many throughfault or inrush events

- Risks for short circuit failure:
  - Transformer design (strength of the windings)
  - Type of blocking
  - Dielectric and thermal condition of the windings
  - Reclosing practice
  - Average number of through-faults experienced by the transformer in a given year
Thermal Risk Aspect

- An important factor in the risk of a mechanical failure is the condition of the paper insulation.
- Thermal risk conditions:
  - Hot cellulose
  - Hot metal
  - Hot cellulose + metal
- Typical influential factors are:
  - Temperature
  - Age of the transformer insulation
  - Relative compositions of produced carbon oxides
  - Oxygen & moisture in the oil
  - Hydrocarbon gases
  - Load profile
  - Cooling equipment – present condition
  - Hot spots in metallic materials such as core or current carrying contacts (determined from DGA)
- End of life cellulose does not necessarily mean high risk of failure.
For long insulation life expectancy, it is important to keep the insulation dry, keep acidity and oxygen concentration of oil low and provide good cooling.

It is assumed that the DP of transformer insulation is approx. 1,000 at the start of life and approx. 200 at the end of life. This graph shows the expected life of thermally upgraded insulation (Insuldur) under various conditions.
### Dissolved Gas Analysis Evaluation - Characteristic Gases

<table>
<thead>
<tr>
<th>Fault Pattern</th>
<th>Key Gas</th>
<th>Secondary Gases</th>
<th>Possible Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Overheating</td>
<td>CO(_2)/CO (Carbon Oxides)</td>
<td>CH(_4) and C(_2)H(_4) if the fault involves an oil-impregnated structure</td>
<td>Discoloration of paper insulation. Overloading and/or cooling problem. Bad connection in leads or tap changer. Stray current path and/or stray magnetic flux.</td>
</tr>
<tr>
<td>Oil Overheating</td>
<td>C(_2)H(_4) (Ethylene)</td>
<td>CH(_4) and smaller quantities of H(_2) and C(_2)H(_6). Traces of C(_2)H(_2) if fault is severe or involves electrical contacts.</td>
<td>Metal discoloration. Paper insulation destroyed. Oil heavily carbonized.</td>
</tr>
<tr>
<td>Arcing</td>
<td>C(_2)H(_2) (Acetylene)</td>
<td>H(_2), and minor quantities of CH(_4), C(_2)H(_4)</td>
<td>Metal fusion, (poor contacts in tap changer or lead connections). Weakened insulation from ageing and electrical stress. Carbonized oil. Paper destruction if it is in the arc path or is overheated.</td>
</tr>
</tbody>
</table>
Dissolved Gas Analysis
Typical Problems Diagnosed

- Overloaded transformers
- Overheating caused by problems with cooling systems
- Local overheating caused by blocked oil duct inside the transformer
- Overheating due to oil circulating pump problems (bearing wear, impeller loose or worn)
- Overheating due to circulating stray currents in the core, structure, and/or tank
- An unintentional core ground may cause heating by providing a path for stray currents.
- Bad connections in the leads or by a poor contact in the tap changer can cause a hotspot
- Discharges of static electrical charges that build up on shields or core and structures that are not properly grounded may cause hotspots that produce gassing
- Hotspots that may be caused by electrical arcing between windings and ground, between windings of different potential, or in areas of different potential on the same winding, due to deteriorated or damaged insulation
- Windings and insulation that may be damaged by faults downstream (through faults), causing large current surges through the windings
- Voltage surges caused by nearby lightning strike or switching surge or closing out of step may result in immediate arcing or arcing that develops later
- Aged insulation that may be damaged by a voltage surge. When this happens, clearances and dielectric strength are reduced. Partial discharges and arcing may develop during a through fault and cause total mechanical and electrical failure
- High noise level (hum due to loose windings) can generate gas due to heat from friction
## Advanced Diagnostics for Power Transformers

### Decisive factors/Side information

<table>
<thead>
<tr>
<th>Production of gases</th>
<th>Application, load profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Age</td>
</tr>
<tr>
<td>Temperature</td>
<td>Design</td>
</tr>
<tr>
<td>Oxygen concentration</td>
<td>Normal/abnormal events</td>
</tr>
<tr>
<td>Single/multiple analyses</td>
<td></td>
</tr>
<tr>
<td>Mass and volume</td>
<td></td>
</tr>
<tr>
<td><em>Oil type</em></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spurious signals</th>
<th>Tapchanger-leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not relevant gases</td>
<td>(rusting, chemical reactions, previous gassing, etc..)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loss of gases</th>
<th>Loss through conservator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open or Closed conservator</td>
</tr>
<tr>
<td></td>
<td>Load profile</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other aspects</th>
<th>Accuracy of analysis (do not mix data from different labs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>“Burn-in”</td>
</tr>
<tr>
<td></td>
<td>“Brothers and sisters”</td>
</tr>
<tr>
<td></td>
<td>Reason for analysis and previous history</td>
</tr>
<tr>
<td></td>
<td>Normal behaviour</td>
</tr>
</tbody>
</table>

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Electrical Risk Aspect

- Involves both design and condition issues
- Elements involved:
  - Inherent design dielectric strength
  - Testing done on the unit (impulse level, switching surge done?)
  - Location (near lightning prone areas)
  - Design of the over voltage protection (arrestor type)
  - Dissipation factor (\(\tan \delta\), power factor) of the insulation
  - Oil quality results
  - The amount and distribution of dissolved gases in oil
  - Wind farms (tend to have higher rate)
Risk Calculation – Accessory Risk Aspects

- Accessory failure refers to the loss of service of the transformer due to either the failure or operational breakdown of an accessory:
  - oil coolant pumps
  - tap changers
  - bushings

- The risk of accessory failure is based on:
  - Type of accessory, and
  - Diagnostic evidence from DGA, dissipation factor (tan δ) results, or other analyses.
Risk Calculation - Random Risk Aspects

- External causes not associated with the design or condition of the transformer itself
- Takes into account other types of failure risks not accounted for in the other factors
- Examples
  - Location (i.e. near seismic zone)
  - Static electrification risk (due to the design type, potential high oil velocity, and/or cooling operation philosophy)
  - Type of transformer
Condition Data Assessment

- The history of the following condition data is reviewed:
  - Dissolved Gas in oil Analysis (DGA)
  - Oil Quality (including moisture in cellulose)
  - Furans
  - Power Factor
- Increasing trends and abnormalities are explored
Routine Electrical Testing

- Ratio
- Winding Resistance
- Winding Power factor
- Insulation resistance (meggar)
- Bushing power factor
- Excitation test
Thermal Stresses in Power Transformers

Thermography

- Thermography is a method of inspecting electrical and mechanical equipment by obtaining heat distribution pictures.
- Most components in a system show an increase in temperature when malfunctioning.
- By observing the heat patterns in operational system components, infrared thermography can be used to detect:
  - loose connections
  - unbalanced load and overload conditions
  - component deterioration
  - Oil flow and oil level problems

Criteria for Evaluating Infrared Measurements

- Faults are often identified by comparing heat patterns in similar components operating under similar loads.
- The temperature rises of all objects above a reference point are recorded.
- Severity of hotspots are evaluated in regards to how high they are above the reference temperature.
Thermal Stresses in Power Transformers
Thermal Scans are Valuable
Thermal Scan Value
Example – Loose Bushing Terminal Connection

- When there is a loose connection at the terminal from the bushing to the bus work, it will lead to overheating of the bushing top terminal when under load.
- The thermograph will show the bushing terminal as hot, while the body of the porcelain will show normal temperatures.
Thermal Scan Value
Example – Blocked Oil Flow in Radiators

- In case of a malfunction that stops or restricts the flow of oil through a radiator, this will show up on an infrared scan.
- The image will reveal dim areas where the oil flow is restricted and brighter areas where normal oil flow is taking place.
Overall Risk Assessment
Risk Profile
Importance vs. Probability of Failure

Probability of Failure (%/Year)

Relative Importance

- Urgent Risk
- Priority Risk
- Normal Risk
Typical On-Site Services to Improve Reliability

- Engineering Assessments (MTMP™)
- Diagnostic Testing
- Site internal repairs/upgrades
- Bushing Replacement
- Unit Uprates / Cooling Systems
- Oil processing

- Control system upgrade
- Internal Inspections
- Conservator tank modifications
- Tap Changer Maintenance/Replacement
- Biodegradable fluid retro fills
- Transformer Dryouts
Engineering Transformer Design Study

- Leakage flux calculation

- Temperature calculation of windings & metal parts
  - Determine aging rate and remaining life in cellulose

- Short Circuit Force Calculation

- Dielectric Plots

- Condition Assessment – Maintenance and field measurement aspects

- Life Assessment - Overall Ranking

- Recommendations
# Temperature Calculation

<table>
<thead>
<tr>
<th></th>
<th>Calculated °C</th>
<th>Allowed °C</th>
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<tbody>
<tr>
<td>Average oil rise</td>
<td>42.2</td>
<td>65</td>
</tr>
<tr>
<td>Top oil rise</td>
<td>46.2</td>
<td>65</td>
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</table>

## Regulator

<table>
<thead>
<tr>
<th>Common Winding</th>
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<tbody>
<tr>
<td>Average Rise</td>
<td>62</td>
<td>65</td>
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<tr>
<td>Hot Spot Rise</td>
<td>72</td>
<td>80</td>
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<tr>
<td>Coil Lead Rise</td>
<td>68</td>
<td>80</td>
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<tr>
<td>Cable Rise</td>
<td>58</td>
<td>80</td>
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<table>
<thead>
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<th>Series Winding</th>
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<tr>
<td>Average Rise</td>
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<td>65</td>
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<td>Hot Spot Rise</td>
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<td>80</td>
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<tr>
<td>Coil Lead Rise</td>
<td>71</td>
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<tr>
<td>Cable Rise</td>
<td>68</td>
<td>80</td>
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<th>Tap Winding</th>
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<td>62</td>
<td>65</td>
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<tr>
<td>Hot Spot Rise</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Coil Lead Rise</td>
<td>62</td>
<td>80</td>
</tr>
<tr>
<td>Cable Rise</td>
<td>75</td>
<td>80</td>
</tr>
</tbody>
</table>

| Outer Core Steel Rise Due to Stray Flux | 77 | 100 |
| Core Hot Spot Rise              | 90  | 100 |
| Tie Plate Rise                  | 90  | 100 |
| Core Clamp Rise                 | 75  | 100 |
| Tank Rise (at Regulator)        | 71  | 100 |
Advanced Diagnostic Testing

- PD / Acoustics
- On site induce/PD testing
- SFRA Measurements
- Dielectric Spectroscopy
Frequency Response Analysis (FRA)

Frequency Response Analysis (FRA) is used to verify the geometry of the active part in a transformer (deformation and/or displacement of windings and core).

Example of problems diagnosed:
- Axial Winding Collapse - excessive axial forces during a fault
- Hoop Buckling - excessive compressive forces during a fault
- Shorted Turns - produced by turn-to-turn faults

Interpretation tools:
- Comparison with a reference data from the same unit or results from similar units
- Utilization of own library and experts knowledge
Dielectric Frequency Response (DFR)

The Dielectric Frequency Response test (DFR) provides more information about the dielectric behavior of the insulation system (properties of cellulose and oil insulation separately distinguished). The test consists of a series of power factor or $\tan \delta$ measurements at multiple frequencies.

Example of problems diagnosed:

- Moisture in the cellulose insulation
- High oil conductivity due to aging or overheating
- Contamination of windings
- Core grounding problems

Interpretation tools:

- ABB’s DFR analysis tool (software)
- Comparison with a reference data from the same unit
- Utilization of own library and experts knowledge
Oil Reprocessing

- Acids can be removed from oil to renew the oil
- Use oil rig with fullers earth type system (modern systems are regenerative)
- On line oil processing does a better job removing the acids
- Replacement of oil may need to be done if oil is too degraded
Transformer with FPE Tap changer
Old FPE Tapchanger Removed
New Tank Assembly Being Installed
Transformer with RMV II Tap changer – After retrofit
Load Tap Changer Condition Improvements
Sampling of Tap Changer Retrofit Projects

- Westinghouse URT → UVT
- Federal Pacific TC-25 → UVT
- W URT-HC → Reinhausen RMV-I
- GE LRT → Westinghouse UVT
- Ferranti Packard RT → UVT
- Westinghouse URT → RMV-II
- Moloney MC → Reinhausen RMV-I
- FP TC-25 → Reinhausen RMT-I
- FP LR-525 → Reinhausen RMT-I
- GE LRT-500 → Reinhausen M (in-tank)
- Westinghouse URH → Reinhausen M
- Westinghouse UNR → RMV-II
- GE LR-83 → Reinhausen RMV-II
- Installation of Westinghouse UVT to non-LTC transformer
Transformer Field Dryouts

Purpose for Drying

- Cause of moisture in transformers
  - Is a natural byproduct of aging (function of temperature, oxygen & moisture)
  - Leak (bad gasket) or defect
  - Free breathing of the transformer
    - (On site internal repairs requiring exposure of the unit)
- Deteriorates the electrical & mechanical strength of the windings
- Increases aging rate of the cellulose
- Limits the overload capability
  - Possible to get free water (if a wet unit is rapidly cooled down – winter shutdown)
  - Risk of bubble formation in the insulation at much lower hot spot temperatures (i.e. 140 °C) compared to dry insulation
Low Frequency Heating (LFH) Principles

- Apply a low frequency (1 - 50 mHz) current to the HV windings – approximately 20 – 50% of nominal current
- Benefits of the low frequency
  - Much lower impedance voltage so there is no risk of a flashover
  - Negligible eddy (~$f^2$) or stray losses (~$f^{1.5}$) – thus uniform heating of the windings
  - Reduced power requirement
- Temperature of the windings is carefully controlled
- Apply oil spray during LFH heating to heat non winding insulation
- LFH typical process:
  - Initial heating/circulation of core/coils using hot oil (assisted by LFH)
  - Vacuum
  - Begin cycles of LFH heating with hot oil spray followed by vacuum
  - Temperature progresses up to 110C (winding temp)
  - Final vacuum
- Shorter overall process time compared to hot oil treatment
LFH And Hot Oil Spray

- Vacuum control valve
- Short circuit LV.
- HV.
- LFH Converter
- Oil treatment plant
- Vacuum pumps
Field Dryout Example
BIOTEMP® is a superior dielectric insulating fluid combining...

- 99% biodegradability with non hazardous and non toxic waste
- High fire point, i.e., 360 °C vs. 180 °C for mineral oil
- Much greater ability to hold moisture, i.e., 10 times more than mineral oil

- Highest oxidation stability for a vegetable-based insulating fluid, outperforming the competition in all standard oxidation stability tests currently available

With BIOTEMP®, ABB aims at offering a complete and sustainable solution for both distribution and power transformer applications associating environmental friendliness (high biodegradability), safety (superior fire resistance), reliability and efficiency (high overload capacity)
Reminders
Automation & Power World 2011

- Please be sure to complete the workshop evaluation

- Professional Development Hours (PDHs) and Continuing Education Credits (CEUs):
  - You will receive a link via e-mail to print certificates for all the workshops you have attended during Automation & Power World 2011.
  - BE SURE YOU HAVE YOUR BADGE SCANNED for each workshop you attend. If you do not have your badge scanned you will not be able to obtain PDHs or CEUs.