Assessing Water Content in solid transformer insulation from dynamic measurement of moisture in oil

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Moisture in insulation

In transformer, there is several sources of moisture:

Residual moisture from manufacturing process: Good drying process should result in less than 0.5% moisture in paper

Leaks: Gasket and/or joints could leak

Insufficient maintenance: To be effective, Silica gel system needs constant maintenance, any lapse could result in large amount of moisture into the transformer
Moisture in insulation

In transformer, there is several sources of moisture:

- Paper degradation: The thermal degradation of paper does generate water
- This water will generate yet more paper degradation
- Moisture is strongly absorbed by paper, once inside the transformer, it is difficult to remove.
Moisture in insulation

- Moisture in oil
  • Can lead to water condensation

- Moisture in winding paper is critical
  • Reduces dielectric strength
  • Increased risk of bubbling at high load
  • Accelerates the rate of insulation aging

- Moisture in pressboard barrier is critical
  • Reduces dielectric strength

- Only moisture in oil can be measured
Paper is found in many forms in winding insulation

Cross-sectional view of a 400 kV transformer end insulation (220 kV-side)
Deterioration of oil and cellulose

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Paper consist of fibers

Paper structure

Paper fibre

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Fibers are built from micro fibers - which consist of cellulose molecules

Micro and submicrofibers

Cellulose molecule

DP – Value

Average number of rings in the cellulose molecule chain

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Where does water come from?

COMPOSITION OF PAPER
- - - - - - - Cellulose - - - - - - -

Glucose
Where does water come from?

Glucose
Where does water come from?
Where does water come from?
Where does water come from?

80 °C - 300 °C
Where does water come from?
Where does water come from?
Where does water go?
The water will also degrade the paper.

HOH (water)

Acids

CH$_2$OH

OH

OH

O

CH$_2$OH

OH

OH

O

HOH  (water)
Impact of moisture in oil

Over saturation of oil when WCO > saturation

V. Davydov, EPRI Moisture Management in Transformer Workshop, Nov.2002, Edison, New Jersey
Impact of moisture in oil

**Sensors**

- Sensor Relative Humidity (RH%): 5%
- Sensor Temperature (°C): 75°C

**Water-in-oil saturation curve**

- Water content (ppm)
- Temperature (°C)

**Output**

- Absolute water content in oil (ppm): 20ppm
- Condensation temperature (°C): 10°C
Change in water-in-oil concentration

Water content in oil varies with Temperature
Most of the water is stored in the solid insulation

Insulation Weight Distribution

Water Distribution
Example of water distribution in a 25 MVA transformer with 3% moisture in paper

<table>
<thead>
<tr>
<th></th>
<th>40°C</th>
<th>80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil (25 000 litre)</td>
<td>10 ppm 0.25 kg</td>
<td>80 ppm 2.0 kg</td>
</tr>
<tr>
<td>Paper (2500 kg)</td>
<td>3% 75 kg</td>
<td>2.93% 73.25 kg</td>
</tr>
<tr>
<td>Total</td>
<td>75.25 kg</td>
<td>75.25 kg</td>
</tr>
</tbody>
</table>

• Most of the water is in the solid insulation
• Change in water content of oil does not entail a similar change in the water content of paper
Paper Aging

• Definition, End of life criteria
• Contributing factors

Insulation aging is irreversible
Moisture content in transformer insulation is a persistent concern

Aging transformers tend to build-up moisture

IEEE Std 62 – 1995:

- Dry 0-2%
- Wet 2-4%
- Very Wet 4.5% +

Only moisture in oil can actually be measured
Impact of moisture in paper

The amount of moisture in paper is a very important parameter to know, as it directly affects the following:

- Aging rate of the winding insulation
- Bubbling temperature (limits the amount of overloading of a transformer)
- Dielectric strength of the barriers at the bottom of the winding
Water accelerates ageing of Kraft paper

![Graph showing the impact of water content and temperature on the life expectancy of Kraft paper](image-url)
Oxygen accelerates ageing of paper

- Presence of oxygen has, in laboratory experiments, shown an ageing acceleration by a factor 2-3.
- Above 2000 ppm O₂ showed concentration independent ageing rates.
- Oxygen saturated 30 000 ppm O₂
- Oxygen free 300 ppm O₂

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Example of Winding Paper Degradation

Example of treeing in a wet pressboard barrier

V. Davydov, EPRI moisture Seminar Nov. 2002

Example excessive paper aging
Evolution of fault at weak points

The weak points are candidates for a possible failure

V. Sokolov Cigre Colloquium 1997
Impact of moisture in winding insulation

- Increased risk of releasing bubbles at high load

Residual water in winding insulation can release water vapor bubbles at high temperature.

T.V. Oommen et al, Atlanta, 2001

Impact of moisture in winding insulation

- Increased risk of releasing bubbles at high load
Example of Overheating

Trapped Bubbles

Bubble Emission

V. Davydov EPRI Moisture Seminar 2002
Moisture reduces dielectric strength of pressboard barriers.
Moisture can promote tracking discharges on pressboard barriers.

Surface discharges are more likely on angle rings.

Wet Barriers = Strong Discharges

Alstom T&D, Merida, 2003
Assessing Water Content in Transformer Solid insulation

Two problems:

- Oil saturation curve need to be known
- Transformer must be under thermal stability condition
Determination of water in solid insulation from water in oil

The problem:

- Should we use absolute water content in oil (ppm) or Relative Saturation (RS)?
- Is water content uniform through the transformer solid insulation?
- How do we handle the diffusion time between paper and oil?
Oil saturation characteristics

- Water content in oil can be expressed in ppm
- This value must be related to oil saturation characteristics
- But saturation characteristic vary with type of oil and oil condition
- Therefore it is more convenient to consider Relative Saturation (RS)
Relative Saturation (RS)

- Relative saturation is the moisture content relative to the saturation value at a given temperature.
- At equilibrium, RS in oil = RS in paper.
- It varies within the transformer.
- Example:
  - Sensor: 40°C, RS = 50%
  - Hot spot: 85°C, RS = 10%
Moisture Migration Summary

- Equilibrium curve exist to relate moisture in paper to relative saturation in oil.
- These curves assume Equilibrium exists (the moisture has stopped moving between the oil and paper)
- But this is never the case.
- Many people make errors in using these charts, ‘blindly’ without considering equilibrium conditions which must exist, and their mistakes can be costly
Assessing Water Content in Transformer Solid insulation
Moisture in paper

Equilibrium curves are now available to convert moisture in oil into moisture in paper without considering oil saturation characteristics.

But we still need:
- Temperature of oil-paper interface
- Diffusion time constant
- Facility for integrating results over long period of time
Moisture Migration Summary

- Paper at different temperatures inside the transformer will will have different moisture levels
- Different areas of the insulation system have different thickness (winding insulation versus barrier insulation)
- The Equilibrium condition therefore will take much longer for barrier insulation versus winding insulation
Typical diffusion time constant (in days)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>1mm</th>
<th>2mm</th>
<th>4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 °C</td>
<td>0.9</td>
<td>3.6</td>
<td>14</td>
</tr>
<tr>
<td>60 °C</td>
<td>4.2</td>
<td>17</td>
<td>67</td>
</tr>
<tr>
<td>40 °C</td>
<td>20</td>
<td>79</td>
<td>317</td>
</tr>
<tr>
<td>20 °C</td>
<td>93</td>
<td>373</td>
<td>1493</td>
</tr>
</tbody>
</table>
Moisture in paper varies within the transformer

Guided convection flow through disk windings

Temperature (°C)

Oil
Winding

Moisture content (%) at equilibrium condition

Area of Interest for moisture in paper

1.2% 1.7 2.2 3.3%

Winding insulation Thin barriers
Migration of moisture in transformers

- Moisture content in solid insulation, is not a single value
- It appears impractical to assess the moisture content of the thick insulation
- Lowest part of pressboard barriers is the most critical location and should determine needs for drying
- Sensitivity analysis indicates that the value assigned to diffusion time constant is not critical
Migration of moisture in transformers

- There is a correlation between the amount of water in the oil and in the paper.

- However, this correlation is dynamic and is changing as a function of transformer loading.

- The dynamics of the distribution of water in the transformer is quite complex and changing.
Moisture inside the transformer moves back and forth between the oil and paper by diffusion as a function of temperature.

- Moisture level: 84 ppm
- Moisture level: 32 ppm
What to do?
Hydran M2

Advanced Gas and Moisture monitor

- H2 and CO
- Moisture in oil
- Trending
- 4 analog inputs
- Data Logging
- Networking
- Integrated Modem/TCP-IP
Typical HYDRAN M2 Installation
The Hydran M2 as Advanced Transformer Monitor

- Incipient Fault
- Apparent Power
- Winding Hot Spot
- OLTC Fault
- Cooling Efficiency

- Moisture in Oil, in Windings and in Barriers
- Cooling Status and tracking
- Aging Rate
- Bubbling Margin
- Cumulative aging

Hydran M2
With
Models
Temperature and Load

Top oil

OLTC

Magnetically Mounted Temperature sensor

Ambient Temperature Sensor

Clip-On load sensor
Field experience with on-line moisture monitoring

**US Western Utility**

50MVA, Core type, 230 / 13.8 kV
55°C rise

Hydran M2 mounted on spare cooler outlet
Field data recording for moisture assessment - 50 MVA transformer

Graph showing:
- Temperature, RH%
- Top-oil Temp.
- Sensor Temp.
- Load
- RH% at Sensor
Moisture content in winding insulation - 50 MVA transformer
Moisture content in pressboard barrier - 50 MVA transformer
Moisture and Bubbling Model

- Water condensation temperature
- Winding bubbling temperature
- Bubbling temperature margin, alarm point
- Absolute water content in oil
Moisture and Bubbling Model
HYDRAN M2– Communications, real time survey
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding Hot-Spot Temperature in Winding H</td>
<td>53.2 C</td>
</tr>
<tr>
<td>Calculated Top Oil Temperature</td>
<td>46.1 L</td>
</tr>
<tr>
<td>Calculated Top Oil Difference</td>
<td>-2.2 C</td>
</tr>
<tr>
<td>Cooling Efficiency Index</td>
<td>4.5 C</td>
</tr>
<tr>
<td>Calculated Bottom Oil Temperature</td>
<td>20.1 L</td>
</tr>
<tr>
<td>Thermal Aging Acceleration Factor</td>
<td>0.061</td>
</tr>
<tr>
<td>Moisture Aging Acceleration Factor</td>
<td>1.23</td>
</tr>
<tr>
<td>Global Aging Acceleration Factor</td>
<td>0.065</td>
</tr>
<tr>
<td>Cumulative Aging</td>
<td>2177 Day</td>
</tr>
<tr>
<td>Service Time</td>
<td>00:27:27</td>
</tr>
<tr>
<td>Current Type of Cooling</td>
<td>ONAF</td>
</tr>
<tr>
<td>Cooling Stage 0 Total Activity Time</td>
<td>4653 Hr</td>
</tr>
<tr>
<td>Cooling Bank 1 Total Activity Time</td>
<td>1721 Hr</td>
</tr>
<tr>
<td>Cooling Bank 2 Total Activity Time</td>
<td>63 Hr</td>
</tr>
<tr>
<td>Cooling Bank 1 Feedback Status</td>
<td>On</td>
</tr>
<tr>
<td>Cooling Bank 2 Feedback Status</td>
<td>False</td>
</tr>
<tr>
<td>Load</td>
<td>40.4 MVA</td>
</tr>
<tr>
<td>Water Level</td>
<td>10.4 psi</td>
</tr>
<tr>
<td>Moisture Content in Winding Paper</td>
<td>0.00 %</td>
</tr>
<tr>
<td>Moisture Content in Winding Paper Valid Delay</td>
<td>03/08/06 07:53:37</td>
</tr>
<tr>
<td>Moisture Content in Insulating Barrier</td>
<td>13.3 %</td>
</tr>
<tr>
<td>Moisture Content in Insulating Barrier Valid Delay</td>
<td>03/08/06 12:00:00</td>
</tr>
<tr>
<td>Apparent Power from H Winding</td>
<td>40.4 MVA</td>
</tr>
</tbody>
</table>
How degraded is my insulation?
Detection of paper degradation

CO$_2$ / CO

- **CO$_2$/CO ratios** $< 3$ indicate fault involving paper degradation
- **CO$_2$** can also come from atmosphere in open breathing transformers
- **CO** can come from oil oxidation, paint, varnishes and phenolic resins
Several furanic compounds are generated during paper decomposition. 2FAL is the most stable and most abundant compound.
Detection of paper degradation from furanic compounds

Increasing furanic compound content correlate with falling DP

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Reduction of DP with time

Example of DP reduction with time for:
- Kraft paper
- 3% water content
- 110°C

Note that rate of DP reduction reduces with time; aging is not a linear function.
Mechanical strength is reduces with DP

- Mechanical strength is a function of length of cellulose chains in fibres
- Degree of polymerisation (DP) in cellulose fibres describes ageing condition
- DP of 200 correspond to remaining strength of about 30%

Cigre Publication 323, Oct. 2007
DEGRADATION OF PAPER

CORRELATION BETWEEN 2-FAL and DPV

DEGREE OF POLYMERISATION

2-FURALDEHYDE (ppb, microg/L)

Residual Life

0% 25% 50% 75% 100%
In Conclusion

- As temperature and load change, so does the movement of water inside the transformer, between the paper and the oil
- In Practice, the perfect equilibrium needed to use the published curves almost never exist in a transformer
- Only a dynamic model, computed online in real time, can make a good evaluation of the amount of moisture in the paper, in the areas of interest
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