TLM

Moisture Content Assessment in Power Transformers using Frequency Domain Spectroscopy

Mohammad Tariq
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Moisture in Power Transformers

- How to Estimate and What to Do?

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Content

- The effects of water in a transformer
- How does water get into a transformer
- How can we measure moisture
- Interpretation and guidelines for moisture
- What can we do about it

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Moisture Content Assessment in Power Transformers using Frequency Domain Spectroscopy

Water is one of the worst enemies of a transformer.

- A transformer with low moisture content is like a person in good condition
  - A transformer can be used at high load without risk for catastrophic failure.
  - A person can work hard without risk for heart attack
- A wet transformer is like an overweight person in bad condition
  - The transformer owner has to limit load to avoid bubbling (may lead to catastrophic failure)
  - Moisture in insulation increases the rate of aging
  - The person can not run the marathon...
- Water/moisture and (high) temperature will sooner or later kill the transformer

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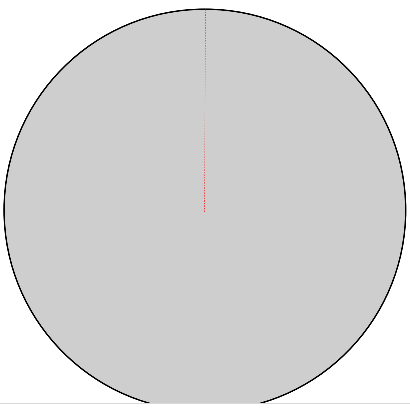
Where is the water?

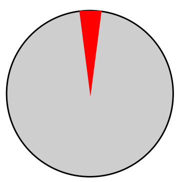
- The insulation in a power transformer consists of oil impregnated cellulose and oil.
  - 60 tons of oil with water content of 20 ppm = 1.2 liter
  - 10 tons of cellulose with 3% water content = 300 liter
- Almost all water is in the cellulose!

20ppm (parts per million) in 60 tons of oil



Typical values for a 300 MVA power transformer at 50 C

3% water in 10 tons of cellulose



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Water effects the transformer performance

- Loading capability
  - Limits the loading capability due to decreased bubbling inception temperature
- Dielectric strength
  - Decreases the dielectric strength of the oil and decreases PD inception voltage
- Aging
  - High temperature and moisture will dramatically accelerate aging that lowers the mechanical strength of the cellulose insulation

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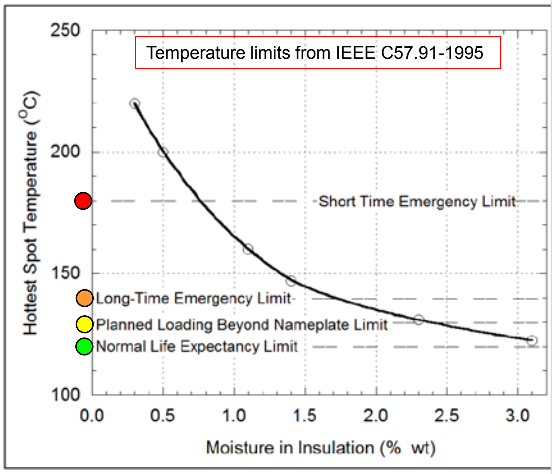
High moisture limits the loading capability

- Moisture determines the maximum loading/hot-spot temperature for bubble inception
- Knowing moisture content and oil quality allows for correct decision on maximum loading
  - Leave as-is
  - Dry-out/re-generate oil
  - Replace/Relocate
  - Scrap



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G. K. Frimpong et al, "Estimation of Moisture in Cellulose and Oil Quality of Transformer Insulation using Dielectric Response Measurements", Doble Client Conference,

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Life of a transformer – Moisture and aging

- During manufacturing, the cellulose insulation in the transformer is carefully dried out before it is impregnated with oil
- The moisture content in the solid insulation of a new transformer is typically targeted to be < 0.5% by weight
- As the transformer gets older, the moisture content will increase
  - Open-breathing transformers, typically around 0.2%/year
  - Sealed conservator transformers, typically around 0.05%/year
- In an old and/or severely deteriorated transformer, the moisture content can be > 4%
- The aging process of the insulation is directly related to moisture content

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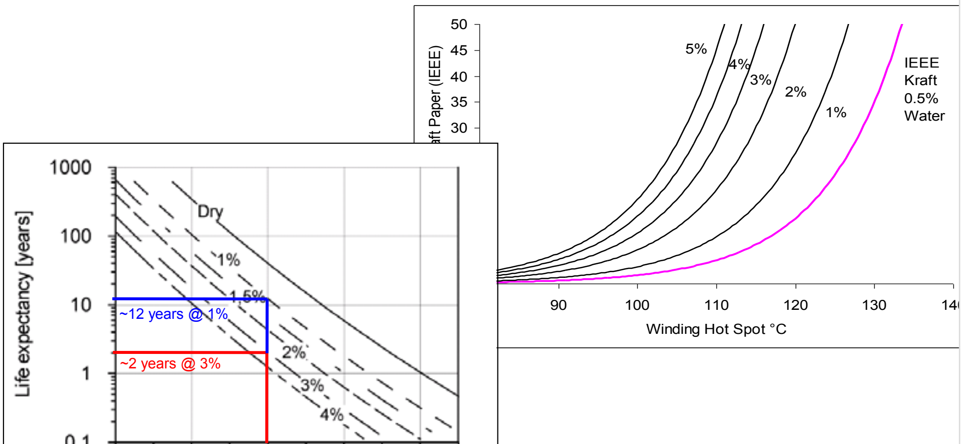
Moisture accelerates aging



Left: *Lars E. Lundgaard, Walter Hansen, Dag Linhjell, Terence J. Painter, "Ageing of oil-impregnated paper in power transformers"*, IEEE PWRD, 2003

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Where does the water come from?

- Leaking gaskets and faulty water traps may expose the inside of the transformer to moisture humid air
- Exposure to humid air during site installation/commissioning
- Exposure to humid air during maintenance
- Normal aging of cellulose produces water
- Insufficient drying at manufacturing

- Typical moisture content in paper/pressboard:
  - New transformer: < 1%
  - Aged transformer: 2 - 4%
- Normal increase of water content is typically 0.05-0.2%/year

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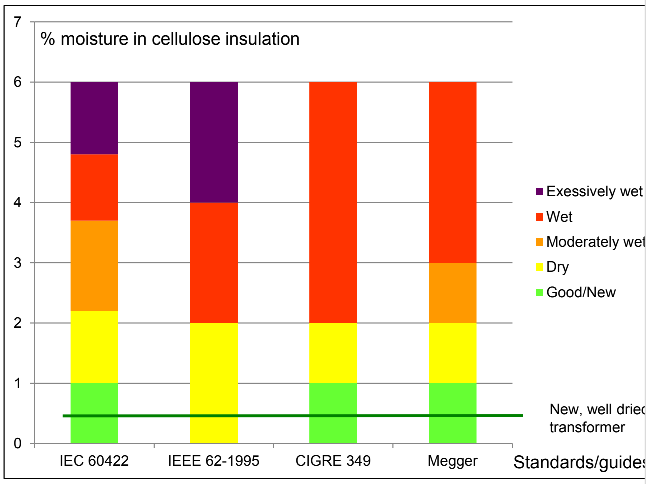
Interpretation of moisture content by various standards and guides

- "Good/New"
- "Dry"
- "Moderately wet"
- "Wet"
- "Excessively wet"



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Moisture levels in practice...

1.0 % ☺

2.6 % ?

4.2 % ☹

Recommended approximate percent by weight of water in solid insulation (IEEE C57.106-2002)

- < 69 kV, 3% maximum
- > 69 - < 230 kV, 2% maximum
- 230 kV and greater 1.25% maximum

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Methods for moisture estimation in cellulose insulation

- Direct method
  - Take paper sample from transformer and measure moisture content using Karl Fisher titration
- Indirect methods
  - Moisture in oil
    - Absolute values
    - Relative saturation
  - Power frequency tan delta/power factor measurements
  - Dielectric response measurements
    - Return Voltage Measurement (RVM) – DC method
    - Polarization-Depolarization Current measurements (PDC) – DC method
    - Dielectric Frequency Response measurements (DFR/FDS) – AC method

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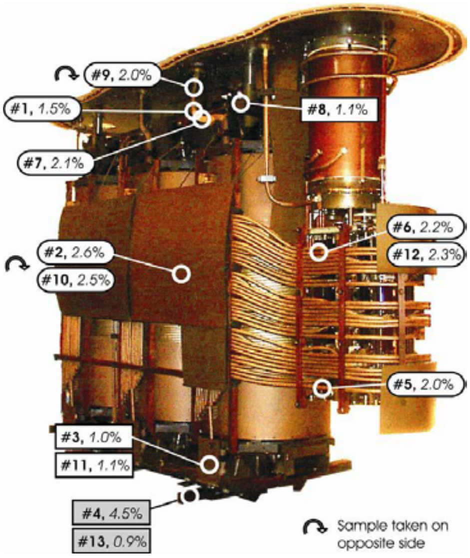
Direct method - KFT on paper samples
– CIGRE brochure 414, 2010

- Only possible during repair or tear-down
- Moisture content in pressboard/paper samples is pending where the sample was located
- Averaging many results is necessary to get a "true" value
- Variations between different laboratories

Not practical as a standard diagnostic method…



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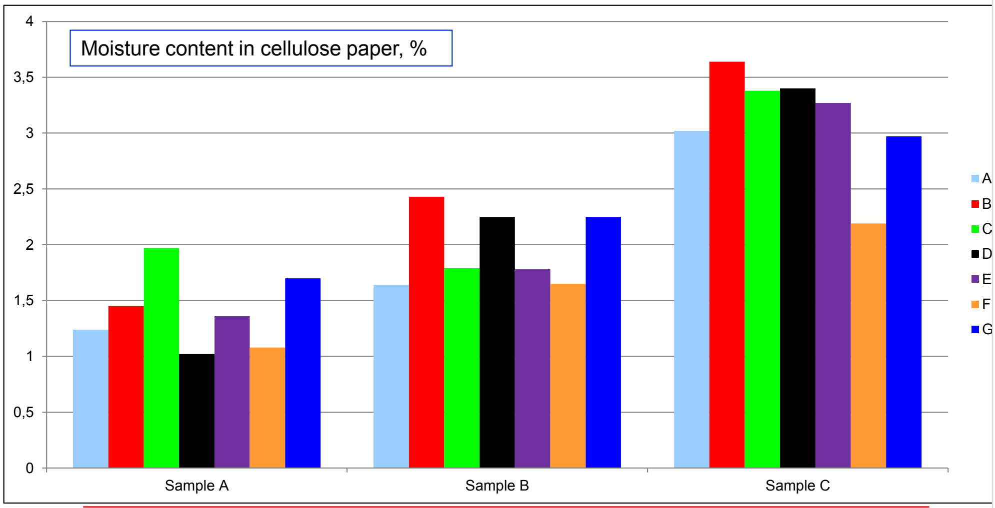
KFT measurements on paper samples
– Laboratory results



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M. Koch, "Creating a Reliable Data Base for Moisture Evaluation of Power Transformers", Pax and KTH Workshop on Variable Frequency Diagnostics, Stockholm, 2007

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Absolute moisture in oil method

1. Oil sampling under service conditions
2. Measurement of water content by Karl Fischer titration
3. Deriving moisture content in paper via equilibrium diagrams

The procedure is easy to perform and very common but affected by substantial potential errors:

- Sampling and transportation of samples
- Large variation in laboratory results
- Diagrams only valid under equilibrium conditions (rarely happens during normal operation)
- Standard diagrams does not cover aged oil and/or cellulose that may have different solubility

The method tend to overestimate moisture in solid insulation…

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Water in oil – Examples of laboratory analysis
– CIGRE Brochure 414, 2010

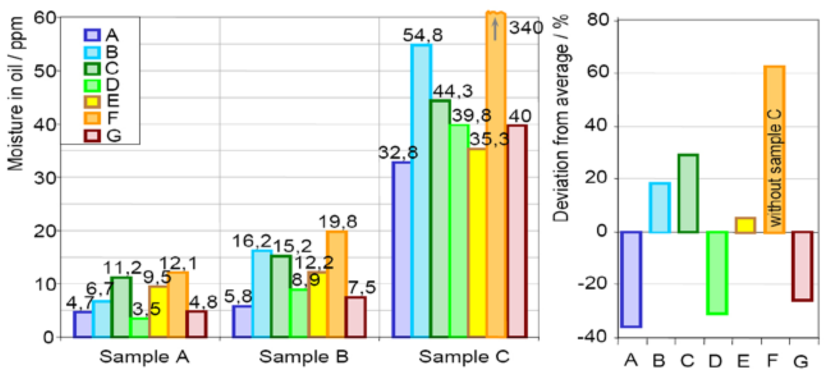

Figure 17: Moisture content in oil in ppm relative to weight as measured by the laboratories (left) and deviation of each laboratory from the average (right)

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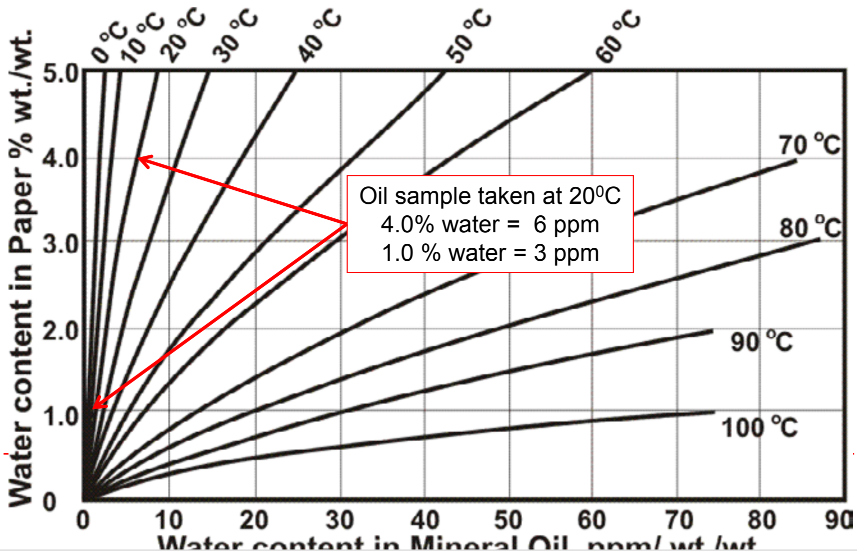
Water In Oil – Equilibrium charts (Oommen)

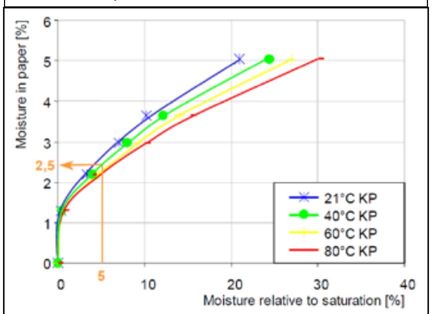
Very difficult to estimate water in paper from oil samples taken at low temperatures!



Moisture saturation measurements (RS)

- Measure relative water saturation (“ppm/solubility”) in oil (%) instead of absolute moisture by weight (ppm)
- More accurate than oil sampling method since no oil handling is involved
- Moisture absorption capacity is less temperature dependent
- Still requires equilibrium and charts are pending material...

Moisture equilibrium chart for Kraft Paper at different temperatures



Water in oil solubility as a function of temperature	
Oil temperature, °C	**Water content in oil, ppm**
0	22
10	36
20	55
30	83
40	121
50	173
60	242
70	331
80	446
90	592
100	772

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Tan delta/power factor measurements

1. Measure tan delta/power factor at actual temperature
2. Convert data to reference temperature (20 C)
3. Compare with guidelines

Guidelines (examples):

- “Tan delta/power factor < 0.5% @ 20C is OK” (IEEE 62-1995)
- “Tan delta/power factor < 1% @ 20C **may** be OK for a service aged transformer” (IEEE 62-1995)
- “Expect tan delta/power factor < 0.3% for a dry transformer” (Doble)

The procedure is easy to perform and very common but is affected by errors and limitations

- Standard temperature correction tables are not accurate for the individual transformer
- Moisture in paper has a low influence on tan delta/power factor at typical measurement temperatures
- Not possible to tell if an increased tan delta value is caused by high moisture in paper or high oil conductivity/dissipation factor

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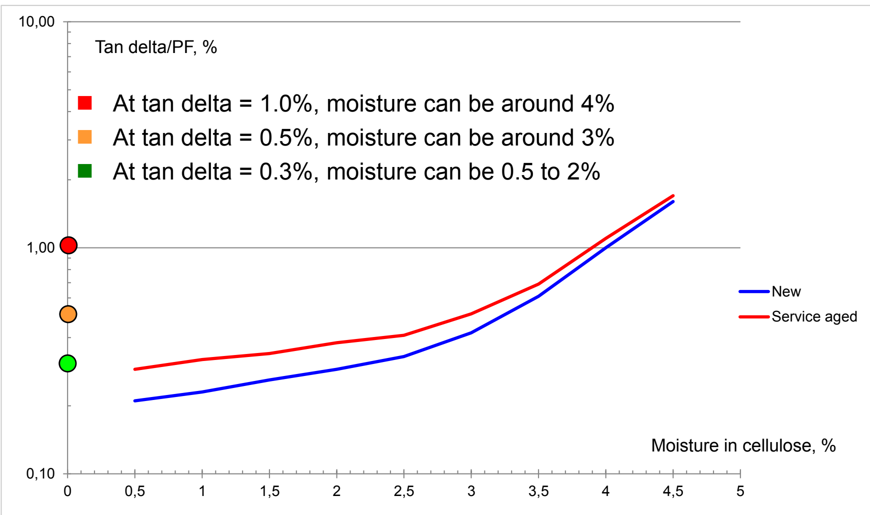
Tan delta (% @ 20C) vs moisture (%) for typical core form new and service aged transformers



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Dielectric Response measurements

- DC methods – Time domain
  - Return Voltage Measurement – Voltage vs time
  - Polarization-Depolarization Current measurement – Current vs time
- AC method – Frequency domain
  - Dielectric Frequency Response measurements – Capacitance and dissipation factor vs frequency

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Methods for DFR measurements

DC (Polarization-Depolarization Current measurements)

- Strength
  - Shorter measurement time at very low frequencies
- Weaknesses
  - More sensitive to AC interference (microamps)
  - More sensitive to DC interference (nanoamps)
  - Limited frequency range (PDC only)
  - Data conversion necessary (combined PDC/DFR only)
  - Discharge before measurement may be needed

AC (Dielectric Frequency Response measurements)

- Strengths
  - Less sensitive to AC interference (milliamps)
  - Less sensitive to DC interference (microamps)
  - Wide frequency range
  - No data conversion
  - No discharge necessary
- Weaknesses
  - Longer measurement time for very low frequencies.

IDAX 5.0 with multi-frequency test signal reduces measurement time with about 40% compared to IDAX 4.x!

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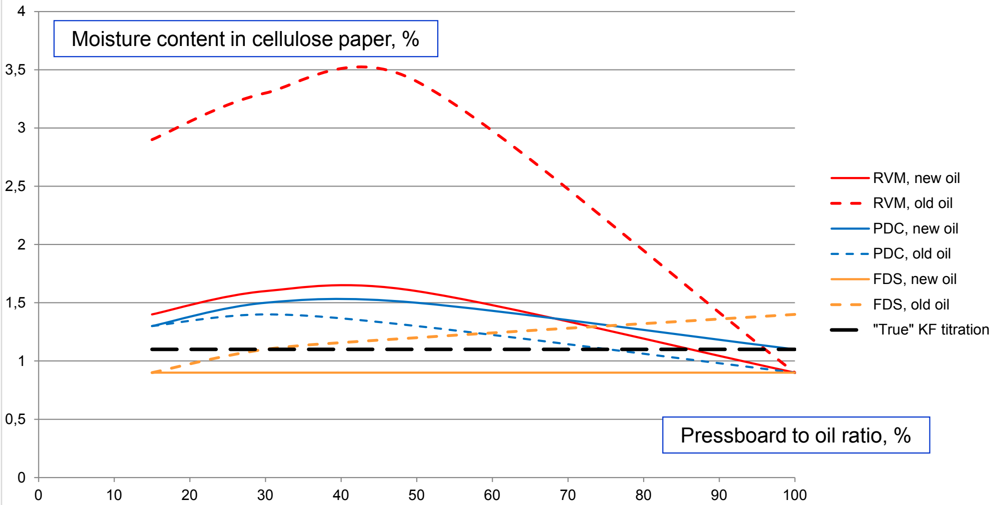
Comparing Dielectric Response measurements
– CIGRE D1-207, 2006



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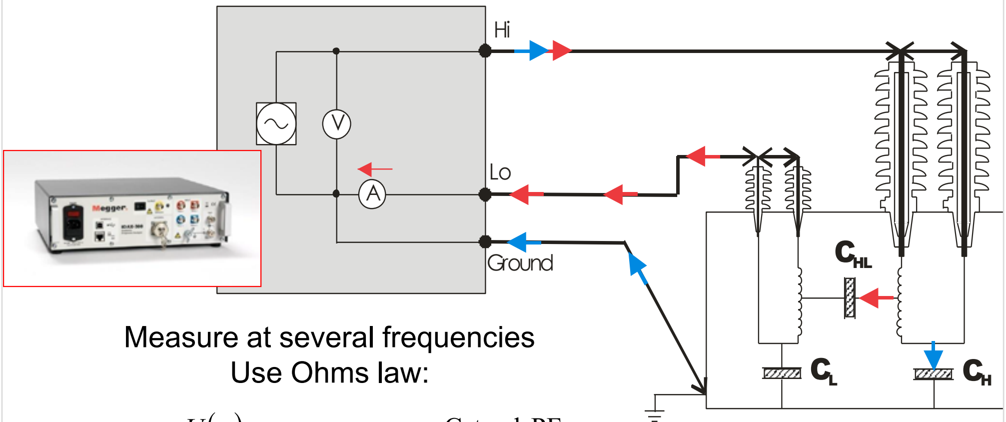
Dielectric Frequency Response Measurements
– Tan delta from mHz to kHz



Measure at several frequencies
Use Ohms law:

$$Z(\omega)=\frac{U(\omega)}{I(\omega)} \qquad Z(\omega) \Rightarrow \begin{array}{c}\text{C, tand, PF} \\ (\varepsilon' \text{ and } \varepsilon'')\end{array}$$

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Recommended frequency range for DFR measurements on oil-paper insulation systems

Insulation temperature, °C	Suggested min frequency, mHz
0-4.9	0.1
5-9.9	0.2
10-19.9	0.5
20-29.9	**1**
30-44.9	2
45-59.9	5
>60	10

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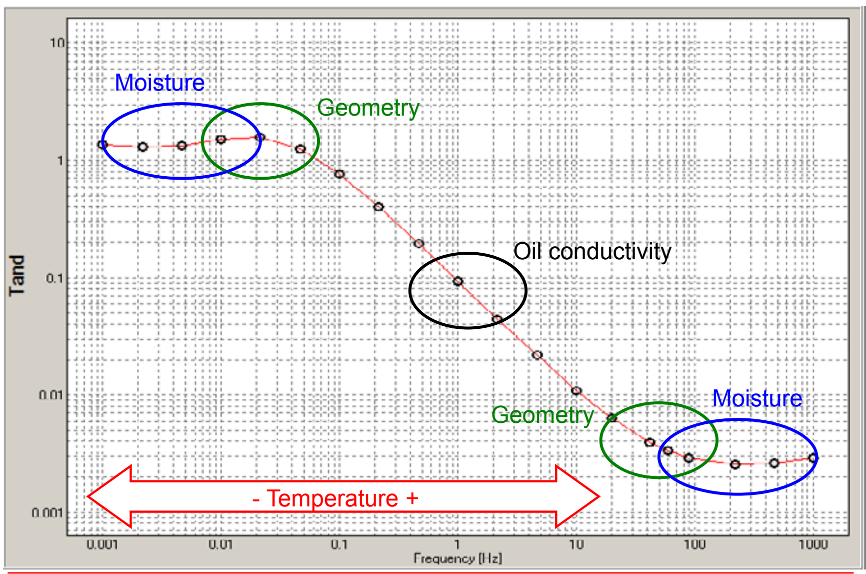
What affects the frequency response?



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FDS/DFR moisture assessment (AC)

- Measure tan delta from 1 kHz to 1 mHz (20 C)
- Analyze results in MODS
- Confirm insulation temperature (winding/top-oil temperature)
- MODS automatically finds best fit between measurement and insulation model by varying parameters that affects the response
- Results:
  - **Moisture in solid insulation**
  - Conductivity/tan delta of the oil
  - Power frequency tan delta/power factor @ measurement temperature
  - Accurate power frequency tan delta/power factor @ reference temperature 20 C
  - Temperature dependence of power frequency tan delta/power factor

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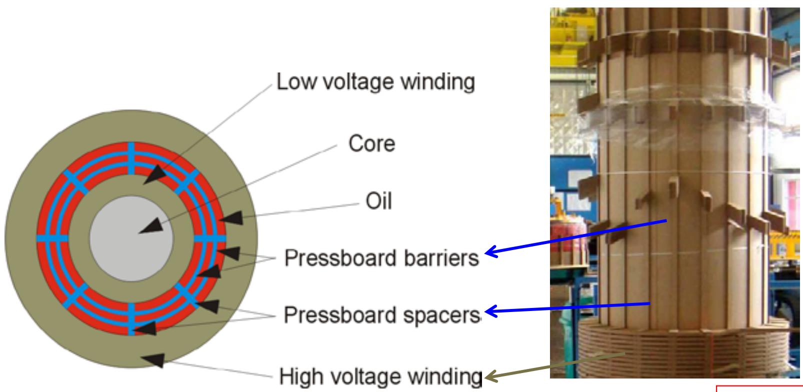
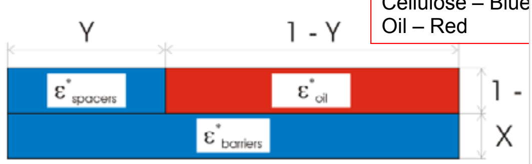
Transformer insulation (capacitor) X-Y modeling



Cellulose – Blue
Oil – Red



Typical values for core form transformer:
X = % barriers in the main duct (15-55%)
Y= % spacers of the circumference (15-25%)

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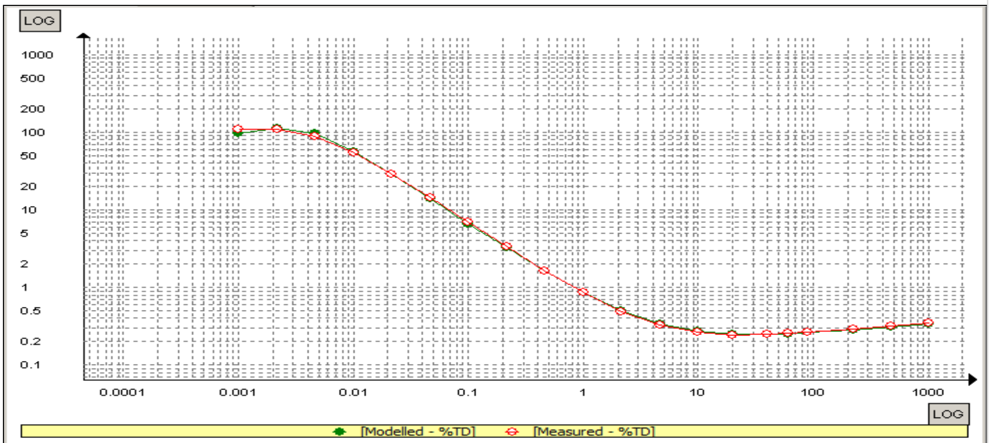
DFR measurement and moisture assessment



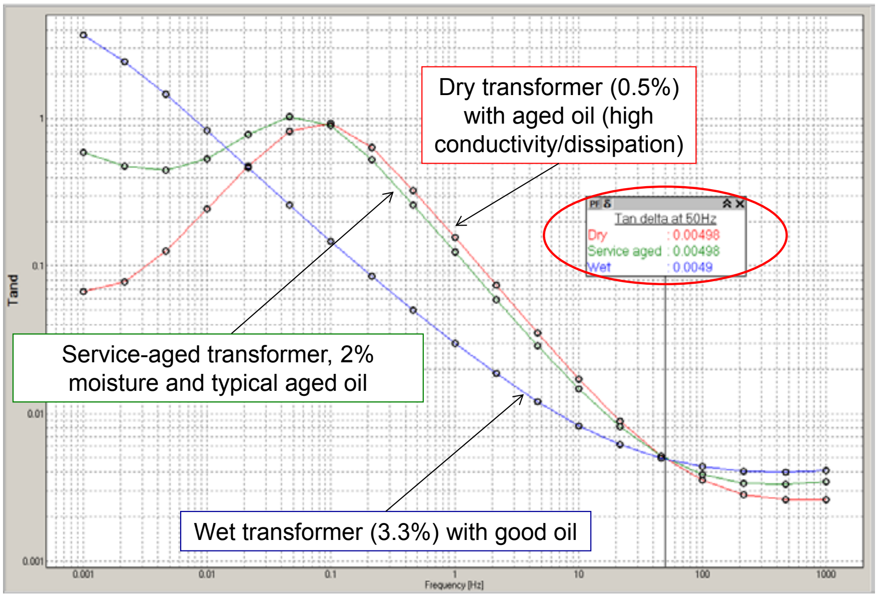
Results @ 50Hz, 24°C

Capacitance (pF)	%TD
6125	0.255

Analysis results

%TD @ 50 Hz & 20°C	Moisture %(wt/wt)	Cond. (pS/m) @ 25°C
0.266	1.0	1.35
< 0.30 % As new	< 1.0 % As new	< 0.37 pS/m As new
0.30 - 0.50 % Good	1.0 - 2.0 % Dry	0.37 - 3.7 pS/m Good
0.50 - 1.0 % Deteriorated	2.0 - 3.0 % Moderately wet	3.7 - 37 pS/m Service aged
> 1.0 % Investigate	> 3.0 % Wet	> 37 pS/m Deteriorated

DFR - Investigating 0.5% tan delta values



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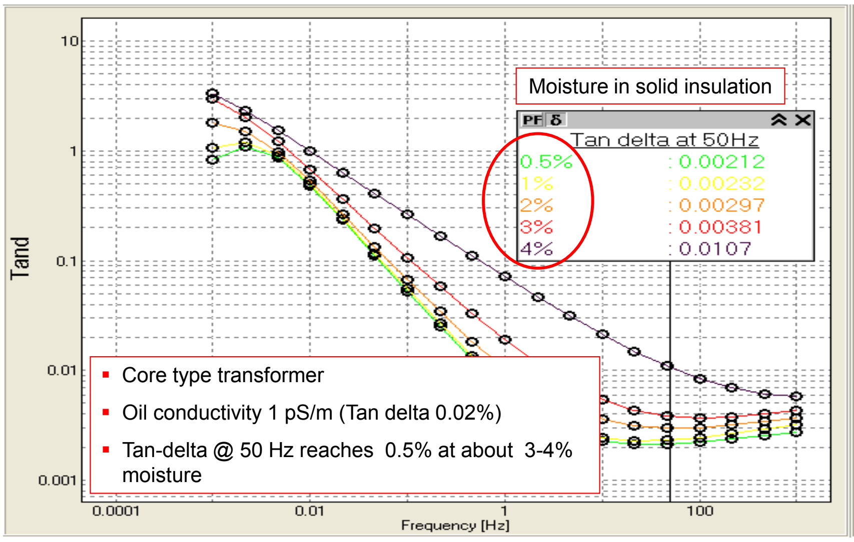
Tan delta vs moisture @ 20 C



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Maintenance based on water in oil analysis…

- Six transformers scheduled for oil regeneration and dehydration based on ppm water in oil data

Transformer	Type	% moisture in insulation (from oil analysis)
1	Core	2.5
2	Core	1.8
3	Core	1.4
4	Core	2.8
5	Shell	*Data not available*
6	Core	3.5
7	Shell	3.3

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"ABB Advanced Diagnostic Testing Services Provide Detailed Results", 2006

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Maintenance based on DFR analysis…

Transformer	Type	% moisture in insulation (from oil analysis)	% moisture in insulation (from DFR)	Oil Cond (pS/m)
1	Core	**2.5**	0.9	0.38
2	Core	**1.8**	0.9	0.49
3	Core	**1.4**	0.9	0.41
4	Core	**2.8**	0.7	1.3
5	Shell	*Data not available*	**1.2**	**1.5**
6	Core	**3.5**	**2**	**3.0**
7	Shell	**3.3**	1	0.30

- Only one or maybe two transformer needed it!

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Transformer drying

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Transformer drying – Methods/Examples

- Two major techniques are used:
  - Drying the insulation by drying the oil – Field
  - Drying the insulation with heat and vacuum – Field and factory
- Drying the oil
  - Molecular sieves
  - Cellulose filters
  - Cold traps
  - Combined oil regeneration and degassing
- Drying the insulation
  - Vacuum and heat
  - Pulsation drying through oil circulation
  - Hot oil spray drying
  - Low frequency heating
  - Vapour phase drying

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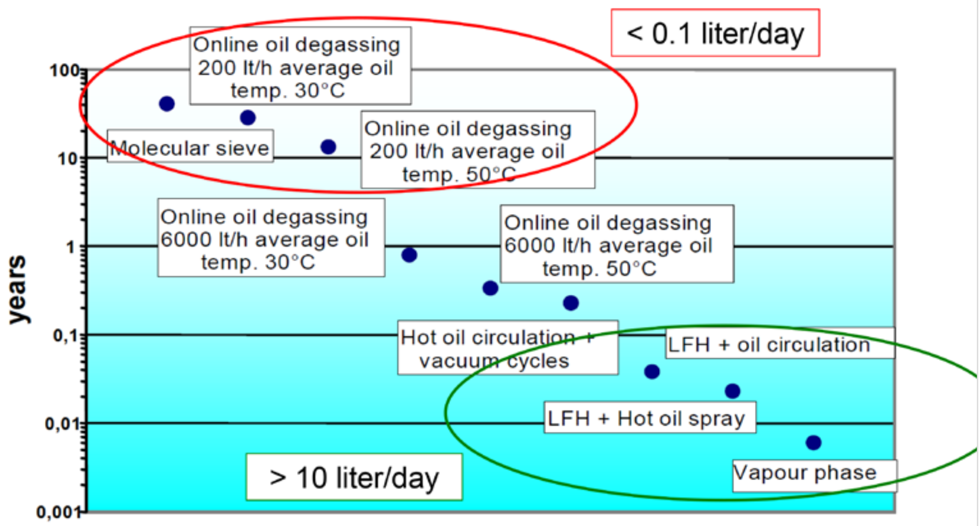
A. Gruber, "Online Treatment of Transformers a... Regeneration of Insulating Oil", TechCon AsiaPacific 2009

Transformer drying – Comparing methods



Drying time to dry a 400MVA transformer with 14 ton insulation from 3% down to 1.5% moisture

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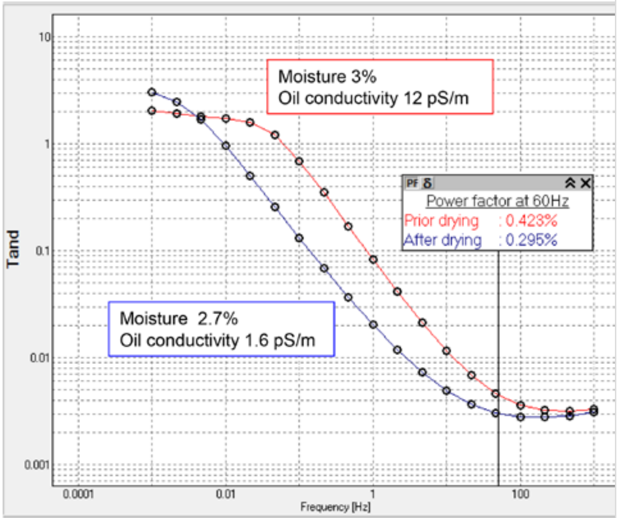
P. Koestinger et al, "Practical Experience With Drying of Power Transformers In the Field, Applying the LFH Technology", CIGRE A2-205 2004

On-line oil regeneration and drying – Example

- 25 MVA manufactured 1972
- 17 days of hot oil circulation with clay filtering (Fuller's earth)
- PF down from 0.4 to 0.3%
- Moisture in cellulose not significantly reduced. 3% before drying and 2.7% after drying
- Degraded oil significantly improved. Conductivity before regeneration 12 pS/m and 1.6 pS/m after filtering



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Poorvi Patel, B. Holmgren, "DFR - A Powerful Tool for Transformer Diagnostics", TechCon AsiaPacific 2009

Summary and conclusions

- Moisture is the worst enemy of the transformer!
  - Limits the loading capability
  - Accelerates the aging process
  - Decreases dielectric strength
- The water/moisture in a transformer resides in the solid insulation, not in the oil
- Dielectric Frequency Response Measurement is a great technique for moisture assessment as it measures:
  - Moisture content in the cellulose insulation
  - Conductivity/dissipation factor of the insulating oil
  - Power frequency tan delta/power factor, accurately temperature corrected to 20 C reference temperature
- Drying a power transformer can take from days to years pending drying process and technology

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