# Using Frequency Domain Spectroscopy to improve Transformer Life Management


## Mohammad Tariq
### Megger


Mohammad Tariq was born 1983 and graduated from University Of Bahrain with distinction on 2005 and joined Megger in early 2006. Currently he is a senior applications engineer with Megger in the field of advanced electrical protection, cable fault location and diagnostics and transformer diagnostics. He was involved in development of relay protection testing software modules and authored several papers , technical notes and application guides.

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## Using Frequency Domain Spectroscopy to improve Transformer Life Management

# 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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## Water in a transformer

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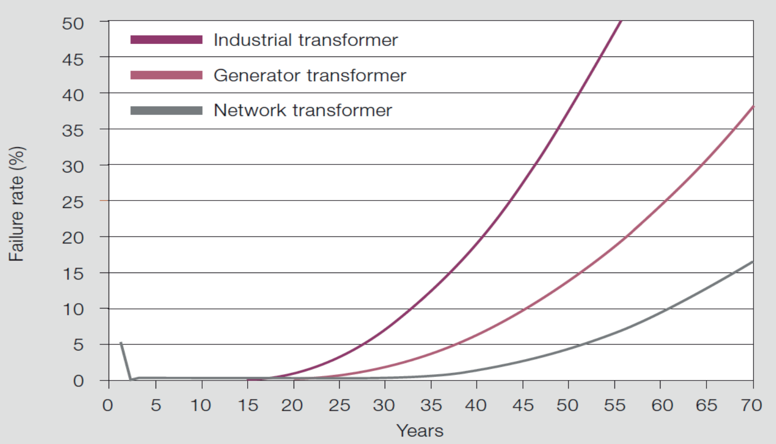
## Transformer failure rates




Source: CIGRE WG 12-05. (1983). An international survey on failures in large power transformers. ELECTRA, 88, 21-48.

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## 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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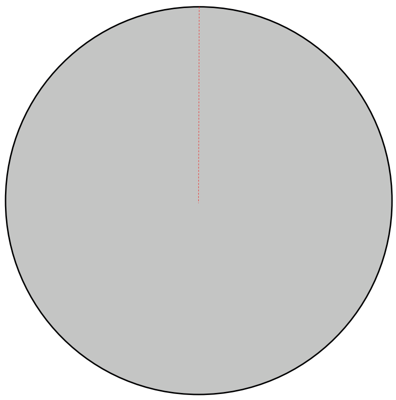
## Where is the water?

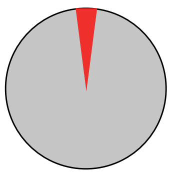
- The insulation in a power transformer consists of oil impregnated cellulose and oil.
  - 60 tons of oil with water content of 20 ppm) = 1.2 liter
  - 10 tons of cellulose with 3% water content = 300 liter
- Almost all water is in the cellulose!

**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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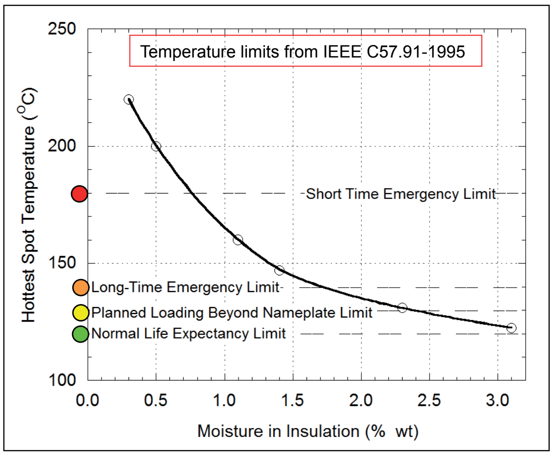
## High moisture limits the loading capability

- 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, Paper 8M, 2001.

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## Life of a transformer – Moisture and aging

- When a transformer is manufactured in the factory, the cellulose insulation is subjected to extended drying before oil impregnation
- After drying, the water content in the pressboard/paper is typically aimed to be < 0.5% by weight
- As the transformer ages, the moisture content will increase progressively
  - 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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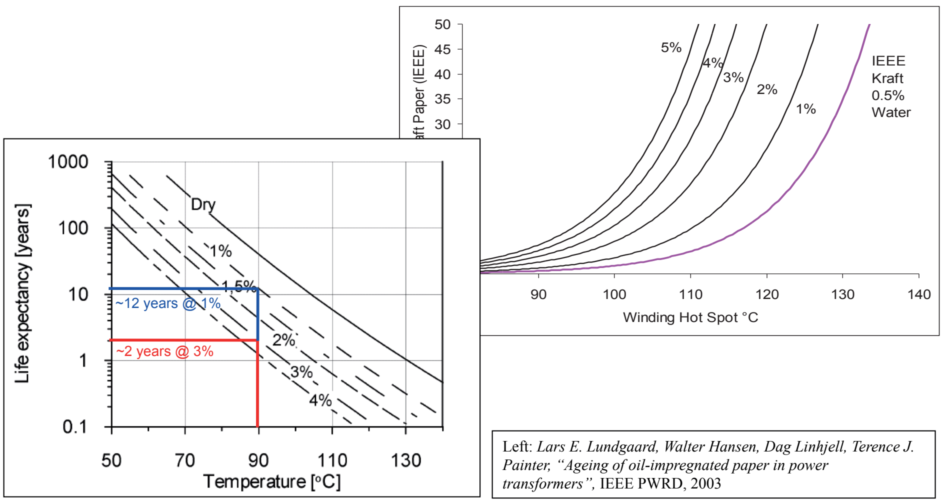
## Moisture accelerates aging




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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## Sources of water

- Leaking gaskets and faulty water traps may expose the inside of the transformer to 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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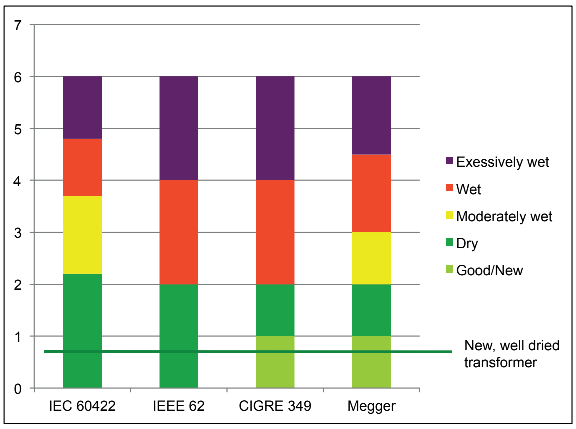
## Interpretation of moisture content by various standards and practices

- < 1% - As new
- 1-2% - Dry
- 2-3% - Moderately wet
- 3-4.5% - Wet
- > 4.5% - Excessively wet

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## Moisture levels in practice...

1.0 % ☺

2.6 % ?

4.2 % ☹

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## Measuring moisture in cellulose insulation

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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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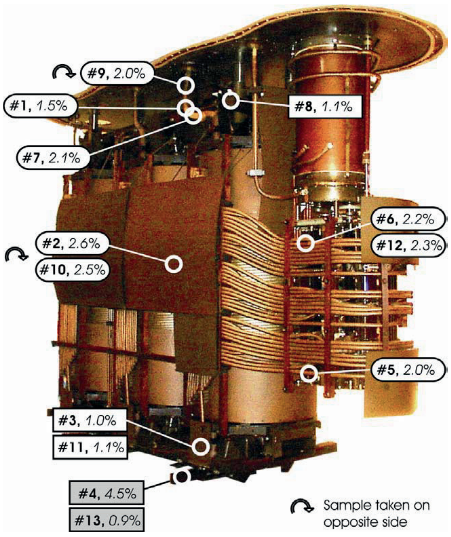
## Direct method - KFT on paper samples

– 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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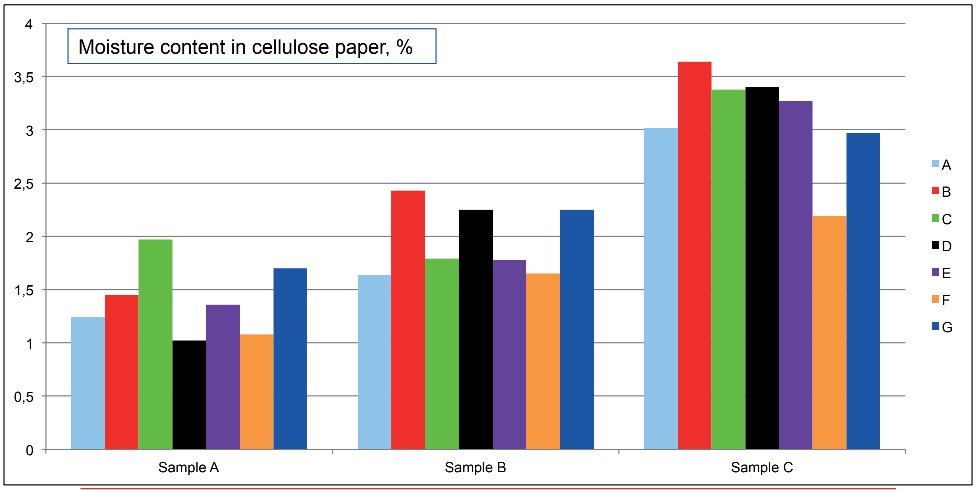
## KFT measurements on paper samples
– Laboratory results




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

## 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

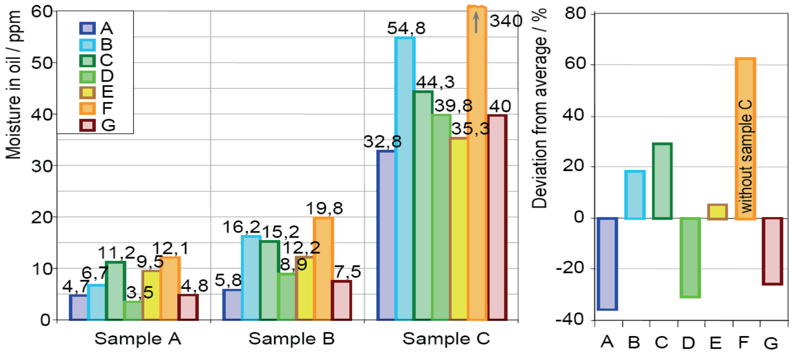


**Figure 17: Moisture content in oil in ppm relative to weight as measured by the laboratories (left) and deviation of each laboratory from the average (right)**

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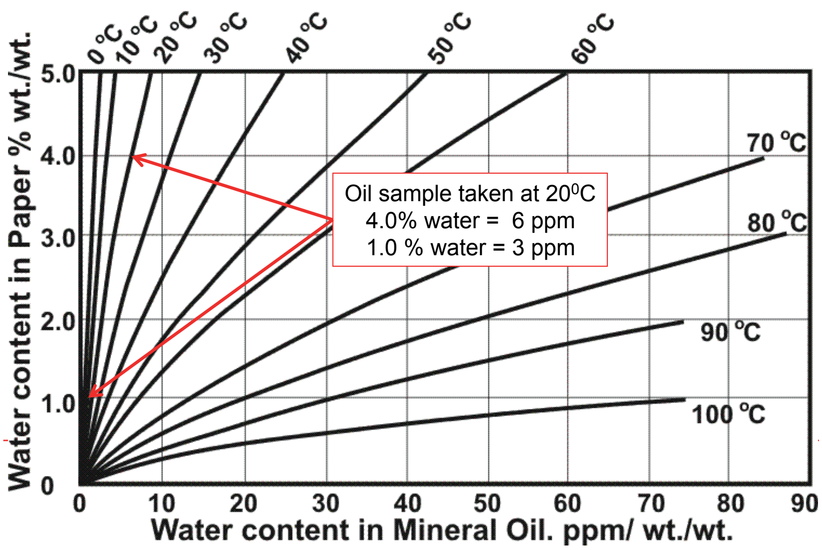
## Water In Oil – Equilibrium charts (Oommen)

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



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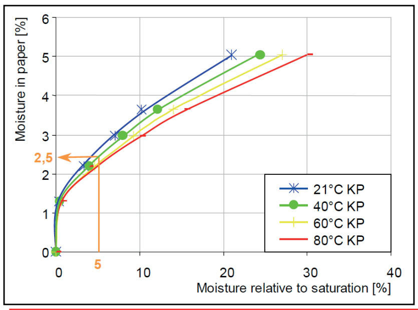
## Moisture saturation measurements

- Uses a special sensor to measure relative 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

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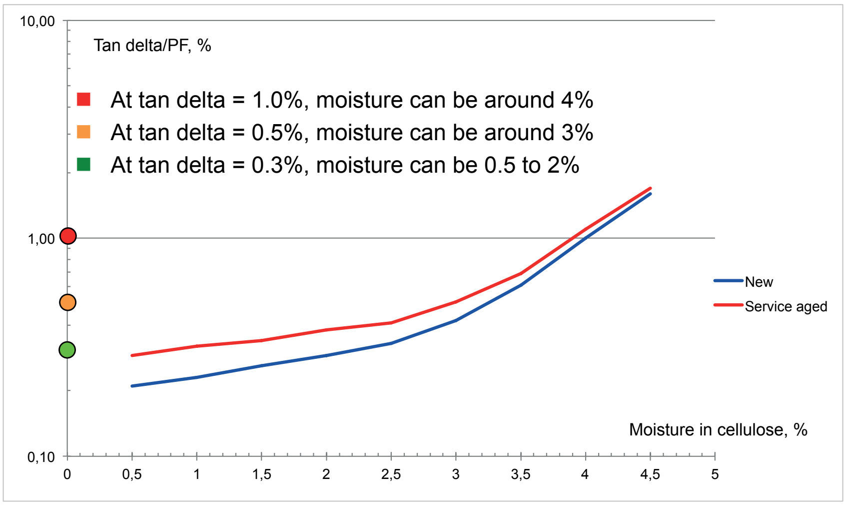
## Tan delta (% @ 20C) vs moisture (%) for typical core form new and service aged transformers

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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 dielectric response measurements

DC (Polarization-Depolarization Current measurements)

- Strength
  - Shorter measurement time for very low frequencies
- Weaknesses
  - Sensitive to AC interference
  - Very sensitive to VLF interference
  - Very sensitive to DC interference
  - Limited frequency range
  - Discharge before measurement may be needed

AC (Dielectric Frequency Response measurements)

- Strengths
  - Not sensitive to AC interference
  - Not sensitive to VLF interference
  - Not sensitive to DC interference
  - Wide frequency range
  - No discharge necessary
- Weakness
  - Longer measurement time for very low frequencies

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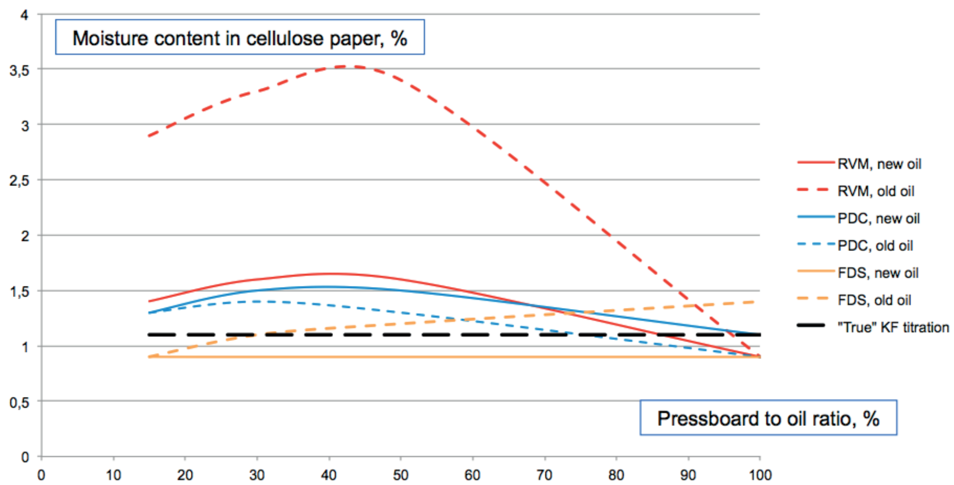
## Comparing Dielectric Response measurements
– CIGRE D1-207, 2006

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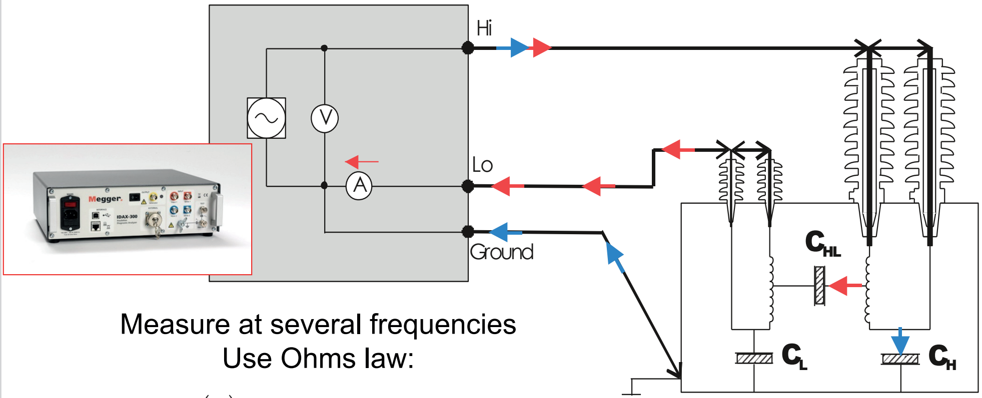
## Dielectric Frequency Response Measurements
– Tan delta from mHz to kHz




Measure at several frequencies
Use Ohms law:

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

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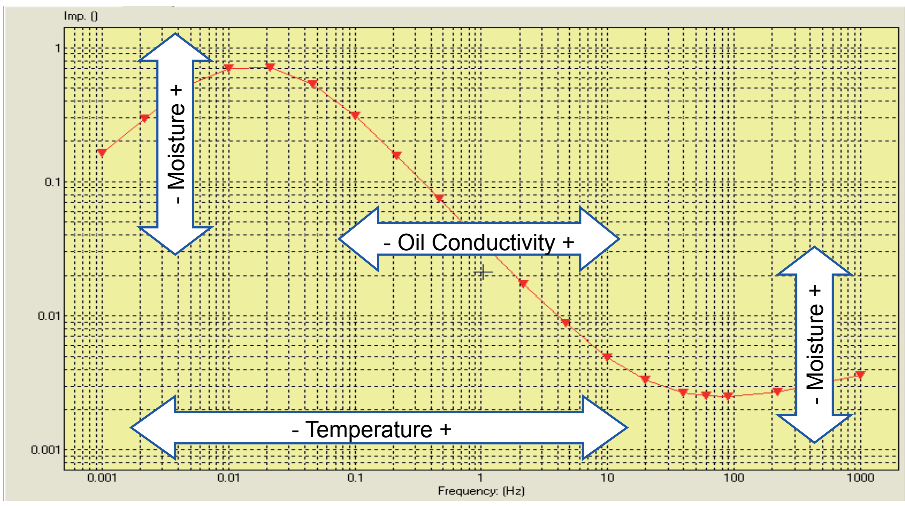
## What affects the frequency response?

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# Using Frequency Domain Spectroscopy to improve Transformer Life Management

## 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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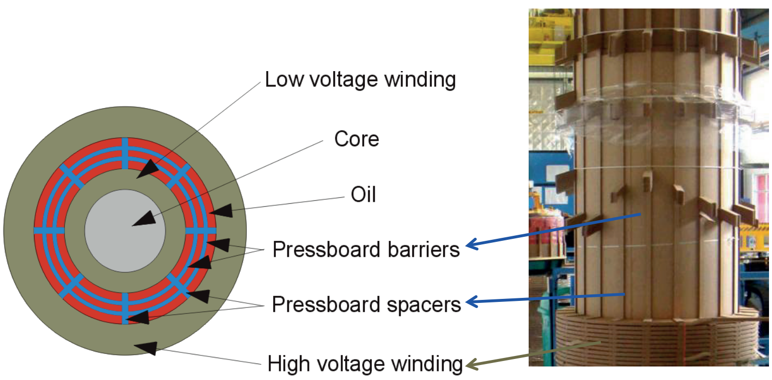
## Transformer insulation (capacitor) X-Y modeling





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

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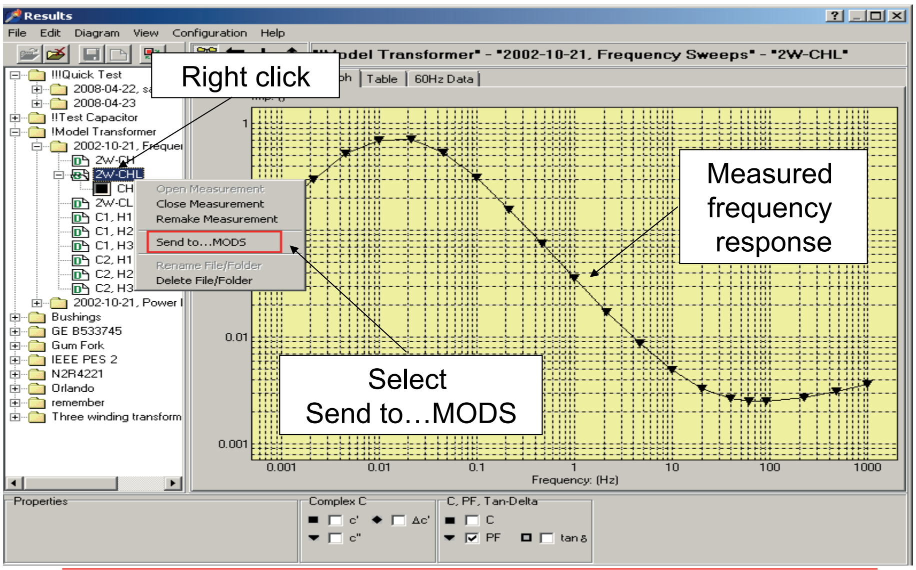
## Moisture estimation process (1-2-3)

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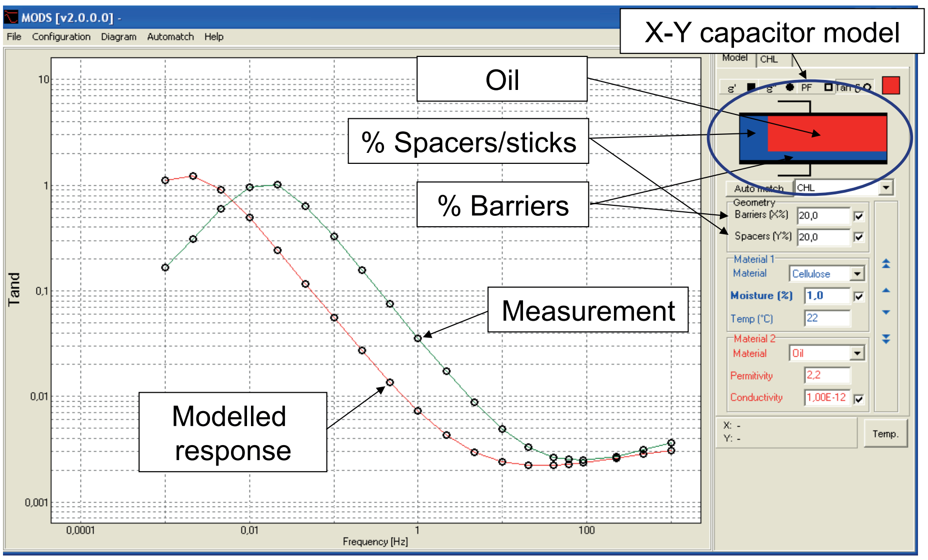
## Moisture estimation process (1-2-3)

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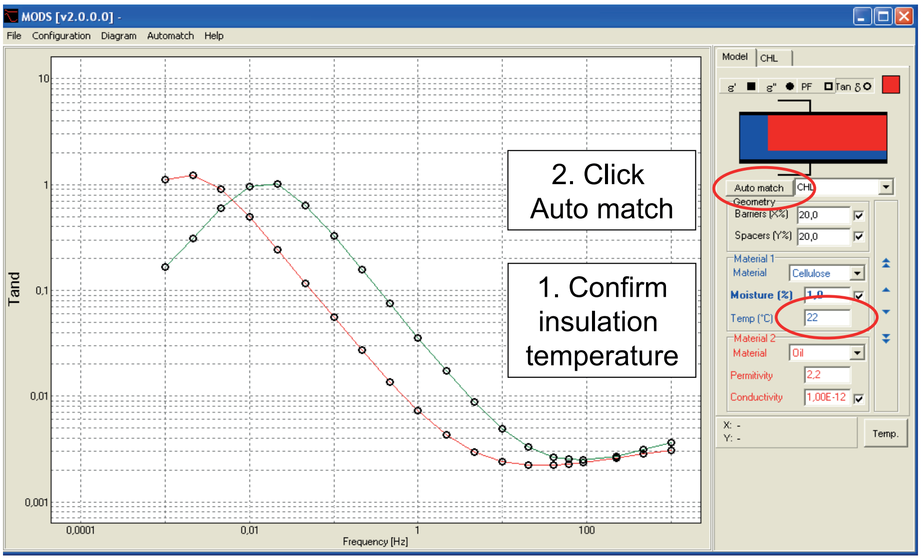
## Moisture estimation process (1-2-3)

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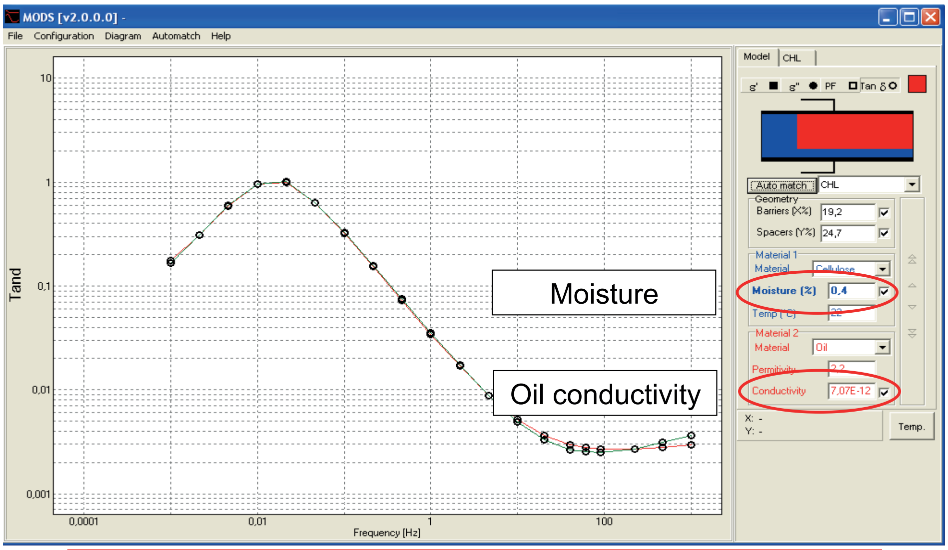
## Moisture estimation process – Results

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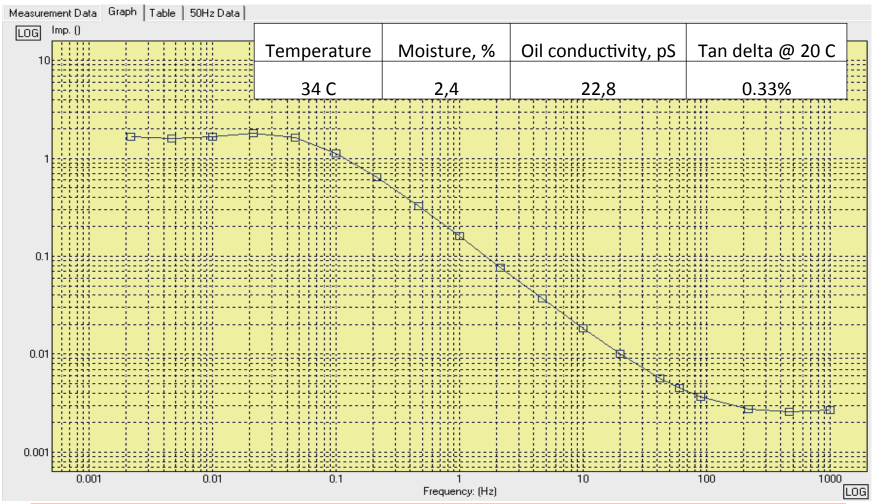
## DFR estimates moisture, oil conductivity and 20 C tan delta in one test!




| Temperature | Moisture, % | Oil conductivity, pS | Tan delta @ 20 C |
|---|---|---|---|
| 34 C | 2,4 | 22,8 | 0.33% |

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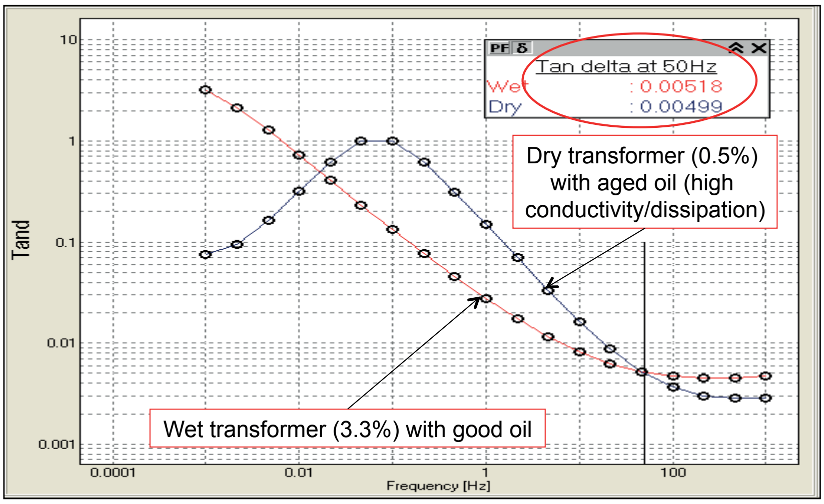
## DFR - Investigating 0.5% tan delta values

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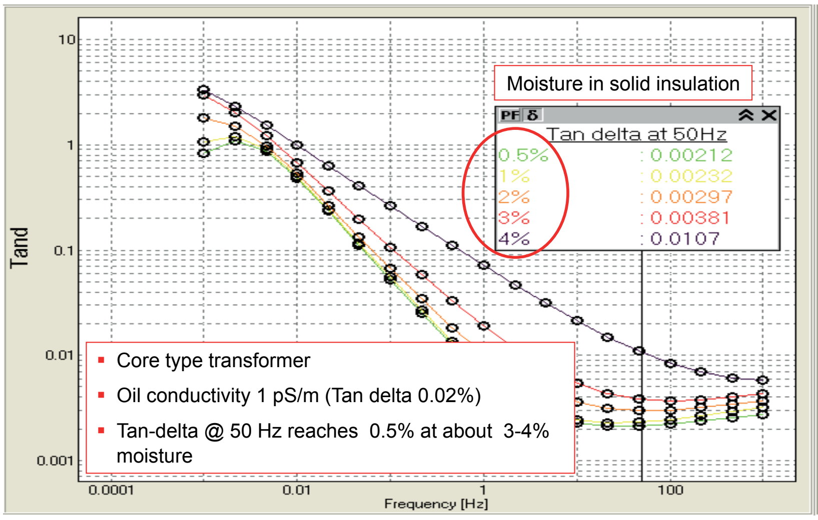
## Tan delta vs moisture @ 20 C

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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

# Using Frequency Domain Spectroscopy to improve Transformer Life Management

## 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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## The added value of DFR measurements

- Estimate the moisture content of cellulose insulation in power transformers, CTs, bushings etc
- Estimate the dielectric properties of insulating oil
- Estimate temperature dependence and perform individual temperature corrections based on the actual insulation material(-s) and condition
- Understanding capacitance changes and dissipation factor increase in power system components
- Detect contamination in the insulating system
- Monitor e.g. dry-out and impregnation processes
- Just for fun...!

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# IDAX/VAX Products for DFR Measurements

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## IDAX 300/350 – Insulation Diagnostic Analyzers


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## VAX020/214/230 – High Voltage Amplifiers


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## IDAX/VAX Test System

**HW**

- Test signal: 0 – 200 V (peak), 50 mA (IDAX300/350)
  0 – 2kV (peak), 50 mA (with VAX020)
  0 – 10 kV (peak), 40 mA (with VAX214)
  0 – 30 kV (peak), 40 mA (with VAX230)
- Frequency: 0.0001 Hz – 10000 Hz
- Capacitance range: 10 pF – 100 µF
- Max interference: 15 mA (RMS) or 1:20 SNR @ 50/60 Hz
- 2-ch measurement: Multiplexing (IDAX300/350)
  Simultaneous (IDAX300S/350S)

**SW**

- IDAX SW for measurement control and analysis
- MODS SW for:
  - Automatic assessment of moisture in solid insulation and oil conductivity/tan delta
  - Temperature dependence analysis by conversion of frequency data to temperature data
  - Individual temperature correction from measurement temperature to 20° reference

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# Using Frequency Domain Spectroscopy to improve Transformer Life Management

## VAX020

- High voltage amplifier for IDAX206/300/350
- Increases IDAX maximum output voltage from 200 V to 2000 V
- Specification:
  - 2 kV output (peak)
  - DC – 1 kHz @ 50 mA (peak)
  - Capacitance range @ max voltage and current
    - 4 µF @ 1 Hz
    - 80 nF @ 50 Hz
    - 4 nF @ 1 kHz
  - Weight 4.4 kg
- Key benefits:
  - DFR in substations with high DC or very low frequency AC interference, e.g. HVDC substations
  - 2 kV capacitance and tan delta testing at power frequency
  - Tip-up testing


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## IDAX300 with VAX020

# Transformer drying

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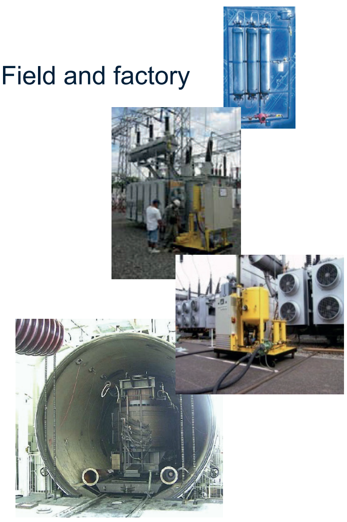
## Transformer drying – Methods/Examples

- 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 and Regeneration of Insulating Oil"*, TechCon AsiaPacific 2009

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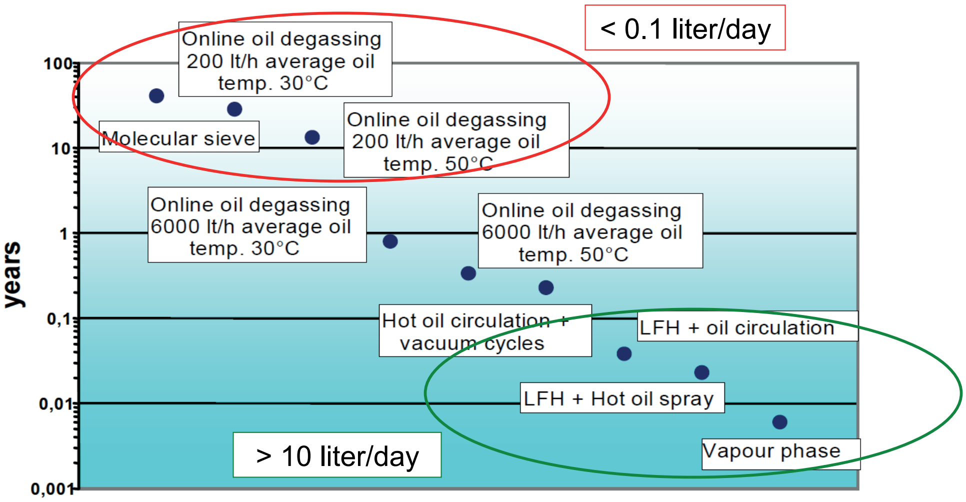
## Transformer drying – Comparing methods




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

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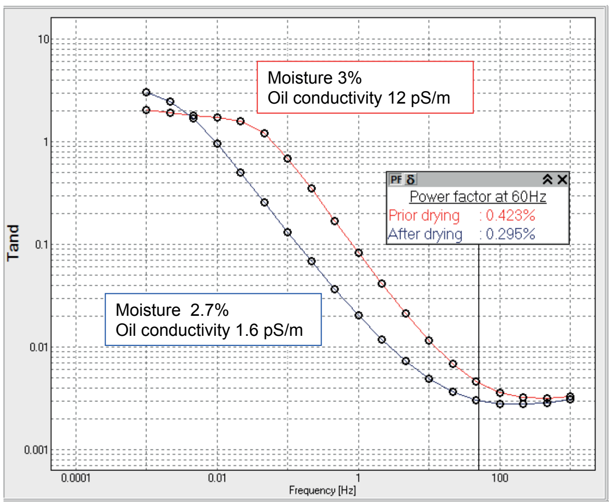
*P. Koestinger et al, "Practical Experience With the Drying of Power Transformers In the Field, Applying the LFH Technology"*, CIGRE A2-205, 2004

## 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

# Using Frequency Domain Spectroscopy to improve Transformer Life Management

## 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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