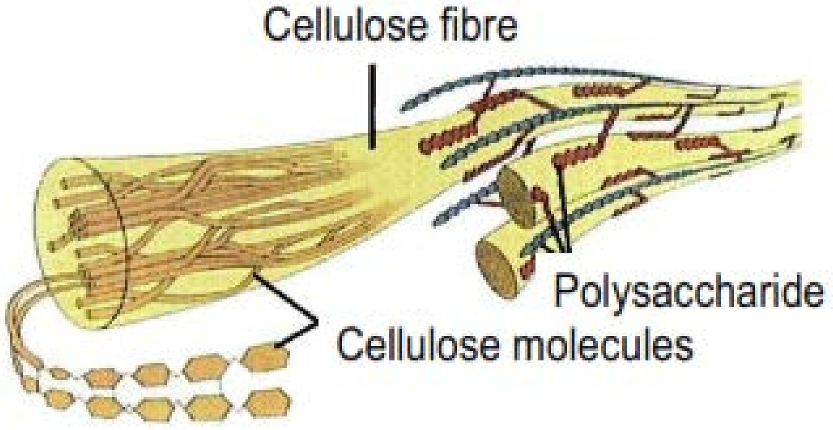
Optimization of the Power Transformer Dry-out Process in the Field
Application of Advanced Diagnostic Technologies

Authors: Diego M. Robalino, Ph.D. & Peter Werelius, Ph.D.

Dallas, TX – September 11-13, 2013

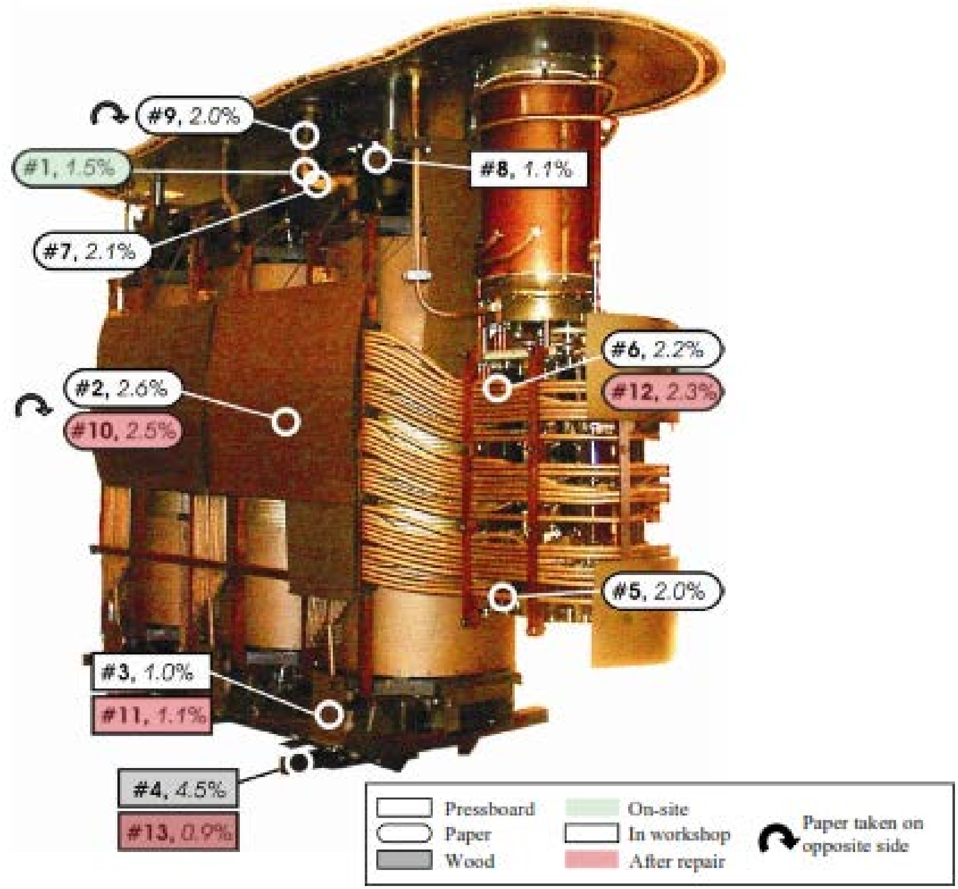
DFR - Application

- Determine moisture concentration in solid insulation
- Determine degree of contamination in the liquid insulation
- Determine presence of contaminants and non-typical responses
- Determine dissipation factor thermal behavior



Moisture in Power & Distribution Transformers

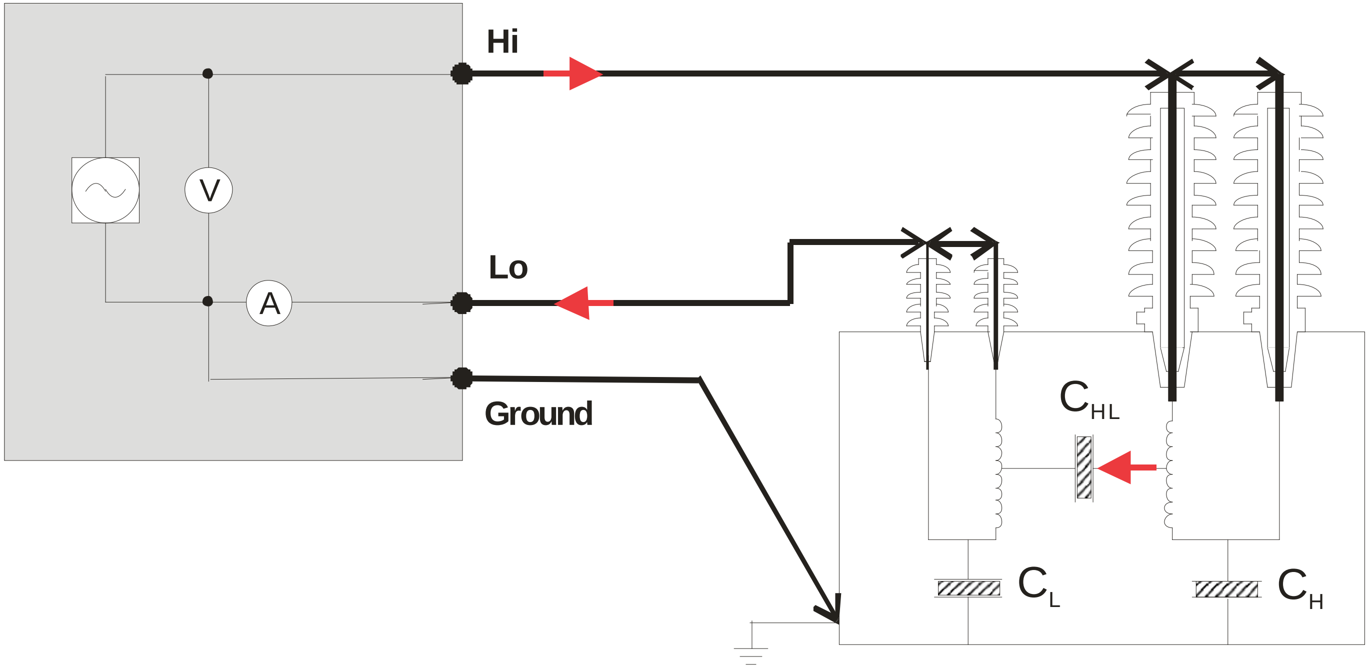
- Moisture Distribution
- Moisture levels measured by means of KFT at different locations in power transformer.



Reference: CIGRE Brochure 414 “Dielectric Response Diagnoses for Transformer Windings”, April 2010.

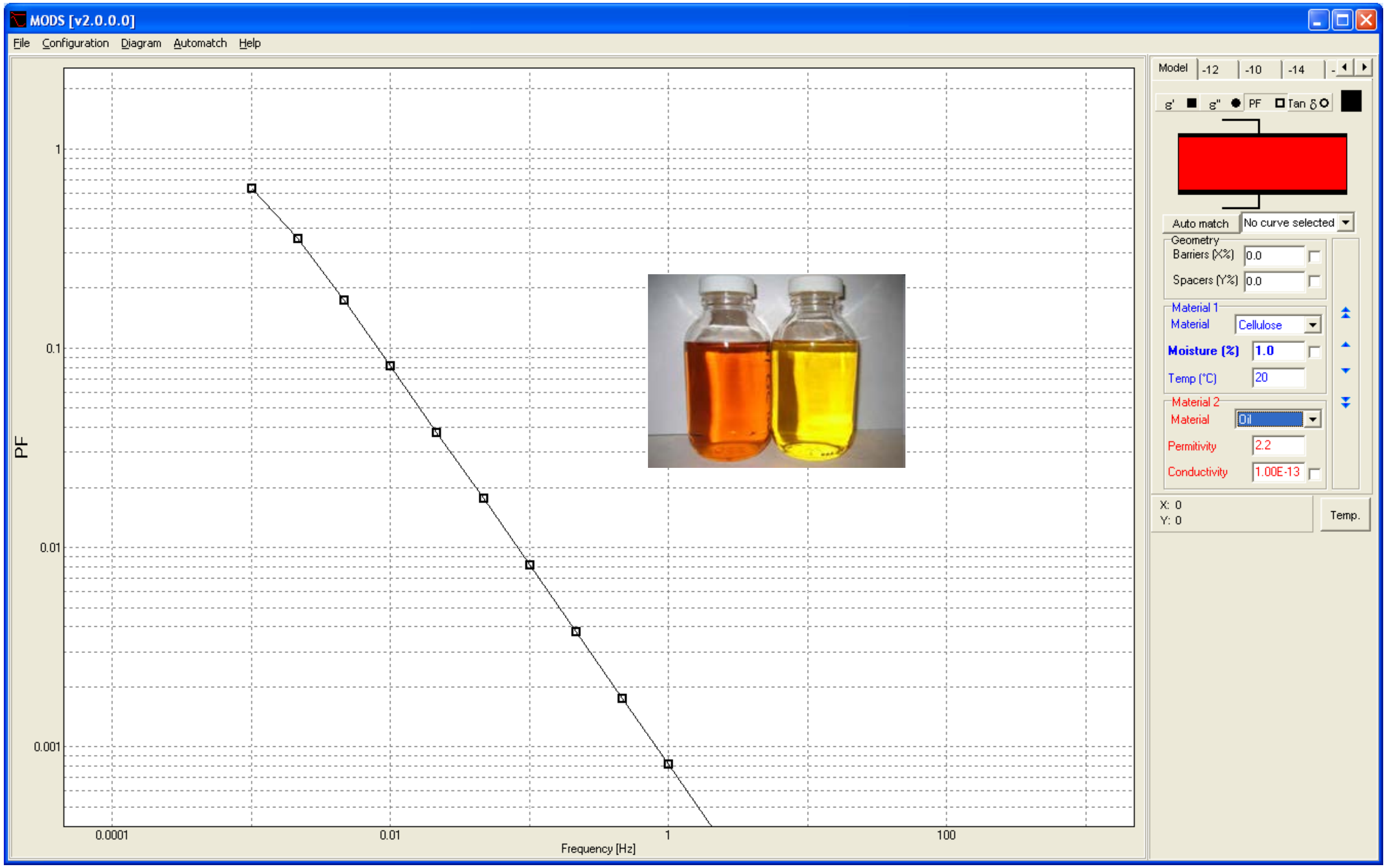
DFR data acquisition

- DFR measurement setup is the same as that applied for capacitance and power factor measurement . The difference is the wide frequency spectrum (1kHz – 1mHz) and the low voltage applied (normally 140 V_{rms}).

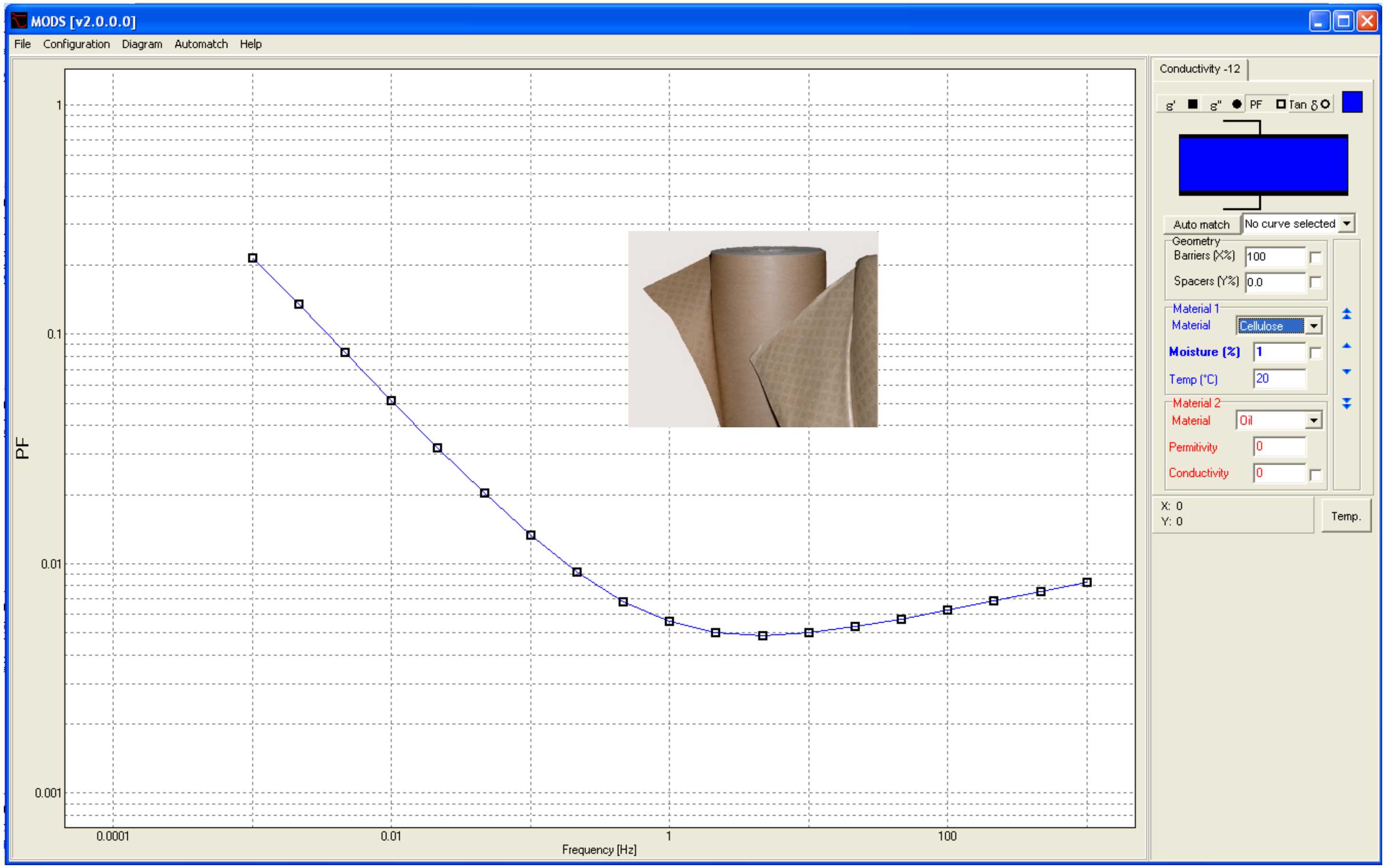


Megger.

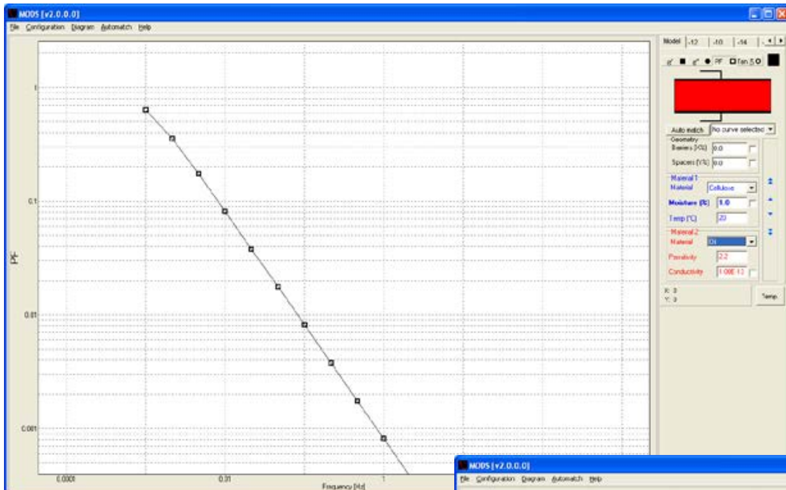
Typical curve: OIL only response



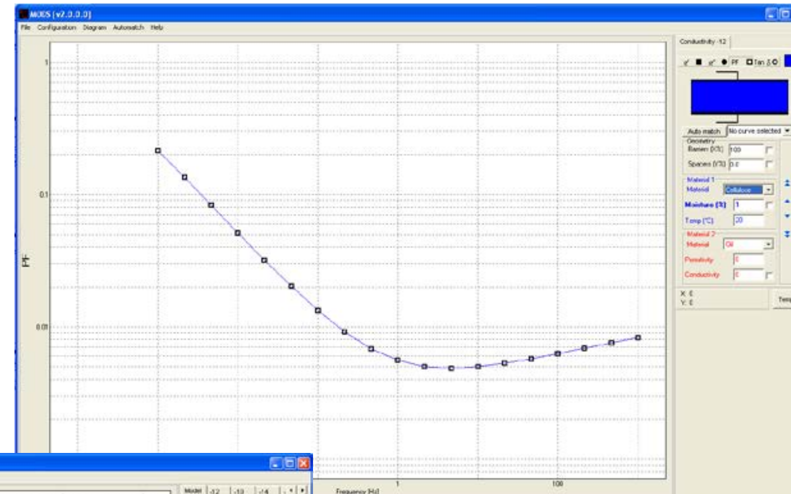
Typical CELLULOSE only response



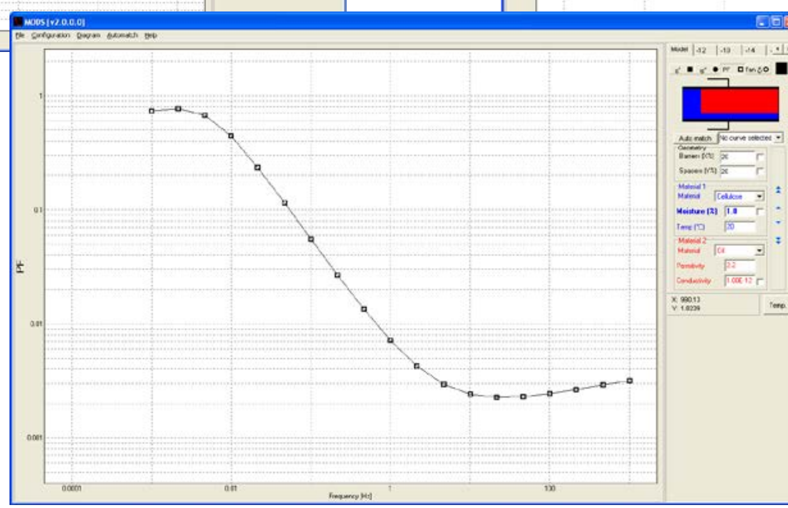
Characteristic Transformer PF Curve = combination of OIL and CELLULOSE response



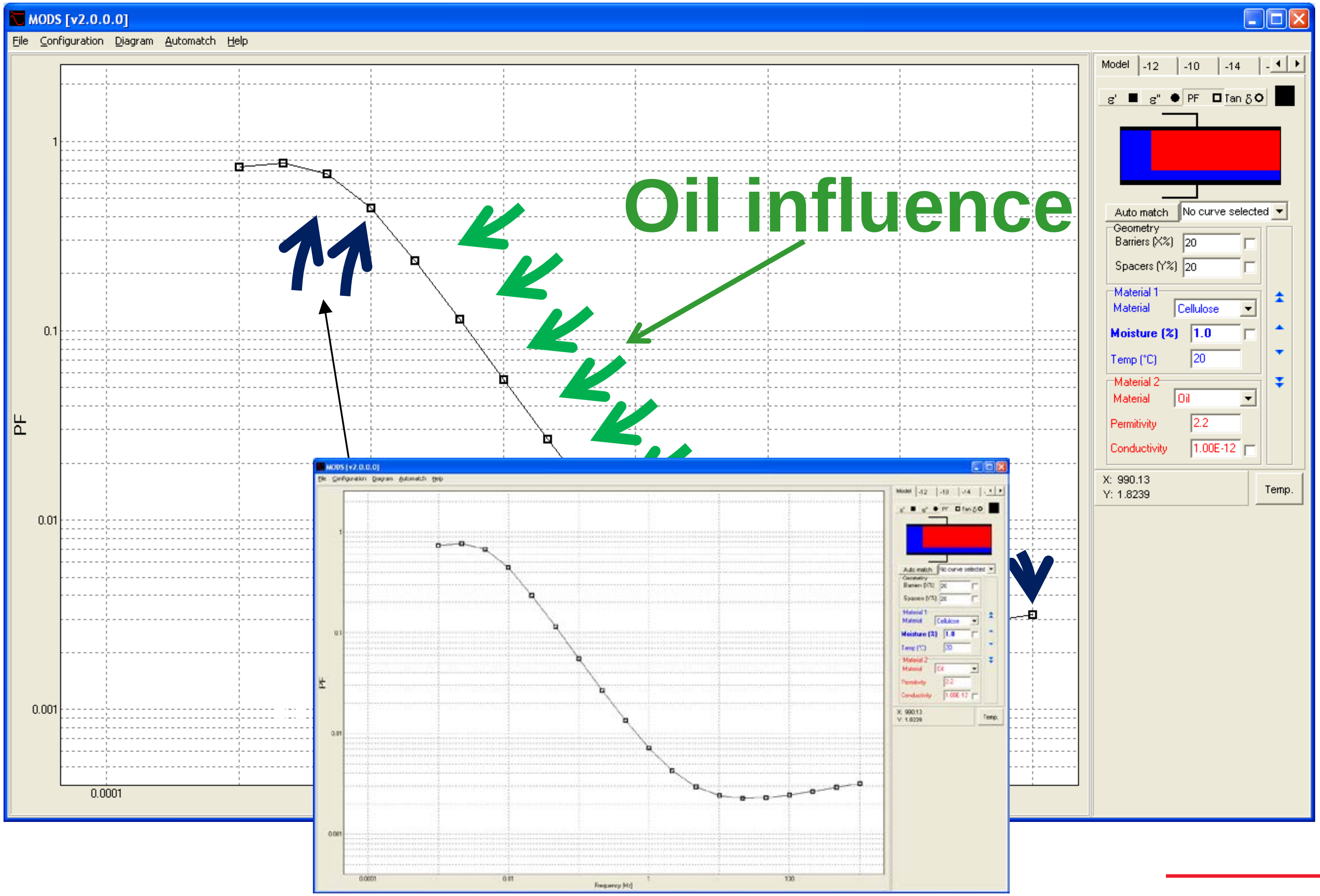
+



=



Typical Curve Transformer Response



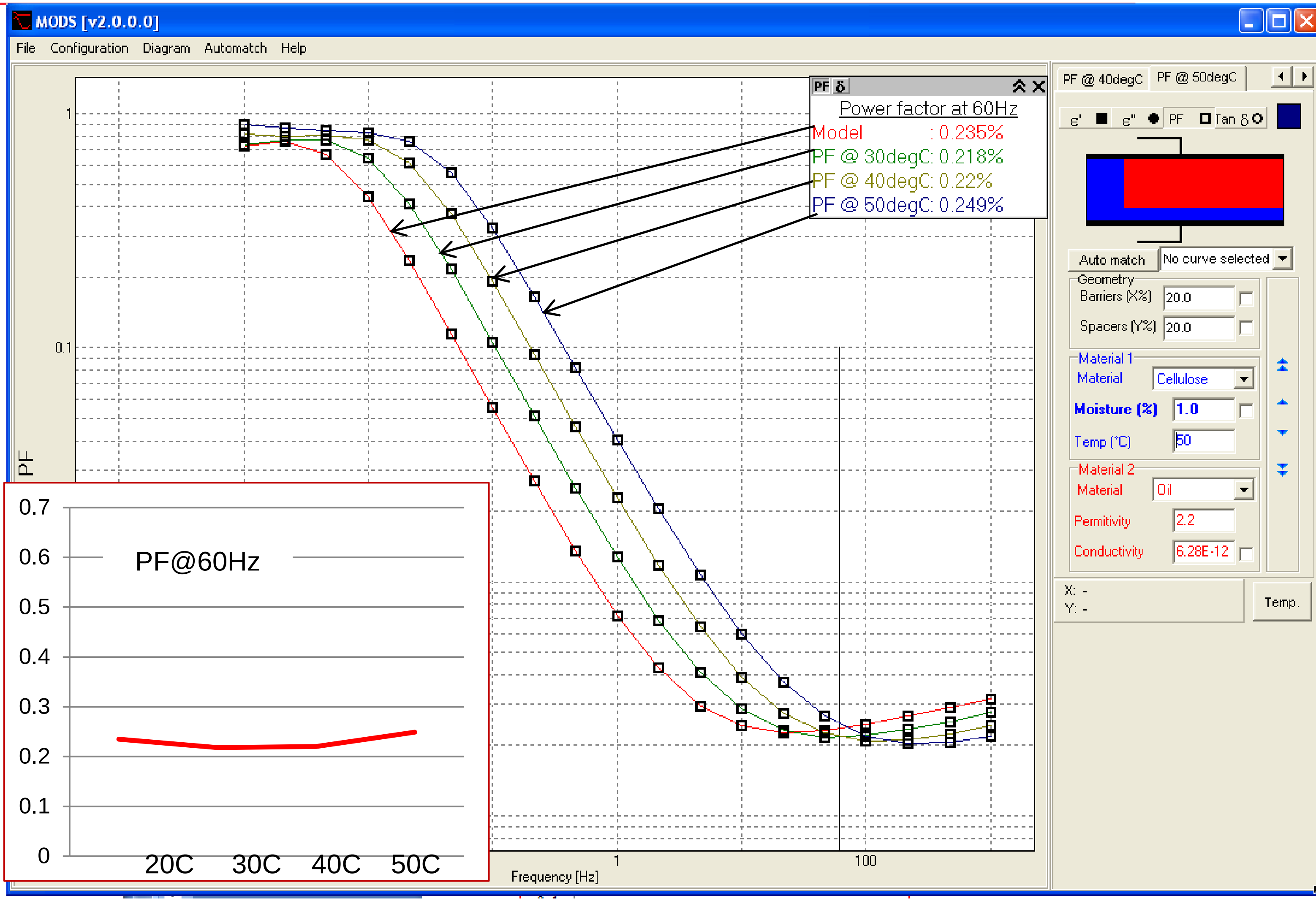
Factors affecting the curve distribution

- Good understanding of the factors that may influence the measurements under field conditions is of crucial importance for the diagnosis reliability.
- Constant and preferably not too low temperature is advantageous for the interpretation quality – at higher temperatures the time necessary for the measurements can be shortened.
- It is recommended to make CHL measurements between main transformer windings.
- In the case of CH and CL measurements, it is also important to make sure that the transformer bushings are dry and clean, and good grounding connection is in place.

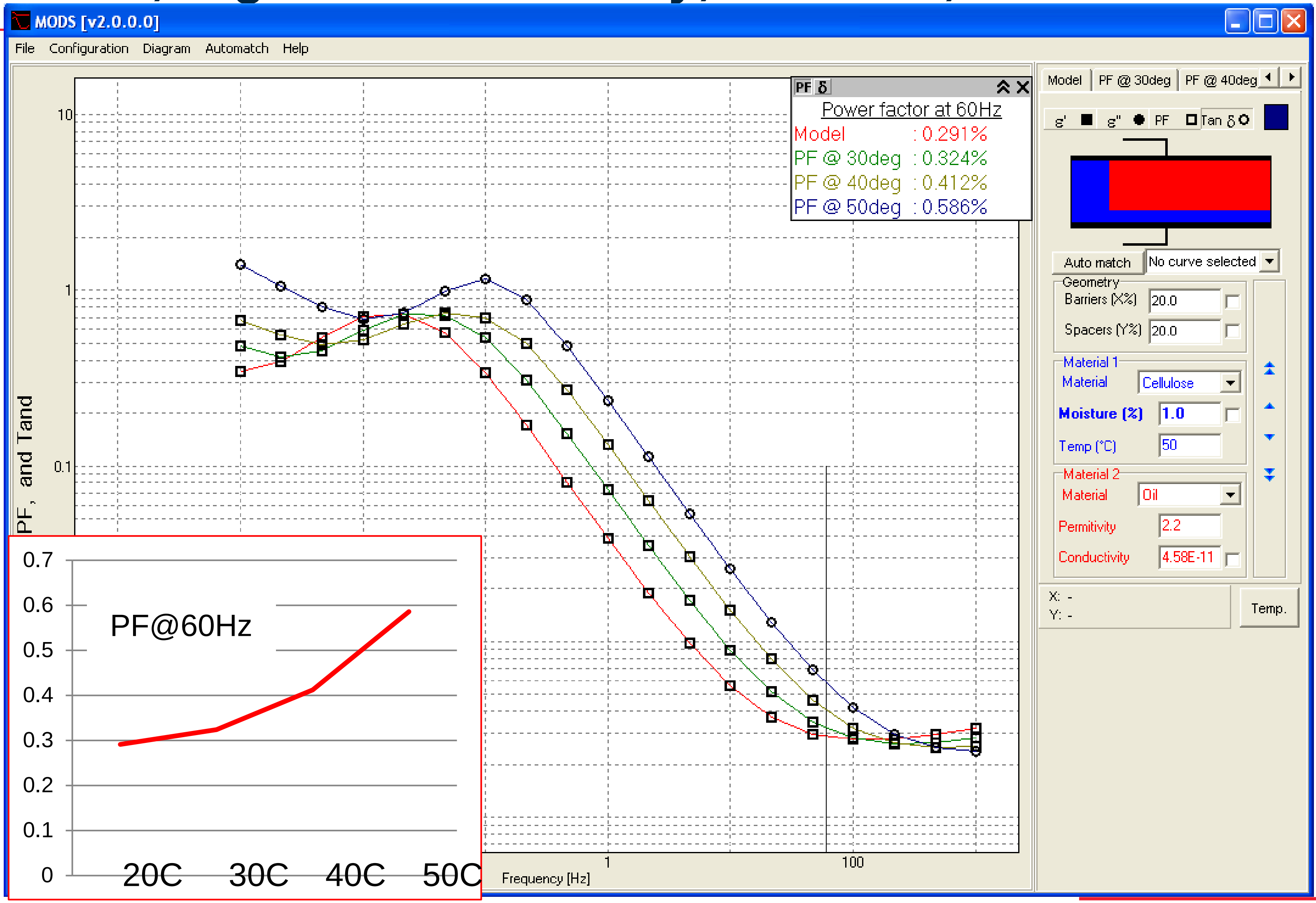
DFR and temperature dependence

- Insulation properties change with temperature
- The Arrhenius equation:
  - A measurement at e.g. 50 Hz, 20C corresponds to a measurement at higher frequency at higher temperature
- Various material have different activation energy
  - Dry paper typically around 1.0 eV
  - Oil-impregnated paper typically 0.9 – 1.0 eV
  - Mineral transformer oil typically 0.4 – 0.5 eV

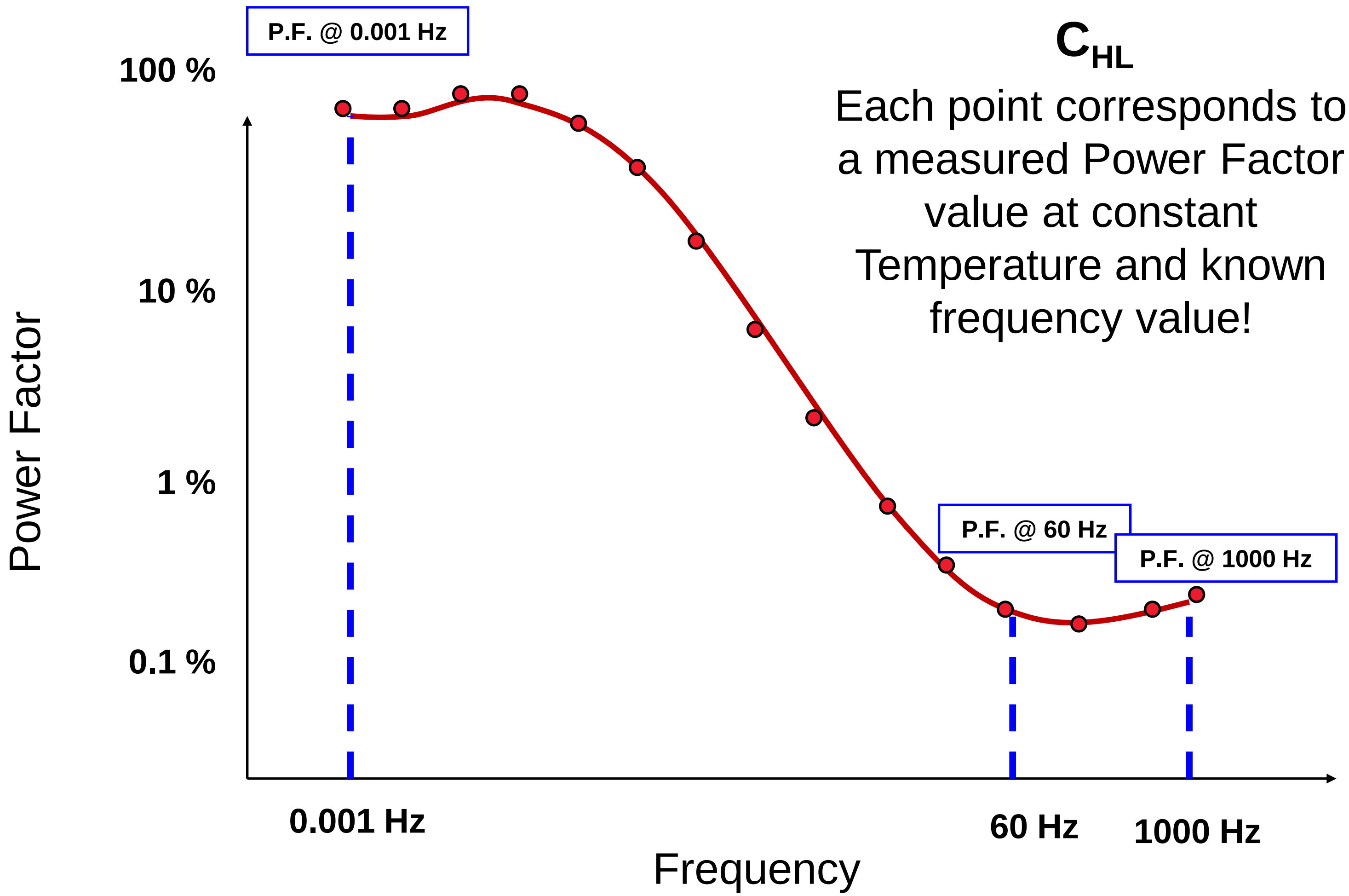
PF, Low oil conductivity, 1% m.c., 20ºC – 50ºC



PF, High oil conductivity, 1%moist, 20ºC – 50ºC



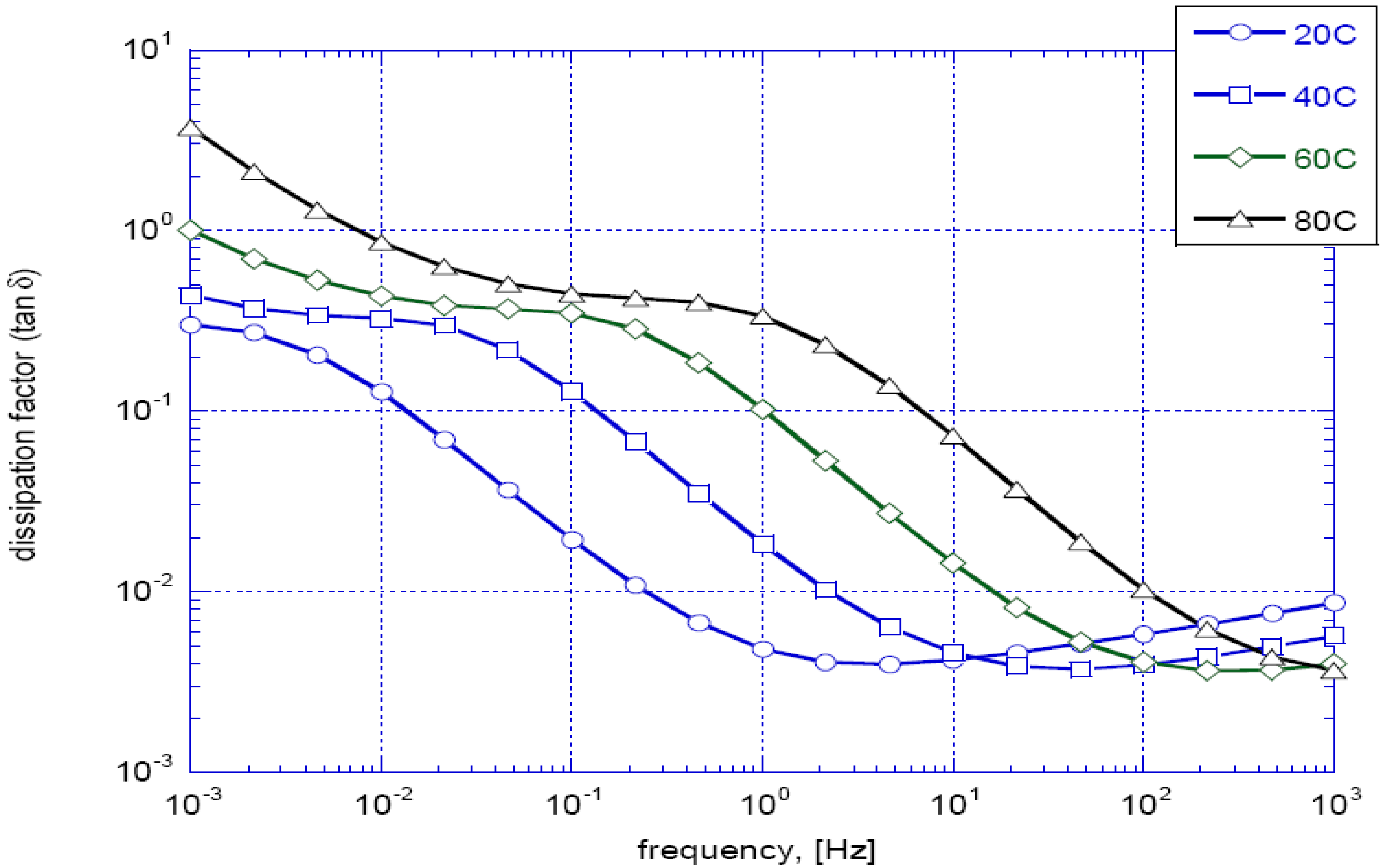
Dielectric Frequency Response Measurement



C_{HL}

Each point corresponds to a measured Power Factor value at constant Temperature and known frequency value!

DFR measurements – oil impregnated Kraft paper, moisture content < 0.5%

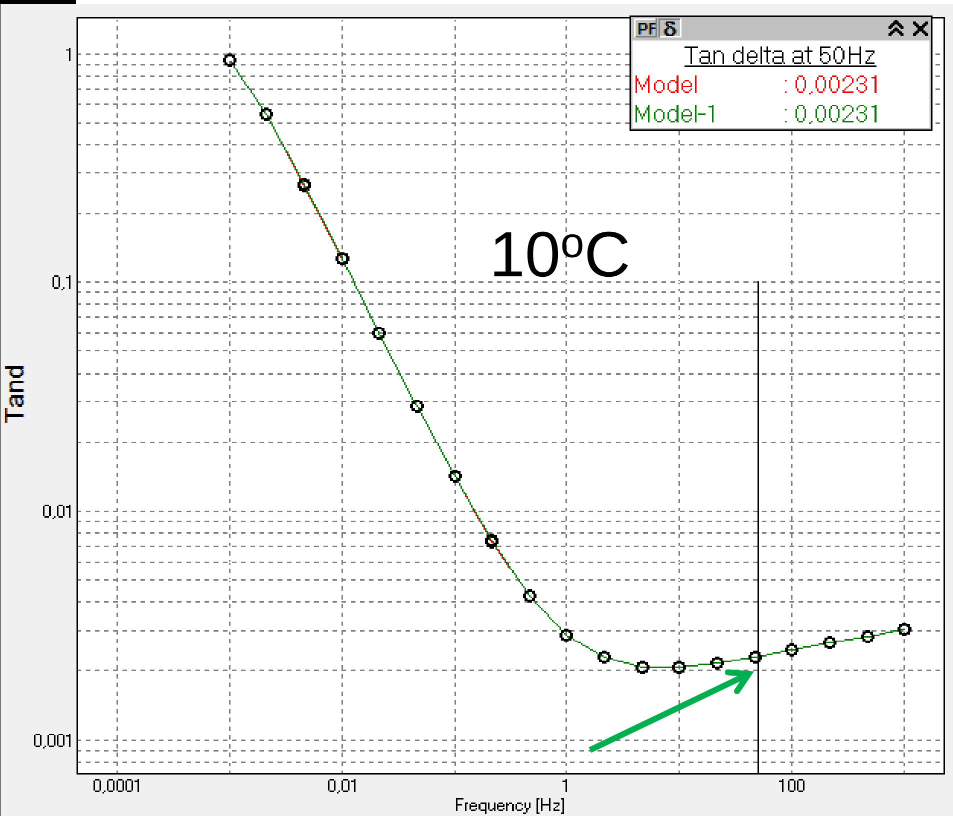


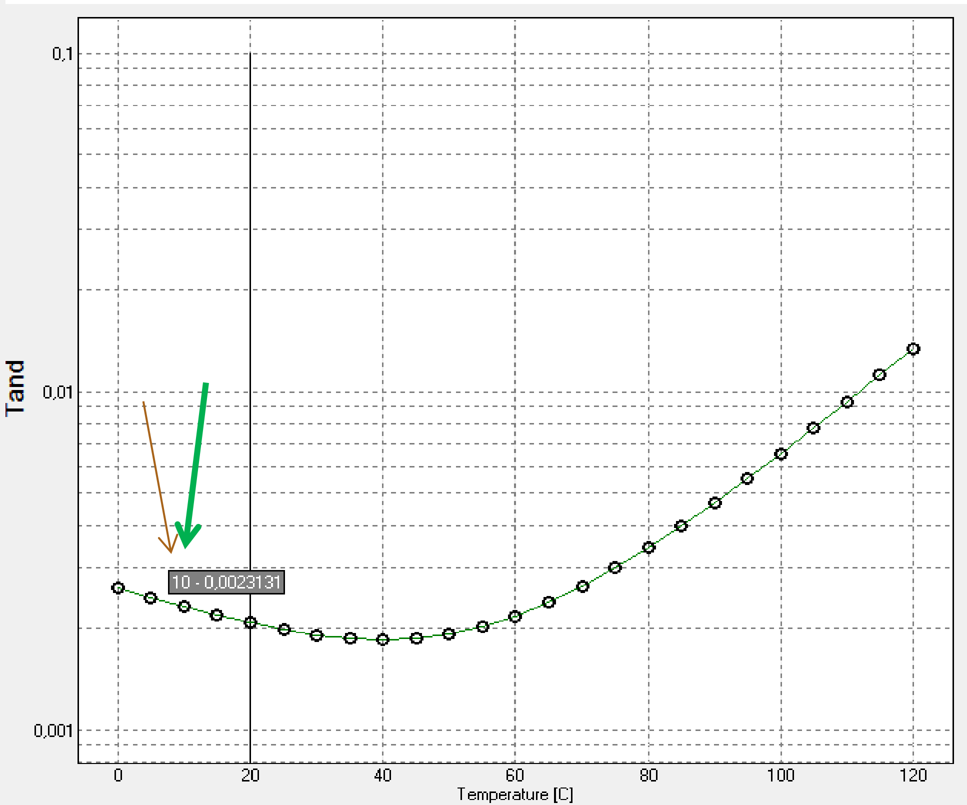
Frequency domain to temperature domain,
more than one materials (e.g. impregnated cellulose and free oil)

$$DF(w, T_2) = DF(w/A_{xy}(T_1, T_2), T_1)$$

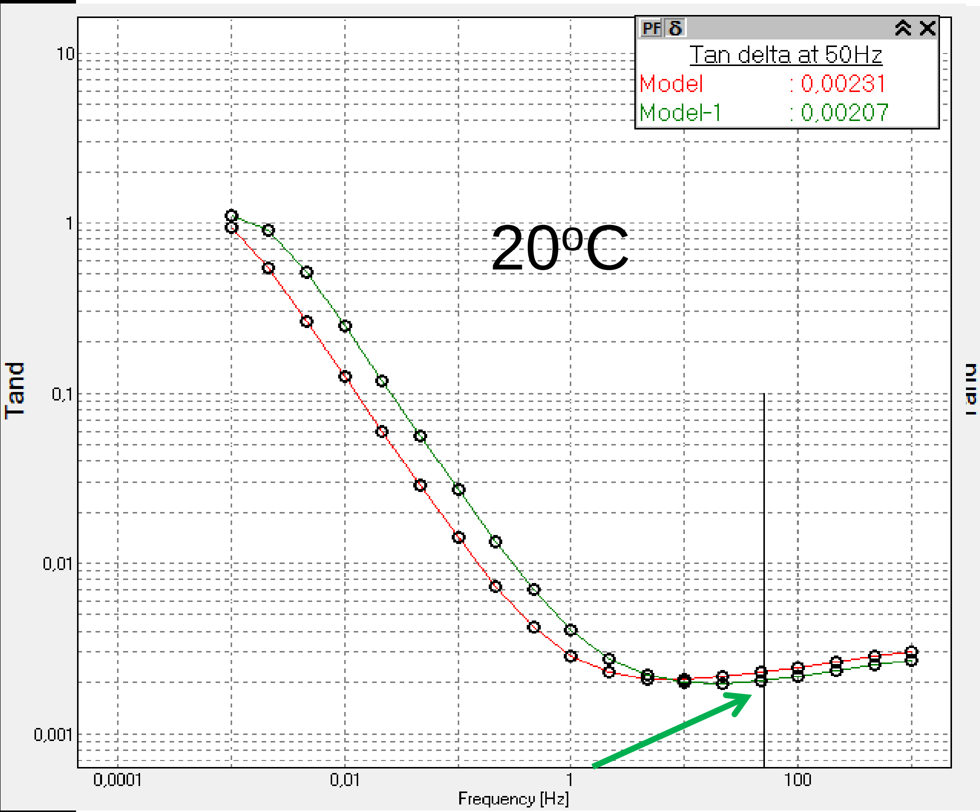
$$A_{xy}(T_1, T_2) = e^{\frac{-E_{x,y}}{k_b}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}$$

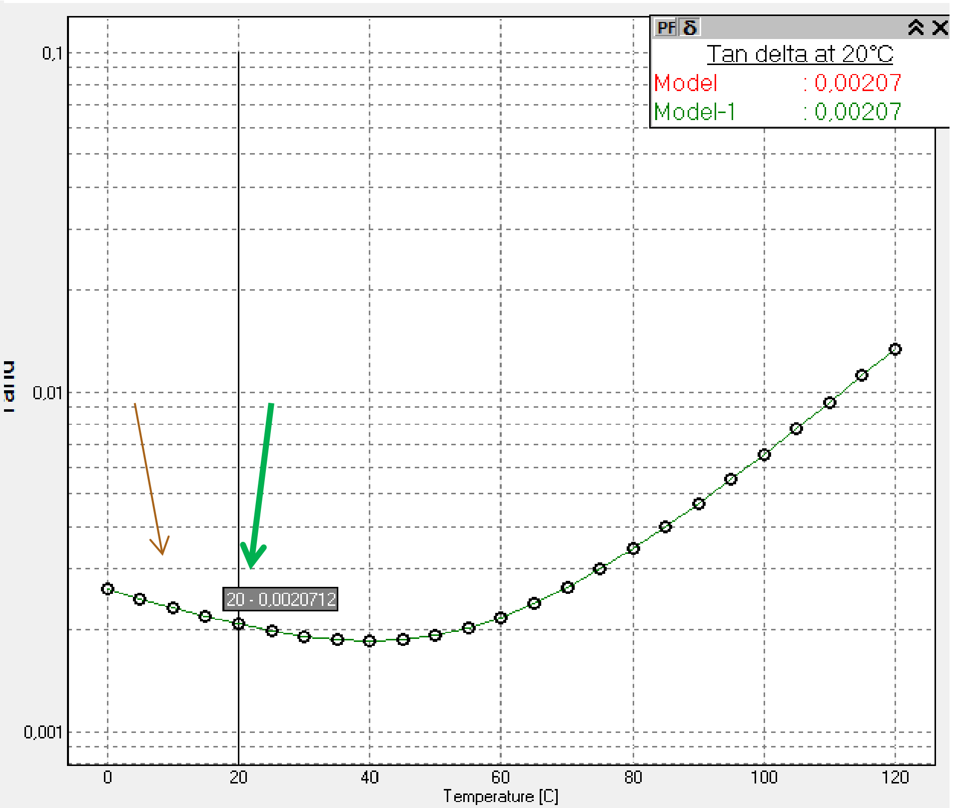
- Example (E-cellulose=0.9eV, E-oil= 0.5eV): Below is an example how a frequency sweep is transformed into temperature domain based on the procedure above



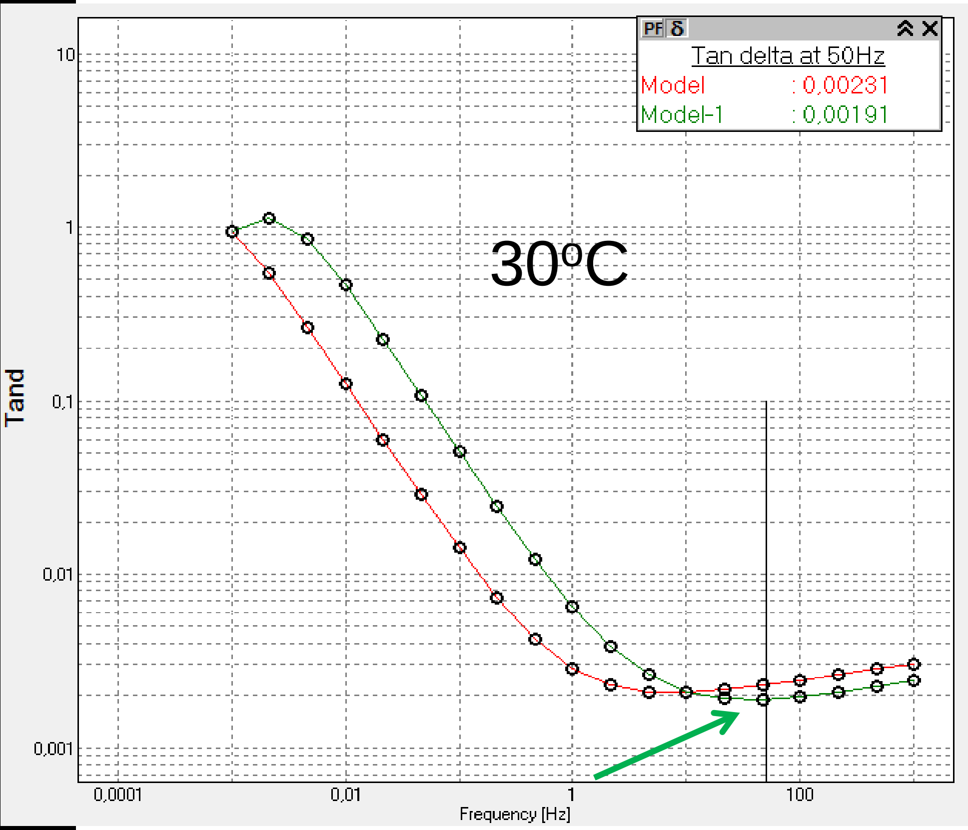


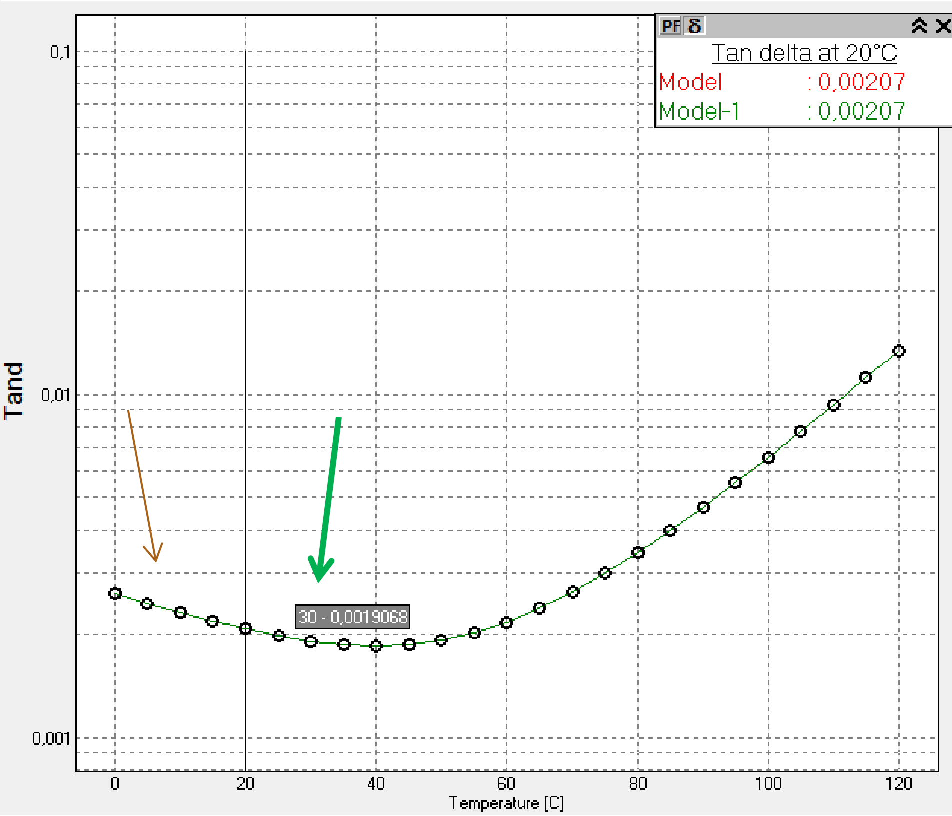
Frequency domain to temperature domain,
more than one materials (e.g. impregnated cellulose and free oil)



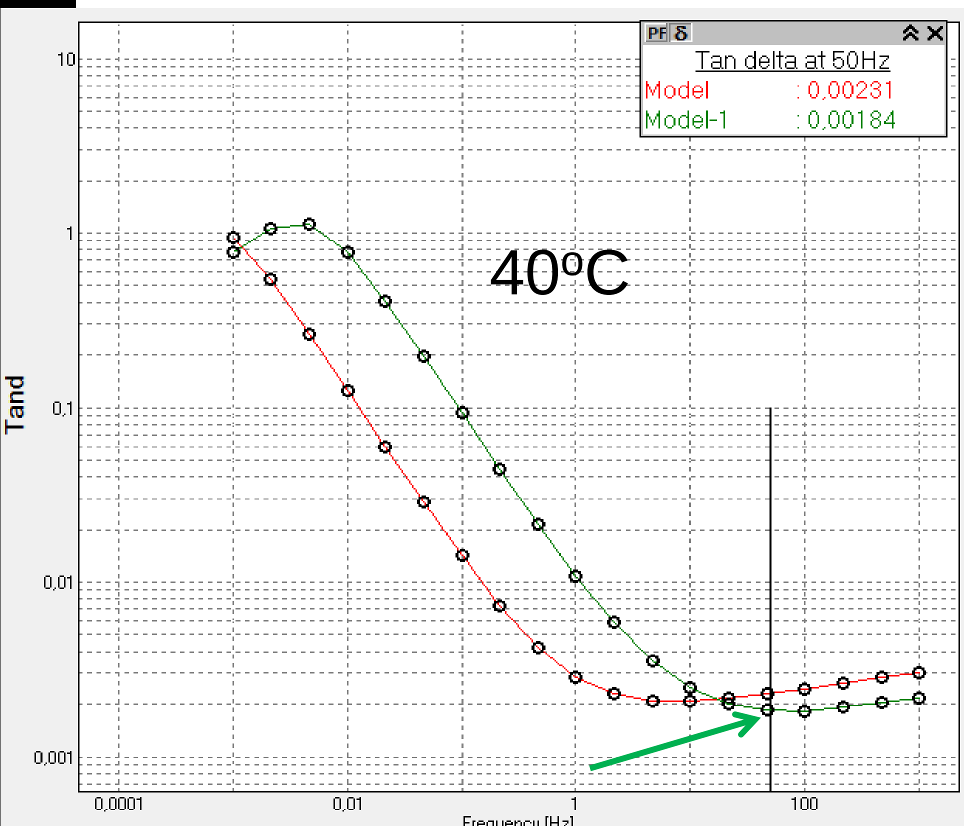


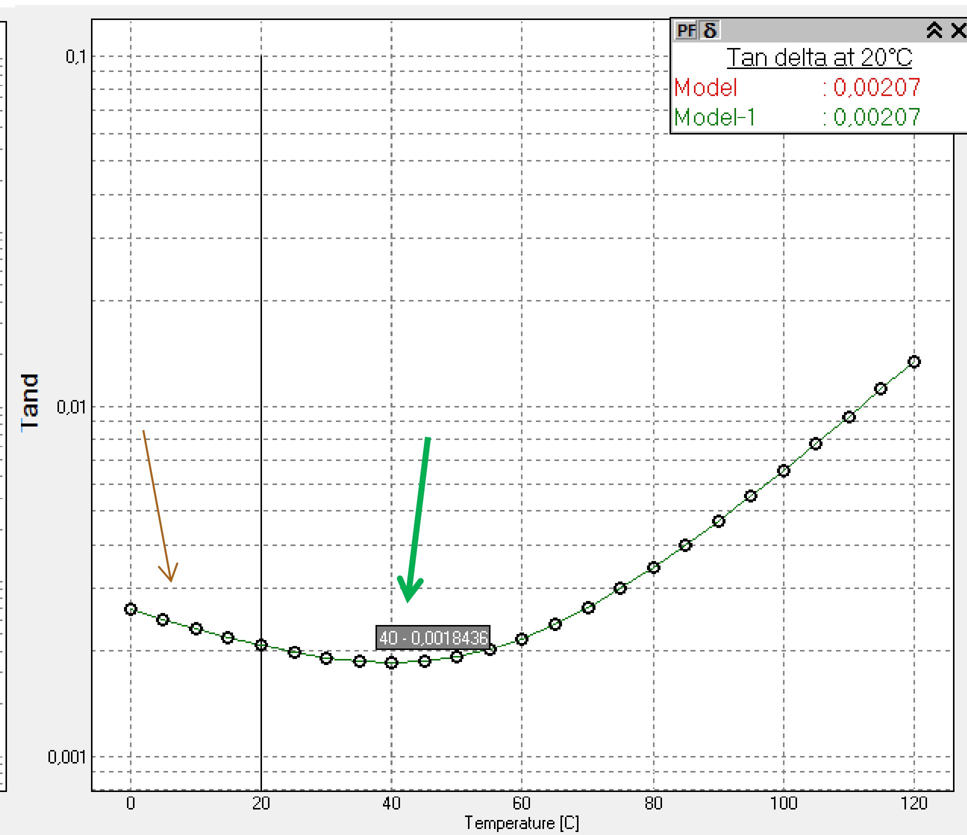
Frequency domain to temperature domain,
more than one materials (e.g. impregnated cellulose and free oil)



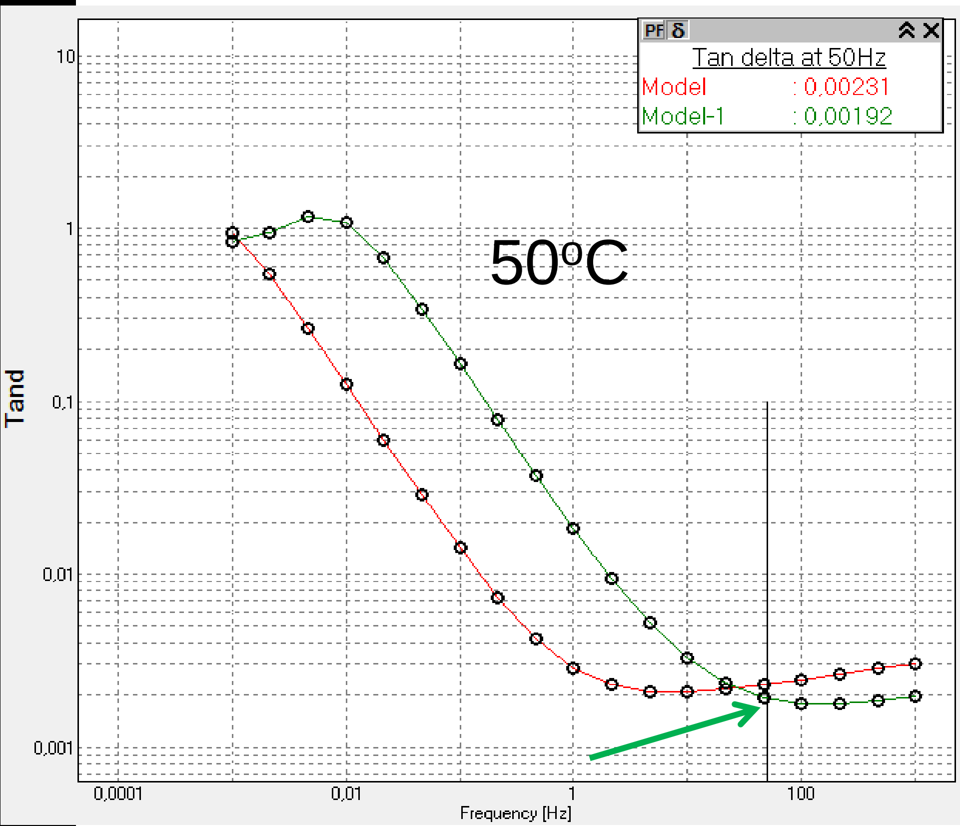


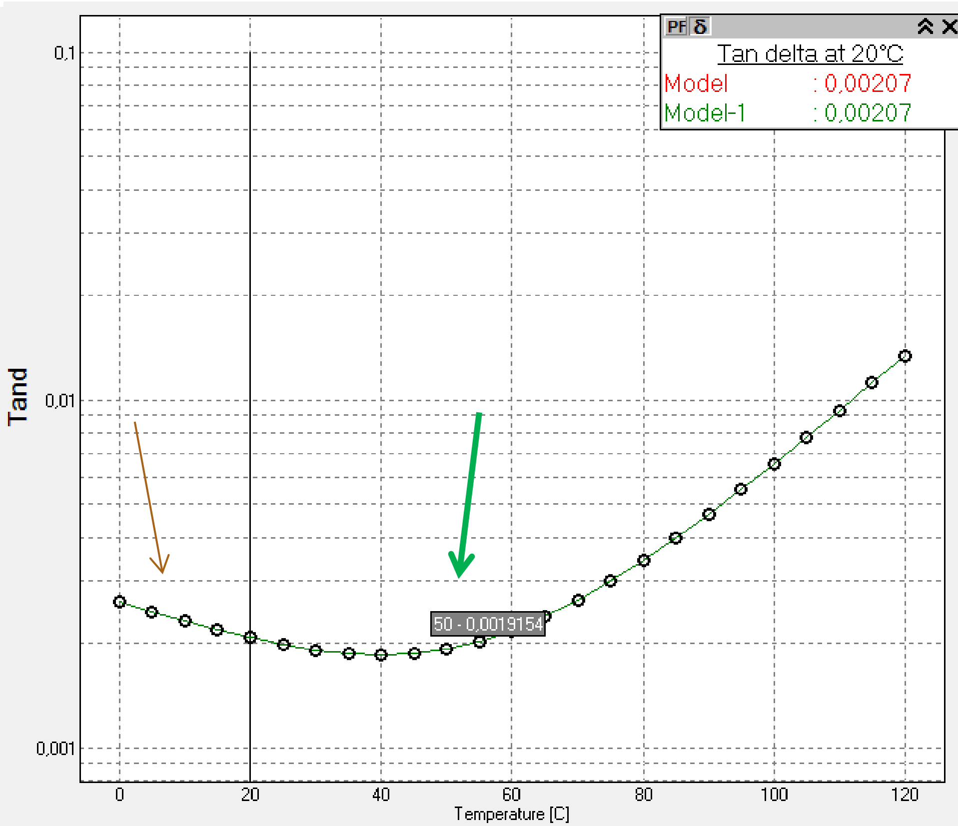
Frequency domain to temperature domain,
more than one materials (e.g. impregnated cellulose and free oil)



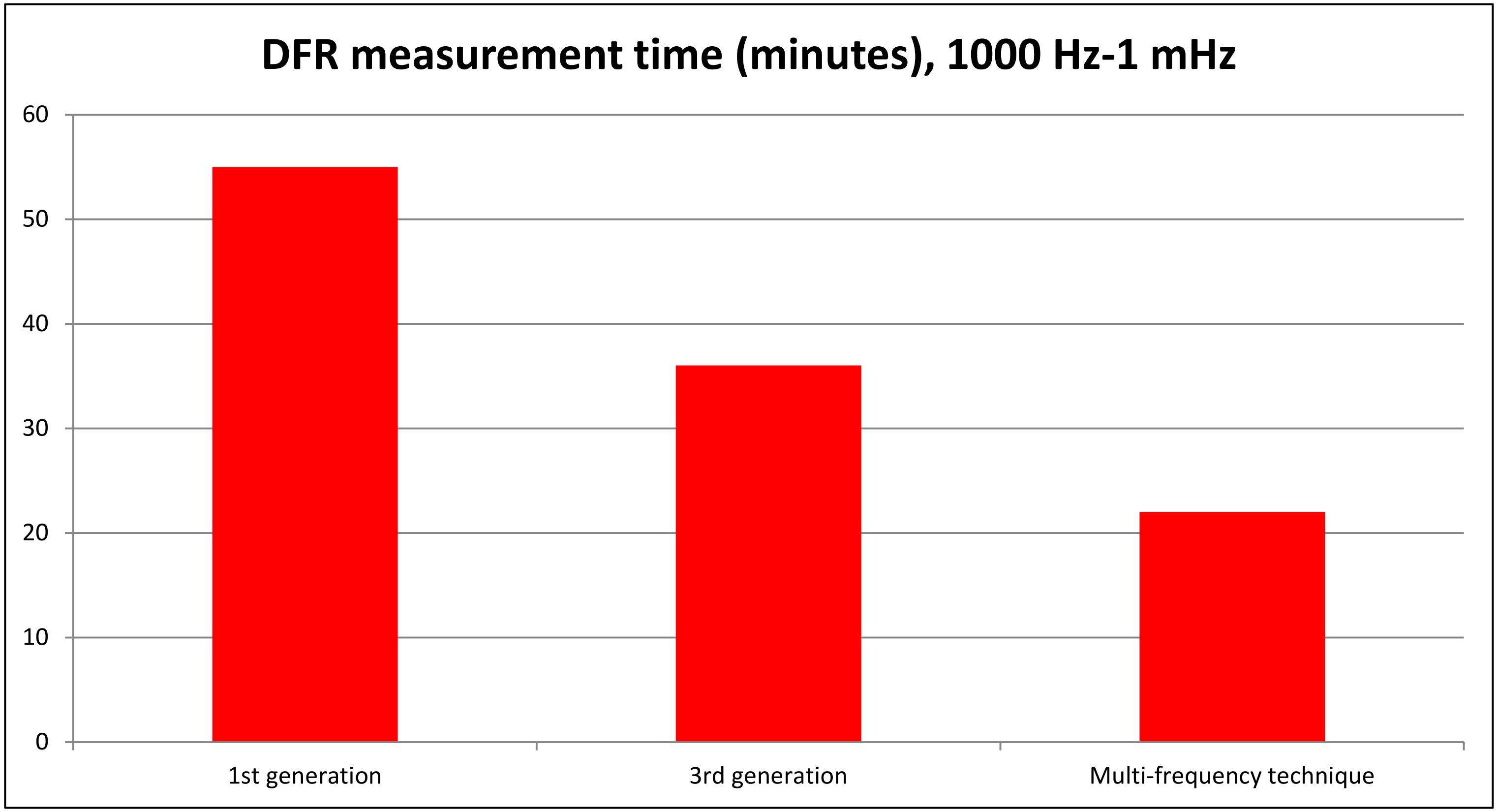


Frequency domain to temperature domain,
more than one materials (e.g. impregnated cellulose and free oil)





DFR measurement time

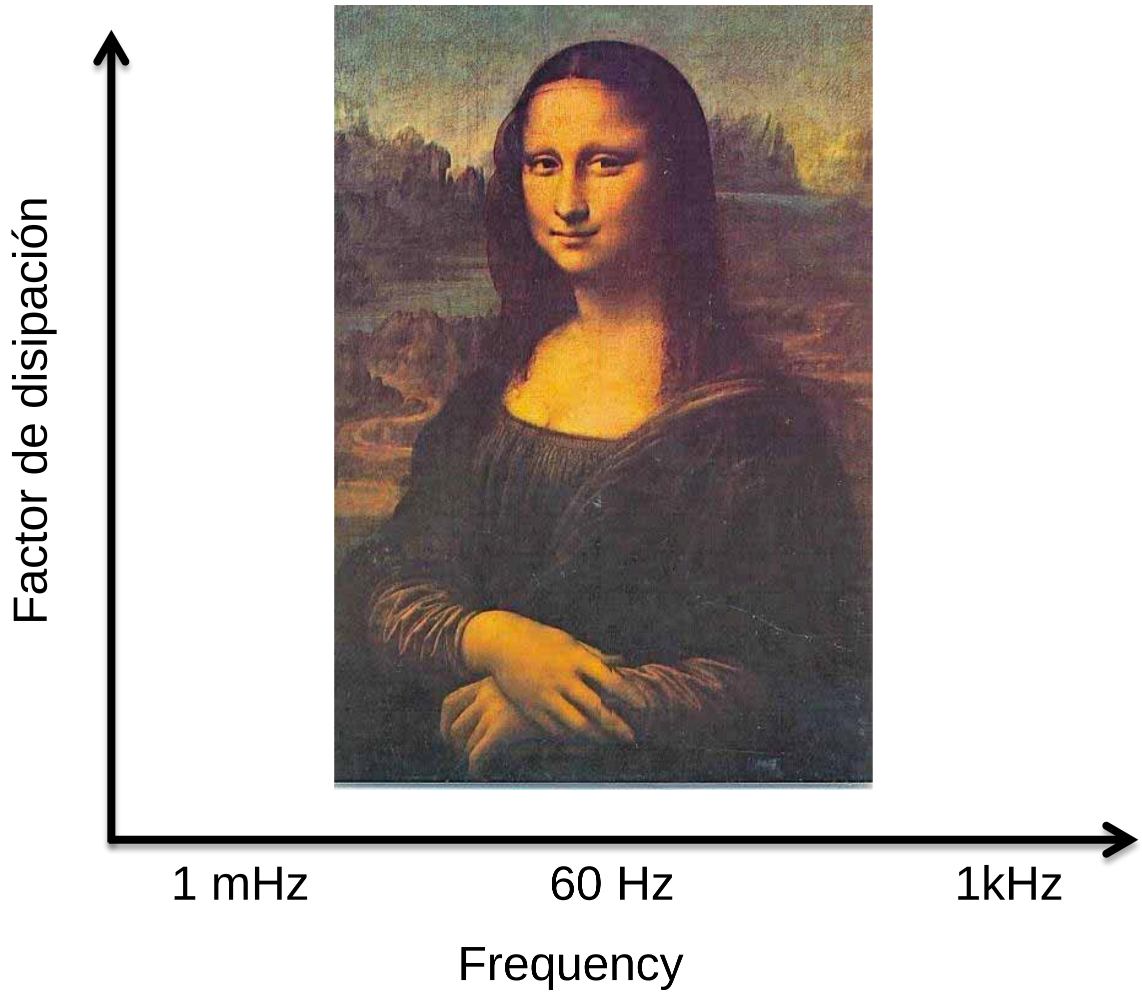


Measurement time with different frequency domain DFR technologies
Frequency range 1 mHz – 1 kHz (20-30 C insulation temperature)

Latest advances in the design improve testing times

Insulation temperature, °C	Suggested min frequency, mHz	Time for IDAX
0-5	0.1	About 3 h 25 min
5-10	0.2	About 1 h 44 min
10-15	0.5	About 43 min
15-25	1	About 22 min
25 - 35	2	About 12 min
35-50	5	About 6 min
>50	10	About 3.5 min

FDS: From one single measurement at line frequency



DFR – Special Applications

- Contamination analysis
- Dry-out / impregnation monitoring
- Oil Immersed CTs
- Bushings

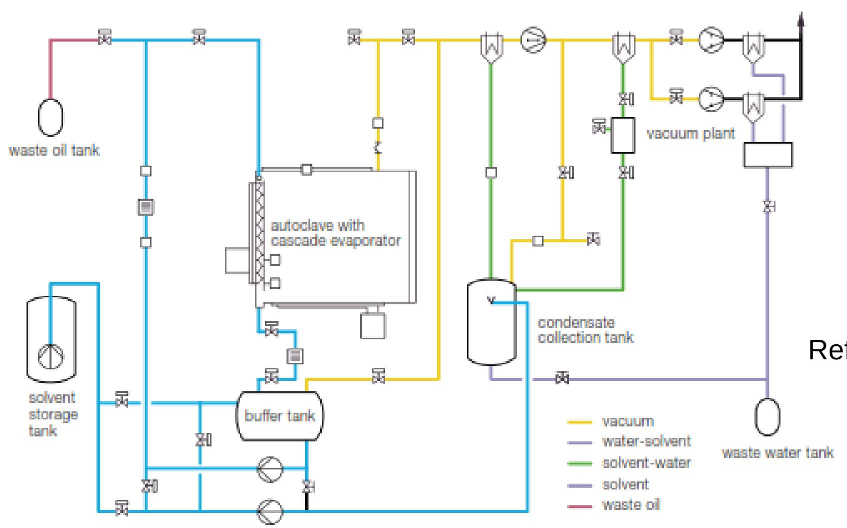
Factory Dry-out

- The challenge

- Most modern power transformers are dried in the factory to a residual water content of less than 0.5% of the weight of paper insulation

- Vapor-phase

- Kerosene vapor-phase drying (KVPD) is mainly suitable for drying transformer core-winding assemblies rated for voltages >110kV and big MVA.



Reference: ABB Micafill Vapor Phase Process Plant

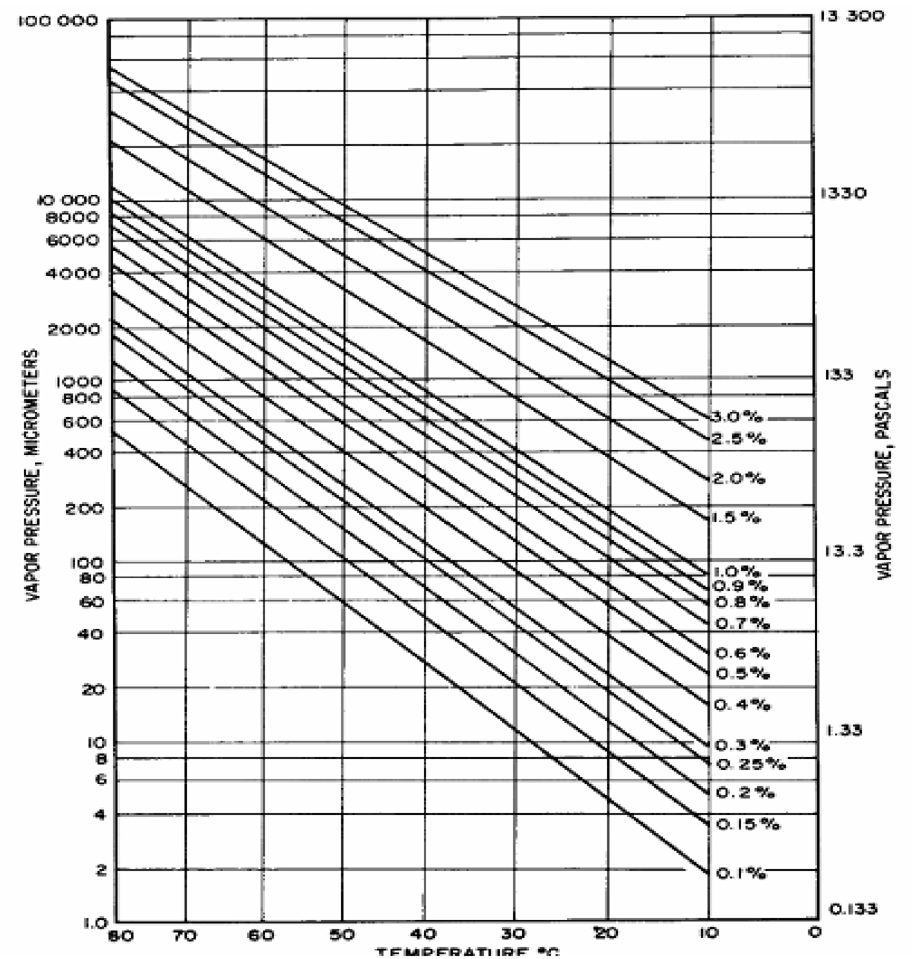
Factory Dry-out

- Thermal

- Vacuum

Factory Dry-out Evaluation

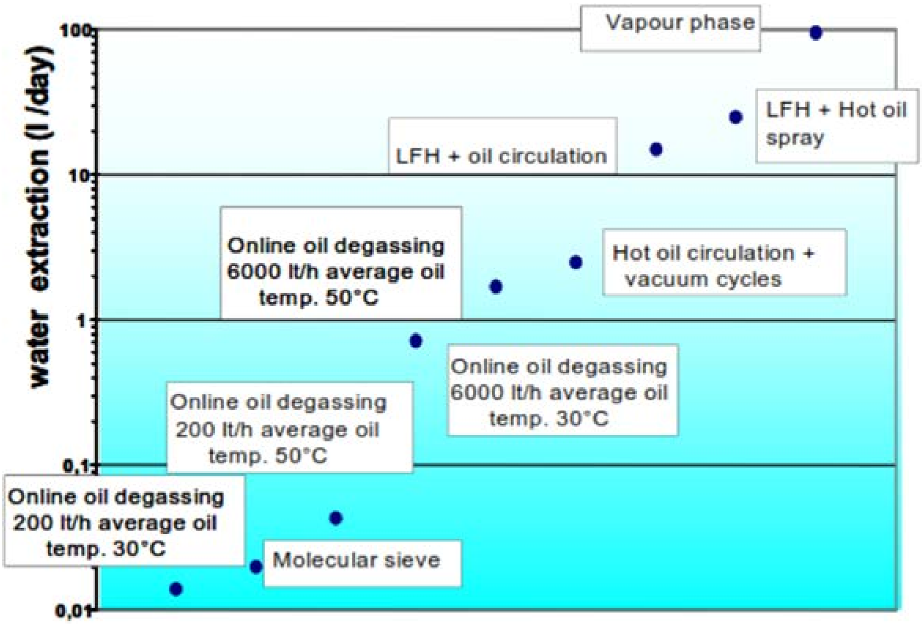
- Dew-Point Test:
  - Dew point measurement of the nitrogen (ASTM D-1933 Type III) in the tank space provide an estimate of the average surface water content of the cellulose insulation after reaching steady-state temperatures.
  - Test duration is from 12 – 24h or until steady state has been reached.



Reference: IEEE Std C57.93™-2007
(Revision of IEEE Std C57.93-1995)

Field Dry-out

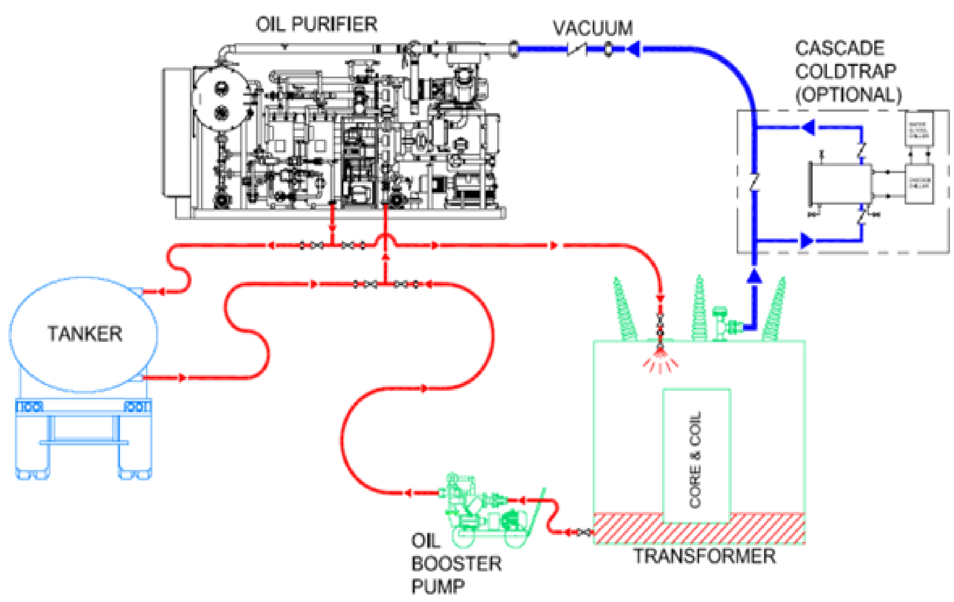
- There are several mechanisms applicable for field dry-out of power transformers.
- A simple way to differentiate the efficiency of the mechanism is by understanding the velocity of the process.



Reference: P. Koestinger, E. Aronsen, P. Boss, G. Rindlisbacher, "Practical Experience with the drying of Power transformers in the field, applying LFH Technology," CIGRE, *Session 2004, A2-205*.

Typical Field Dry-out Process

- The combination of heat and vacuum is a typical and quite efficient approach to extract moisture from the cellulose
- Heat is applied by means of hot oil spray or hot oil recirculation and fast removal. The process also performs filtration, dehydration and degasification of the liquid insulation

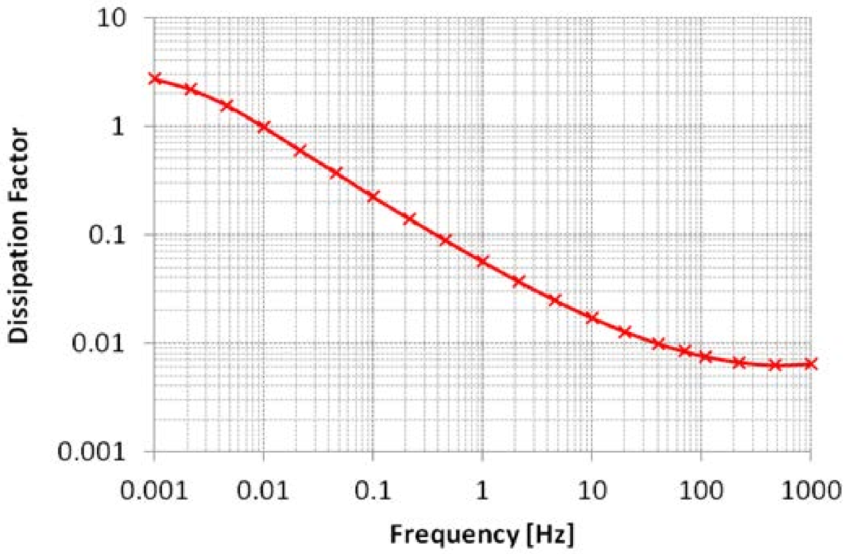


Reference: BARON USA, G. Stevens.
Weidmann/PROLEC Seminar 2012.

DFR Monitoring During Field Dry-out

- The experimental unit
  - 5MVA transformer, 69/12.5kV, Dyn1.
  - %DF = 0.9% @ 20°C.
  - DFR results confirmed the presence of 3.5% moisture in the cellulose and insulation liquid conductivity value of $1.5 \cdot 10^{-12}$ S/m.

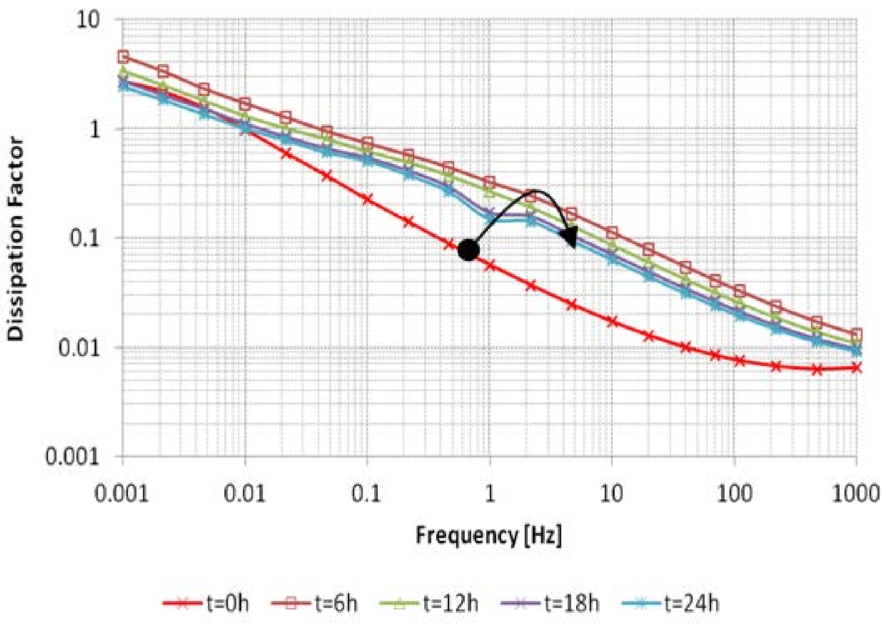
- DFR before process



DFR Monitoring During Field Dry-out

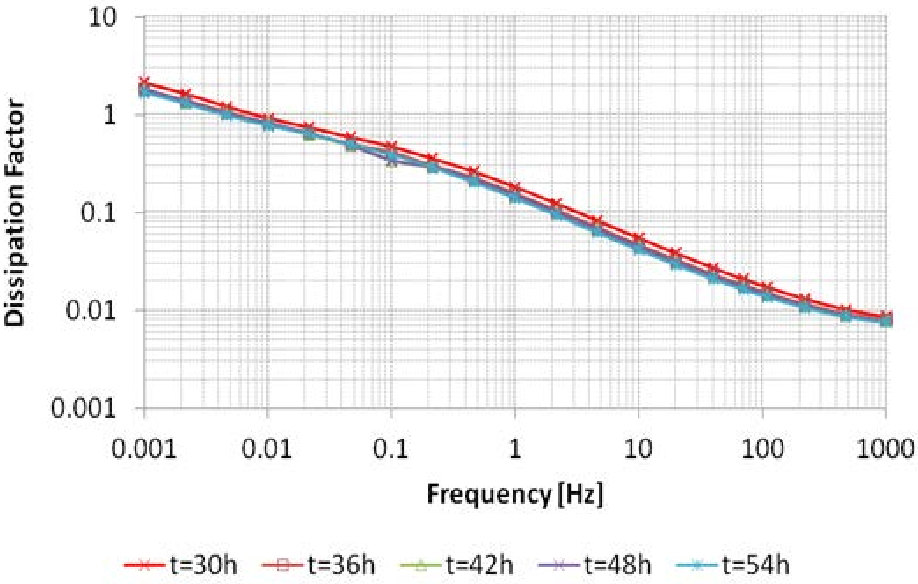
- First 24-h interval
- Measurements performed at every six-hour intervals resemble the same shape of the response obtained after six hours of vacuum and describe a continuous decay of dissipation factor along the whole dielectric spectrum

- The dielectric response



DFR Monitoring During Field Dry-out

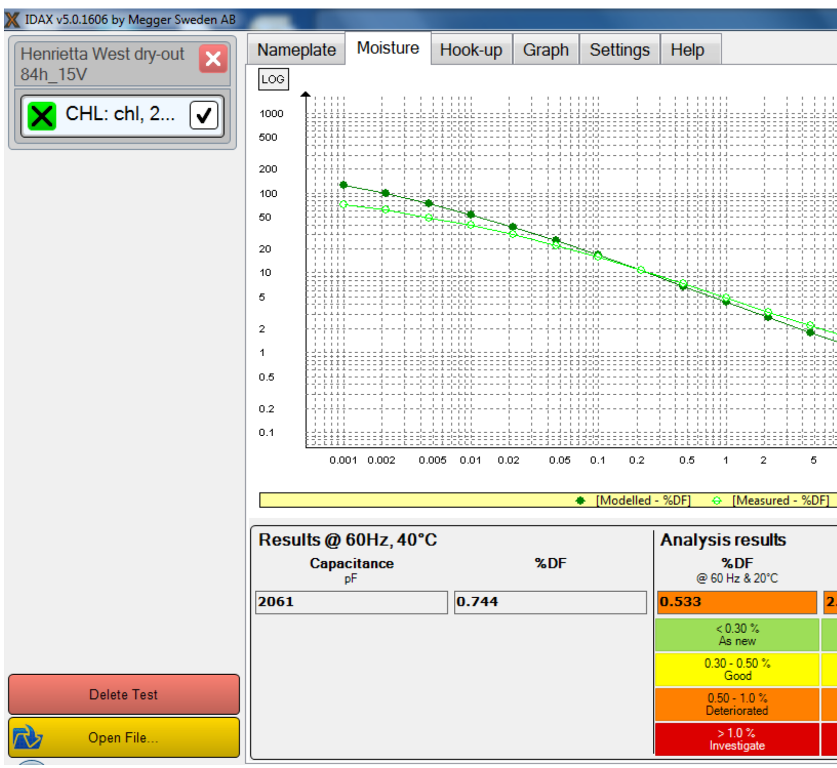
- Another 30h vacuum
  - Once the process is observed to have low or non efficiency, this is a clear indication for the operators to re-heat the core and windings and initiate a new vacuum cycle
- The dielectric response

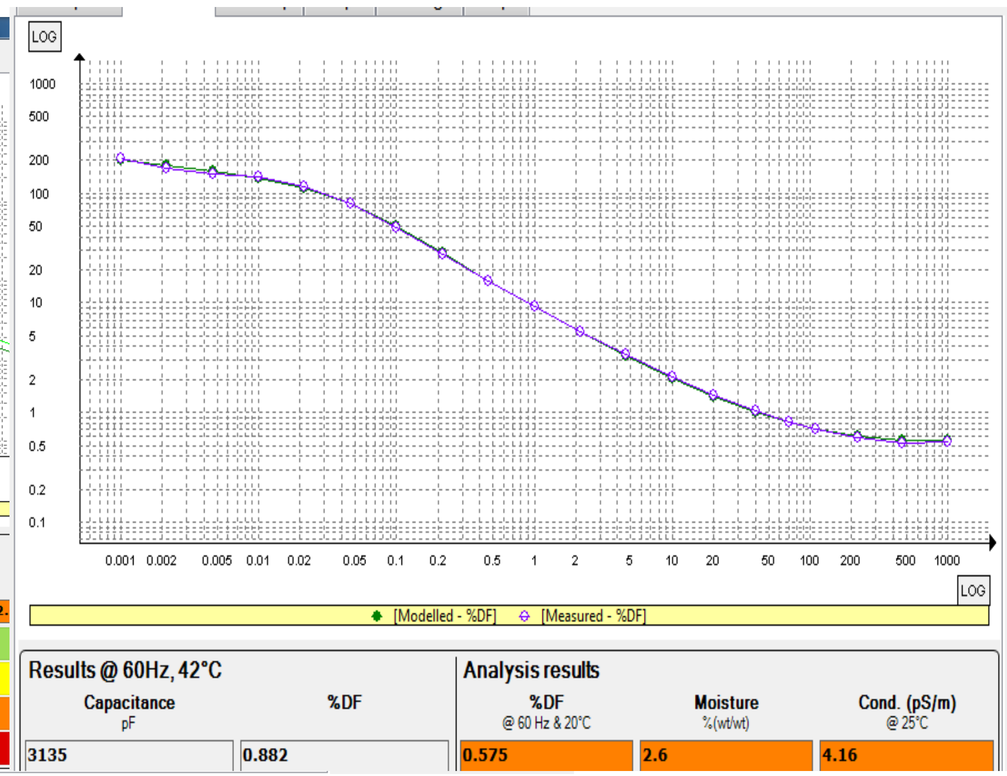


Megger.

DFR Monitoring During Field Dry-out

- Final response during the thermal-vacuum process
- Immersed in oil and after 2 weeks operation





Conclusions: DFR/FDS

- Dielectric Frequency Response (DFR) also known as Frequency Domain Spectroscopy (FDS) is an advanced application of the dissipation factor (tanδ) insulation test.
- DFR discriminates between the moisture concentration in the solid insulation and the contamination of the liquid insulation.
- The DFR instrumentation utilized in the field has evolved to overcome the field challenges such as: testing time constraints and the effect of AC and/or DC induced noise in the substations.
- DFR provides accurate temperature correction of the 60Hz power factor value not based on reference tables but on the unique dielectric response of the tested insulation system.

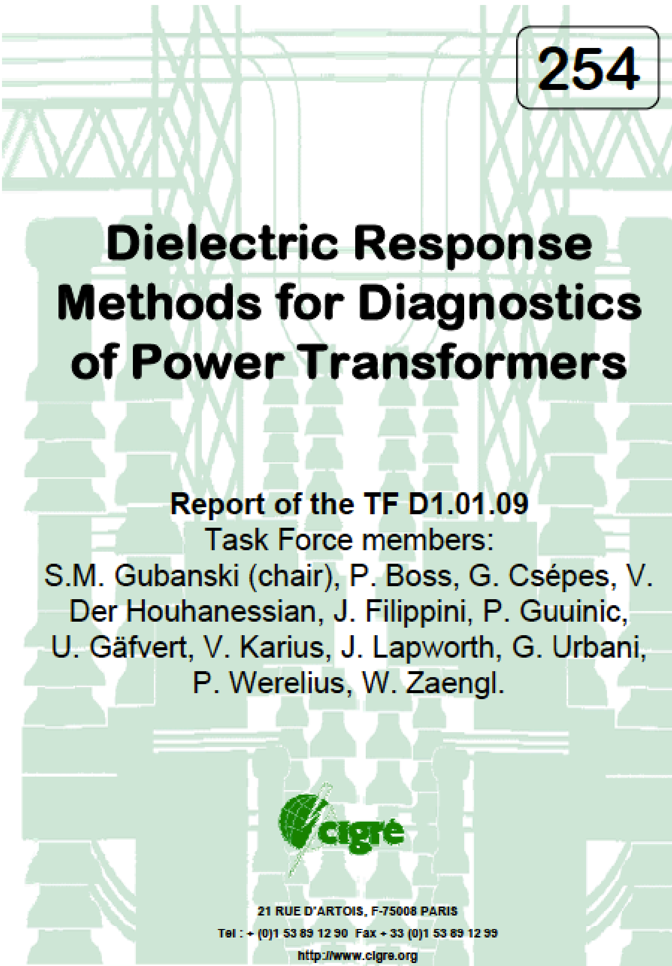
Conclusions: Transformer Field Dry-out DFR Application

- The application of DFR in the field during dry-out process is relevant.
  - It shows the point where the process reduces efficiency and slows down the moisture extraction
- DFR provides a bulk average value of %moisture concentration in the insulation investigated.
  - Other practices may involve the analysis of surface insulation and/or removal of samples that may affect the insulation integrity.
- DFR is a low voltage advances application of power factor testing where the modeling tools allow the operator to monitor the %moisture concentration variation under thermal and/or vacuum conditions.

Applicable standards

- **2004 -** CIGRE report 254, ”Dielectric Response Methods for Diagnostics of Power Transformers” is published
- **2006 -** Project REDIATOOL reported at CIGRE, recommending DFR as a preferred method for moisture assessment of power transformers
- **2009 -** CIGRE Task Force D1.01.14 “Dielectric response diagnoses for transformer windings”
- **2011 –** IEEE Transformer Committee first meeting of a TF to elaborate a DFR guide proposal – March 2012 – TF incorporated as part of the Dielectric Test Subcommittee
- **2013** – IEEE C57.152. Incorporated an informative section: Annex G : Dielectric Frequency Response

References

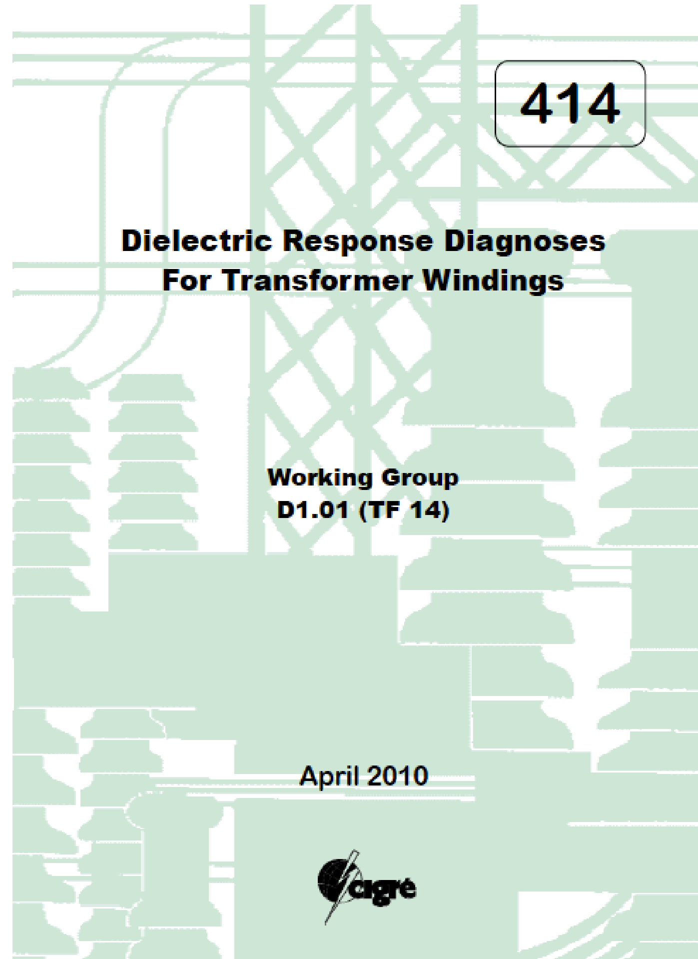

254

Dielectric Response Methods for Diagnostics of Power Transformers

Report of the TF D1.01.09
Task Force members:
S.M. Gubanski (chair), P. Boss, G. Csépes, V. Der Houhanessian, J. Filippini, P. Guuinic, U. Gäfvert, V. Karius, J. Lapworth, G. Urbani, P. Werelius, W. Zaengl.

cigré

21 RUE D'ARTOIS, F-75008 PARIS
Tel : + (0)1 53 89 12 90 Fax + 33 (0)1 53 89 12 99
http://www.cigre.org


414

Dielectric Response Diagnoses For Transformer Windings

Working Group D1.01 (TF 14)

April 2010

cigré

References

IEEE STANDARDS ASSOCIATION — IEEE

IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std C57.152™-2013
(Revision of
IEEE Std 62™-1995)

Annex G

(informative)

Dielectric frequency response

G.1 General

Dielectric frequency response (DFR) refers to a measurement of the dielectric properties, expressed as, e.g., capacitance (C) and power factor (PF), of an insulation system as a function of frequency. This is also known as *frequency domain spectroscopy* (FDS), which is an advanced diagnostic test for the field. Any factory testing is only for a signature and not an acceptance test for the power transformer. The effect of moisture and ionic contamination on the dielectric properties of the insulation system is more pronounced at low frequencies. For a mineral oil/cellulose insulation system used in transformers, the elements involved in this analysis include the moisture in the cellulose material, the conductivity of the oil, and the presence of contaminants or other materials that affect the capacitance or dielectric loss of the system.

QUESTIONS ?

- Megger North America
- +1 800 723 2861
- +1 214 330 3519
- diego.robalino@megger.com

References

- U. Gäfvert, G. Frimpong, and J. Fuhr, " Modeling of Dielectric Measurements on Power Transformers", paper 15-103, CIGRE session 1998.
- A. C. Gjaerde, L. Lundgaard, and E. Ildstad, "Effect of Temperature and Moisture on the Dielectric Properties of Oil-Impregnated Cellulose", paper 1060-1, Proc. of the ISH, 1995.
- V. Der Hauhanessian, Measurement and Analysis of Dielectric Response in Oil-Paper Insulation Systems. Doctoral Thesis, Swiss Federal Institute of Technology Zurich, Diss. ETH. No. 12832, Zurich, 1998.
- U. Gäfvert, L. Adeen, M. Tapper, P. Ghasemi, B. Jönsson, "Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostics of Power Transformers", Proc. Of the ICPADM, Xi'an, China, 2000.
- S.M. Gubanski, J. Blennow, B. Holmgren, M. Koch, A. Kuechler, R. Kutzner, J. Lapworth, D. Linhjell, S. Tenbohlen, P. Werelius, "Dielectric Response Diagnoses for Transformer Windings," CIGRE WG D1.01 (TF 14), Brochure 414, 2010
- Cheng, J. ; Werelius, P. ; Ohlen, M. "FEM analysis of the transformer insulation XY model," Proceedings of the Transmission & Distribution conference, 2012
- Ernst, W., Kau Ho, Levin, A. "Dry-out properties of insulating paper in distribution transformers", Proceedings of the Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2012
- Valery G. Davydov, "Moisture Related Phenomena in Transformers and Reactors: Need for Development of a New Reference Document," Proceeding TechCon North America 2012.
- P. Koestinger, E. Aronsen, P. Boss, G. Rindlisbacher, "Practical Experience with the drying of Power transformers in the field, applying LFH Technology," CIGRE, Session 2004, A2-205.