Insulation Diagnostic Methods
(for Transformers and Bushings)

Jill Duplessis, Megger

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Content

- Dielectric/Insulation
  - Function and Health Criteria
  - Behavior and Loss
- Dielectric Assessment/Test Methods
  - Traditional Power Factor (P.F.) Measurement
  - Dielectric Frequency Response (DFR)
    - Narrow band (1 – 500 Hz), a.k.a., variable frequency P.F.
      - Diagnostic Advantages
      - Individual Temperature Correction (ITC)
    - Wide band (0.1 mHz – 1 kHz)
      - Diagnostic Advantages
- Summary

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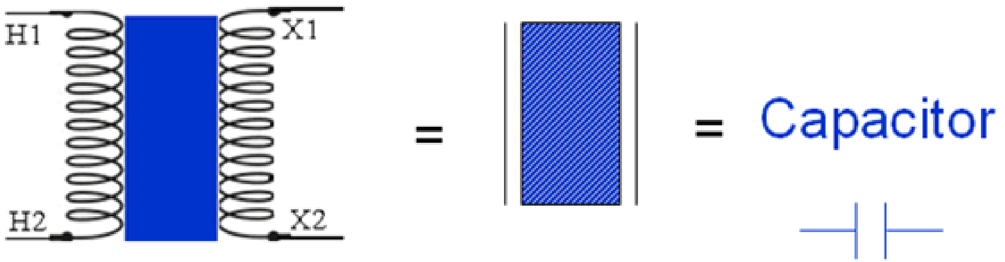
DIELECTRIC/ INSULATION

Dielectric/Insulation

- IEEE Defines Insulation as: “Material(s) that provides electrical isolation of two parts at different voltages.”
- Electrical isolation means that I_R is practically zero.



- Dielectrics perform best when they are clean, dry, relatively void-free, and used within a certain temperature range.

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Dielectric/Insulation

- Adversaries to a Dielectric's good health
  - Heat
  - Moisture
  - Oxygen

- As an asset owner, what does awareness of my dielectric's health gain me?

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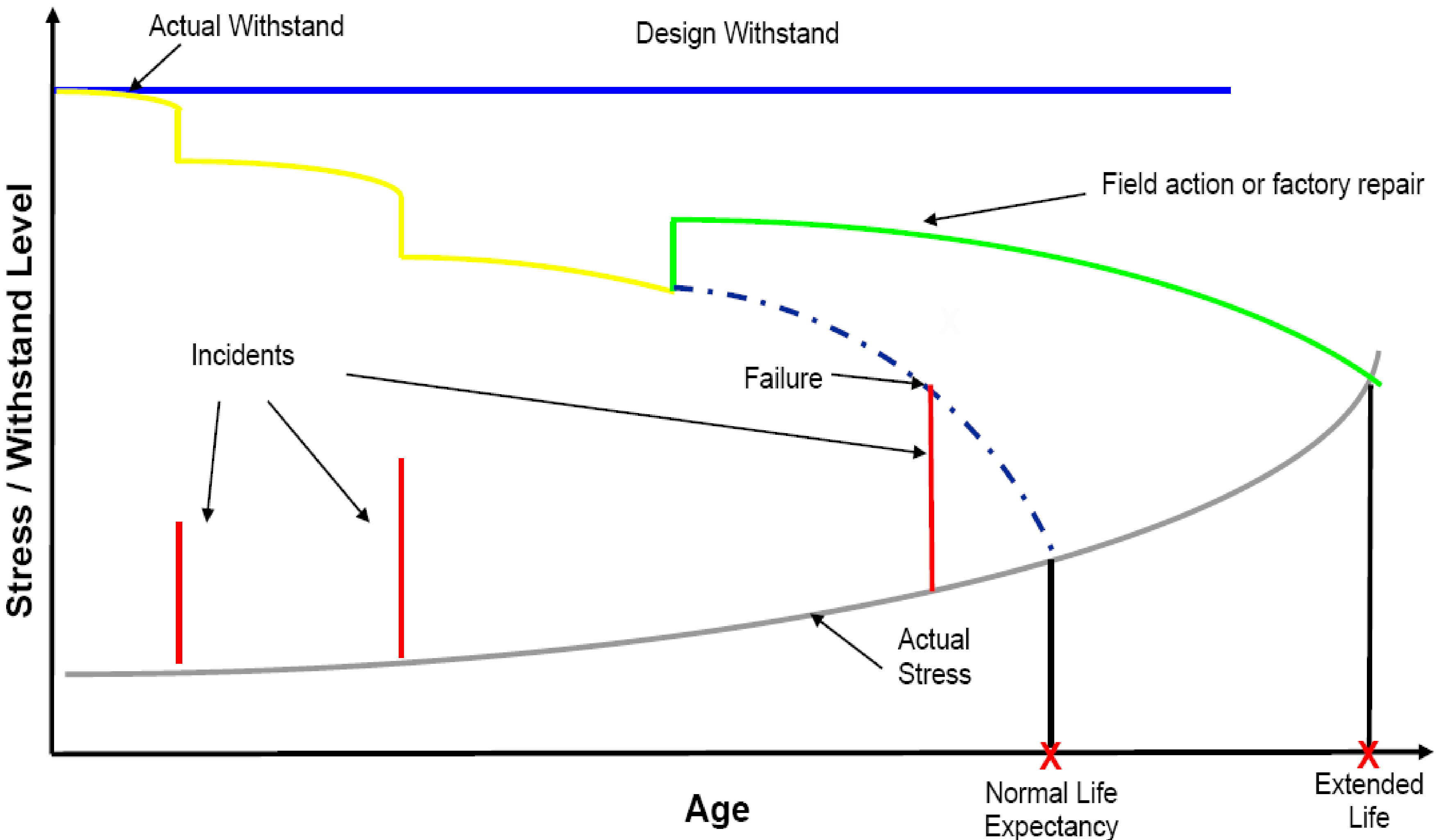
Influencing the Life of a Transformer



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Investigating a Dielectric's Health

- Characteristics that portray a Dielectric's state of health
  - Losses
    - Conductive
    - Polarization
  - Capacitance

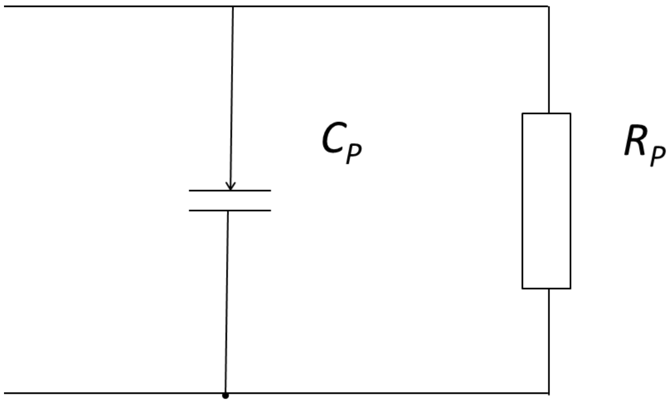
- Understanding behavior - Generally in science:
  - Observe and measure
  - Create a model
  - Verify model by experiments
  - Extend model (only) if necessary

Dielectric Model

- a tool that correctly replicates the expected electrical response of an insulation system when we apply a voltage
- created using electrical components that together emulate the behavior of the insulating system of materials.
- With a good model, we can confidently predict how the dielectric response will change when undesired changes occur.

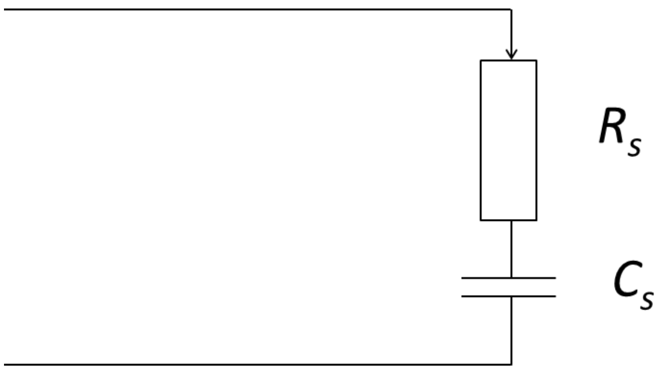
Dielectric Losses

Conductive Losses



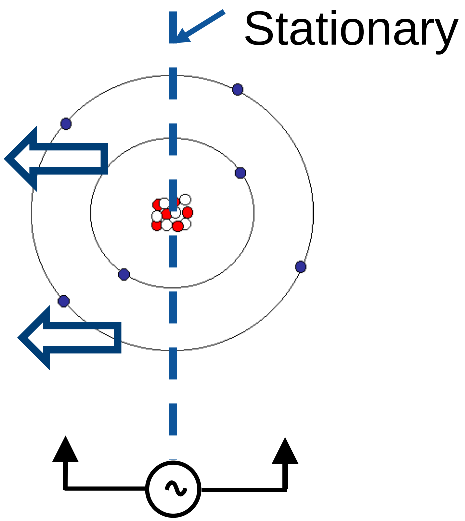
- Represents the swing between a purely insulating system and a completely conducting one

Polarization Losses



- Models polarization losses (e.g., electronic, ionic, orientational, hopping, interfacial)

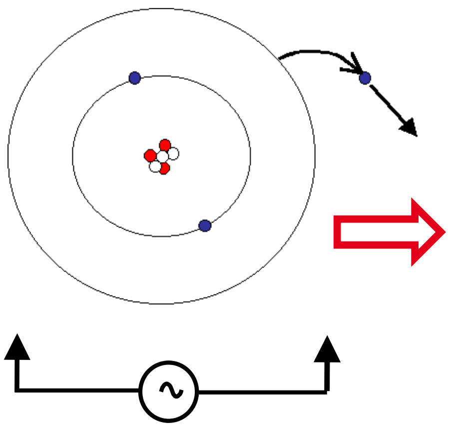
Polarization Losses



Test Voltage

- **Electronic:**

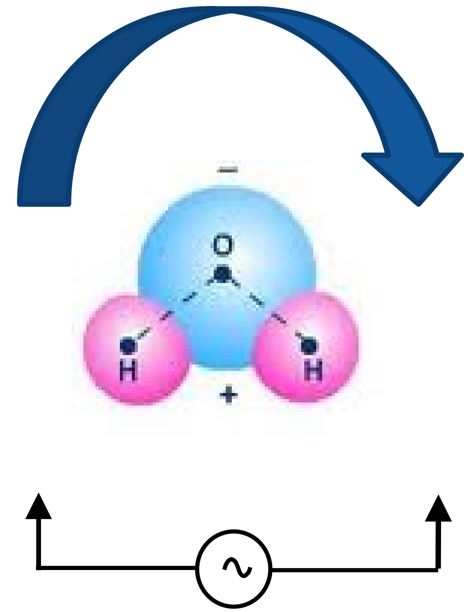
Displacement of the electron cloud



Test Voltage

- **Ionic:**

Displacement of the whole atom



Test Voltage

- **Orientational:**

permanent dipoles align in direction of the applied field

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Polarization Losses (associated with mobile & trapped charges)

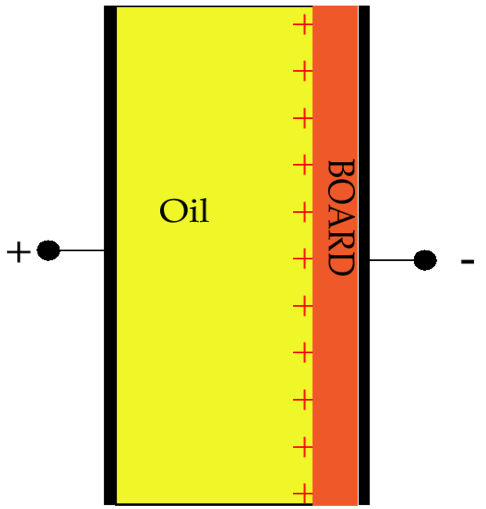
Hopping Polarization

- Created by localized charges that move freely for a short time but then become trapped & spend most of their time in a localized state.

Interfacial

- Produced by the separation of mobile, charged particles that form positive & negative space charges at the interfaces between different materials.

Dominate at
$f < 10$ Hz



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TEST METHODS

Traditional Power Factor

- Other names
  - Cos ϴ
  - Dissipation Factor
  - Tan delta, Tangent δ

- To date, the most widely-used electrical method to determine the dielectric health of an asset

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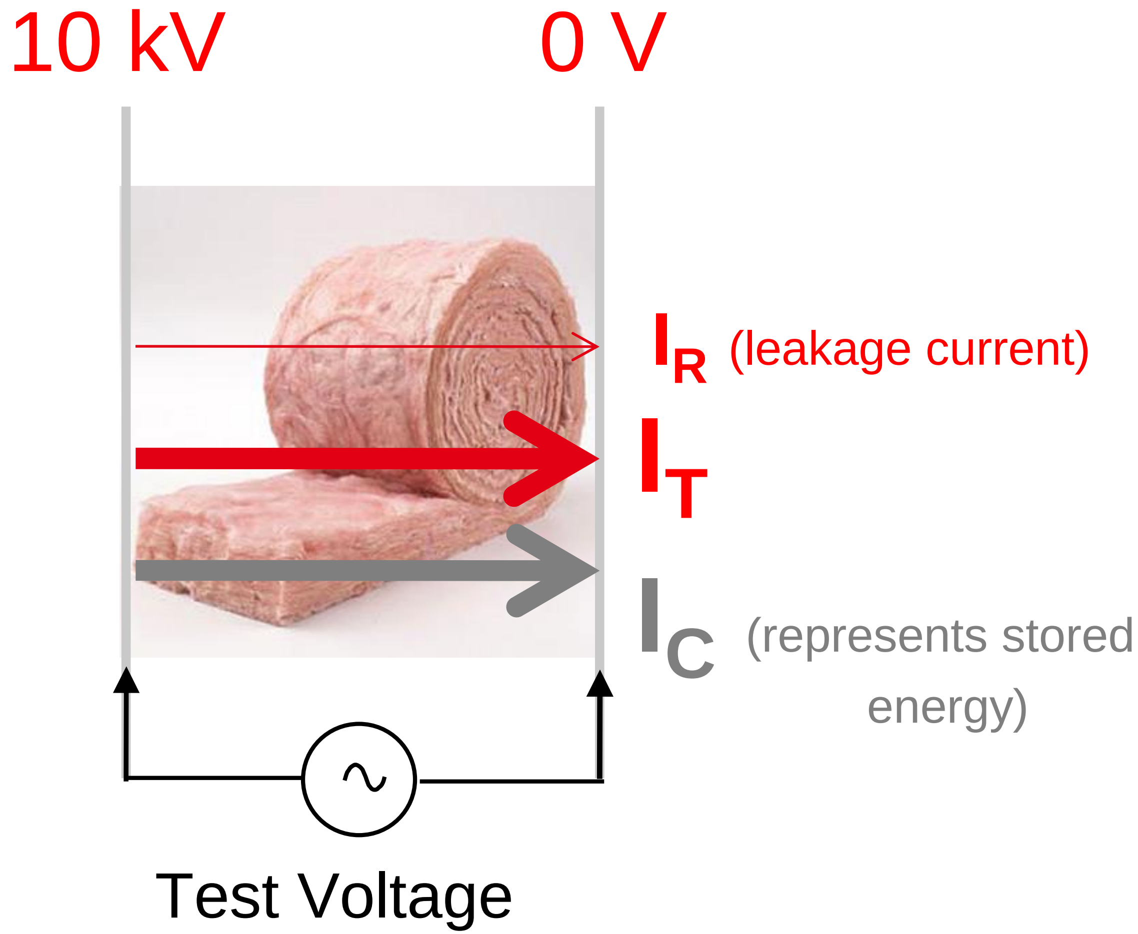
Executing a Power Factor Test



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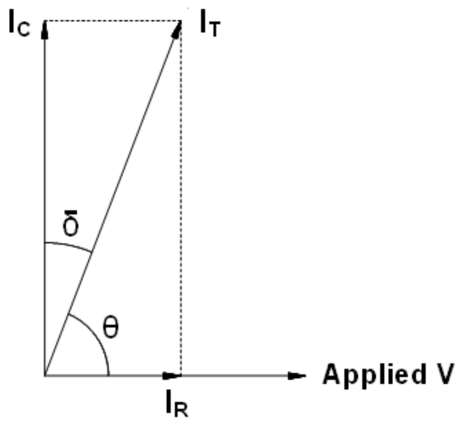
Calculating Electrical Characteristics

- Losses (Watts) = $E \times I_R$
- Capacitance = $[I_C / (E\omega)]$
- Power Factor = $(I_R / I_T) = \cos\Theta$



- Power Factor is a number that represents a system's losses relative to its overall size
- Power Factor = Relative losses so allows a user to directly compare different sized insulation systems (by their power factors) and know which one is performing more efficiently

Power Factor

- P.F. describes the amount of energy lost by the system relative to the total energy to which it is subjected.

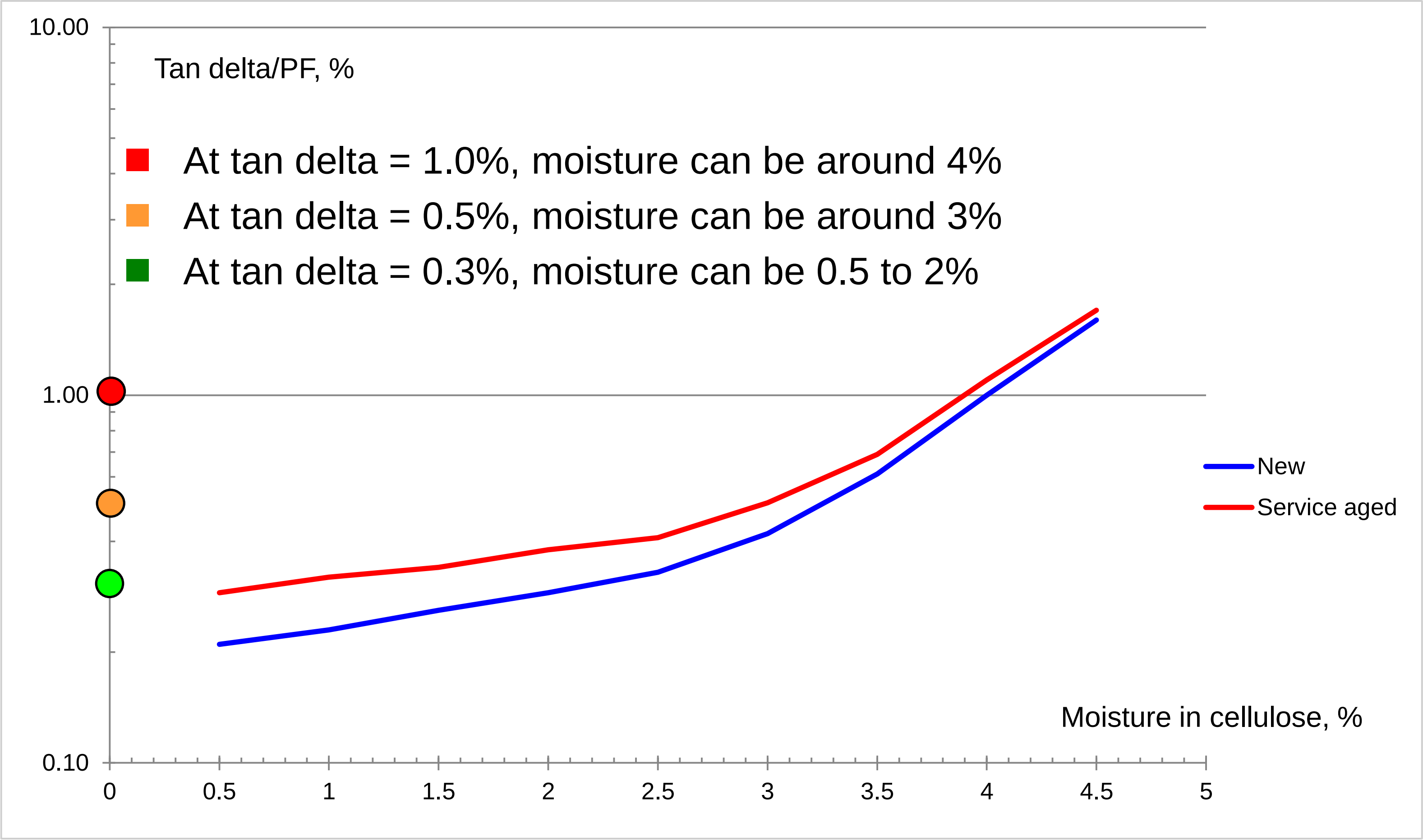
- P.F. is an index that ranks the efficiency of an insulation system on a scale of a 0 to 100, where 0 indicates a completely insulating system.

- Assessment Approaches:
  - Comparison with previous
  - Trending
  - Comparison with limits

Deficiencies of Power Factor

- Averaging Test
  - Impacts ability to see a problem
  - Impacts ability to discriminate between localized problems (immediate attention required) and widespread general deterioration (regular monitoring)
- Not acutely sensitive to problems at line frequency
- When a problem is indicated, impossible to differentiate and characterize the source – leaving "why has my P.F. changed?" unanswered

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



An Extra Challenge

- Lack of sensitivity to problems at 60 Hz means that small changes in P.F. may be significant.
- Trending is the best analytic tool.
- Challenge becomes filtering other variables that may be influencing test results so that trending is meaningful
  - Test temperature!!
  - Influence of bushings (excessive surface leakage, deteriorated bushing(s))
  - Test preparation mistake
    - Use of rubber blankets to achieve clearances
    - Failure to physically isolate terminals

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Getting more from a P.F. Measurement

- Further segmentation of the system **Diagnostic**
  - Use of an accessible core ground as a test point
  - The Cross-Check Method
  - Using the DETC to segment the winding

- Measuring P.F. at Multiple Frequencies **Routine**
  - Narrow Band Dielectric Frequency Response (multiple frequency insulation test)
  - Wide Band Dielectric Frequency Response

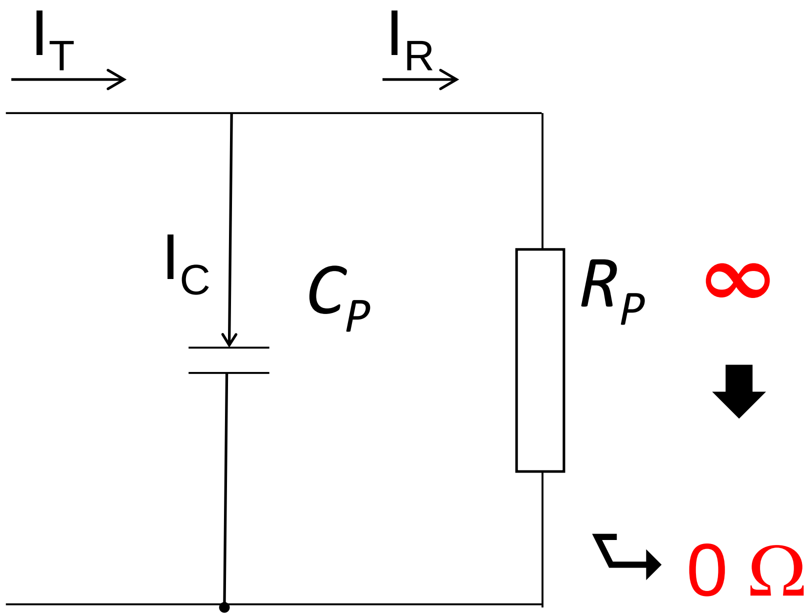
Narrow Band Dielectric Frequency Response

MEASURING P.F. AT MULTIPLE FREQUENCIES

Multiple Frequency Insulation Test

- Enhanced ability to see conductive losses at lower frequencies

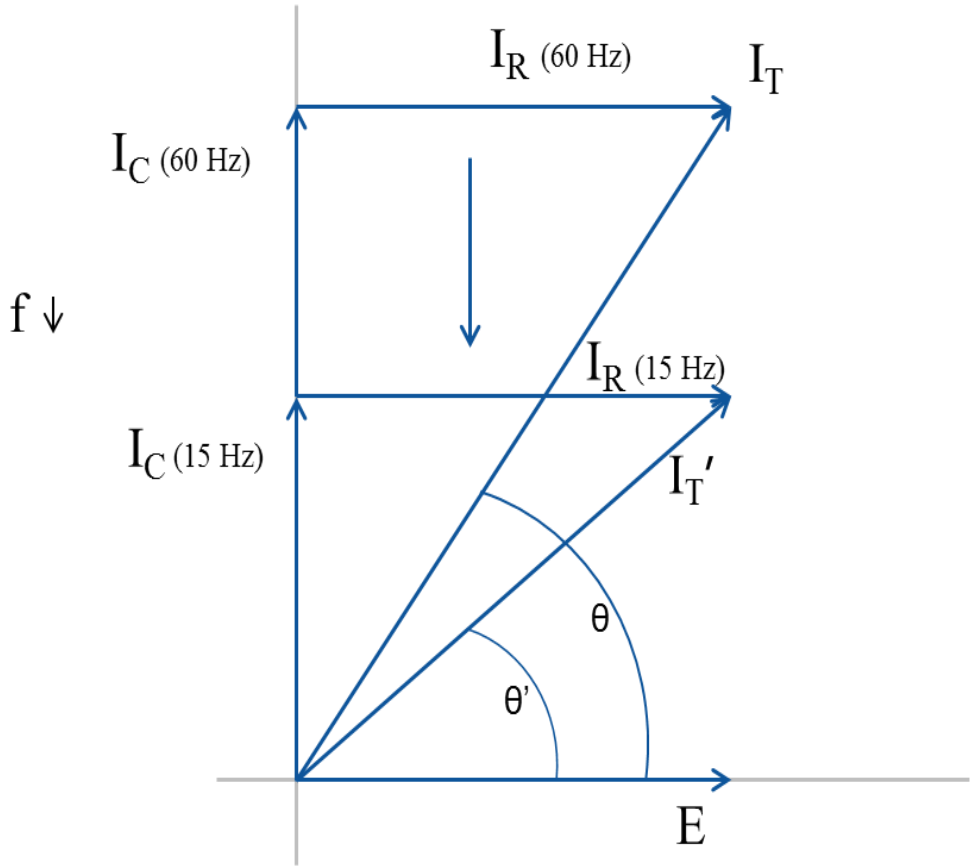
Power Factor = (I_R/ I_T)



(Insulating)

(conducting)

Same Conductive Losses are More Visible at Low Frequencies



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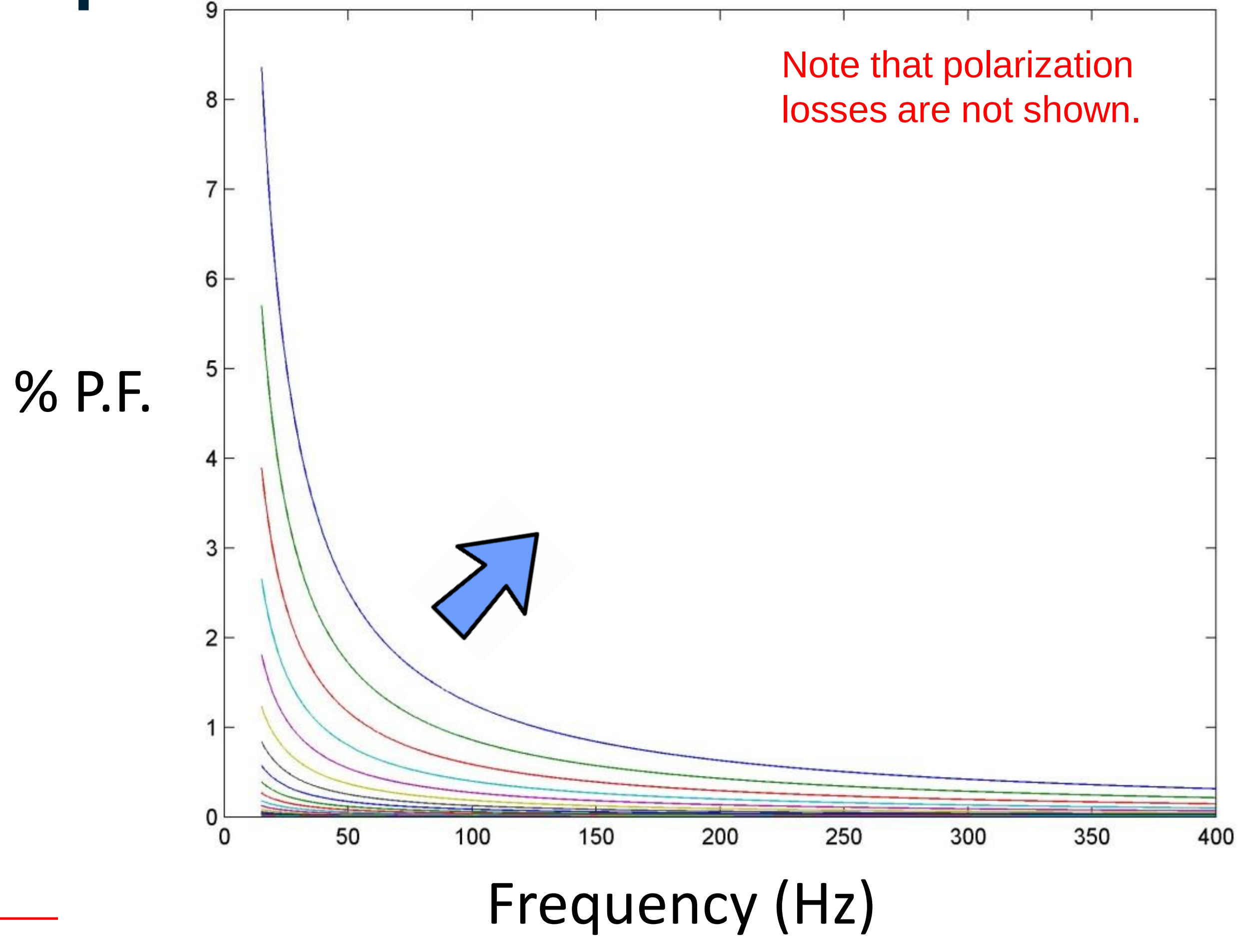
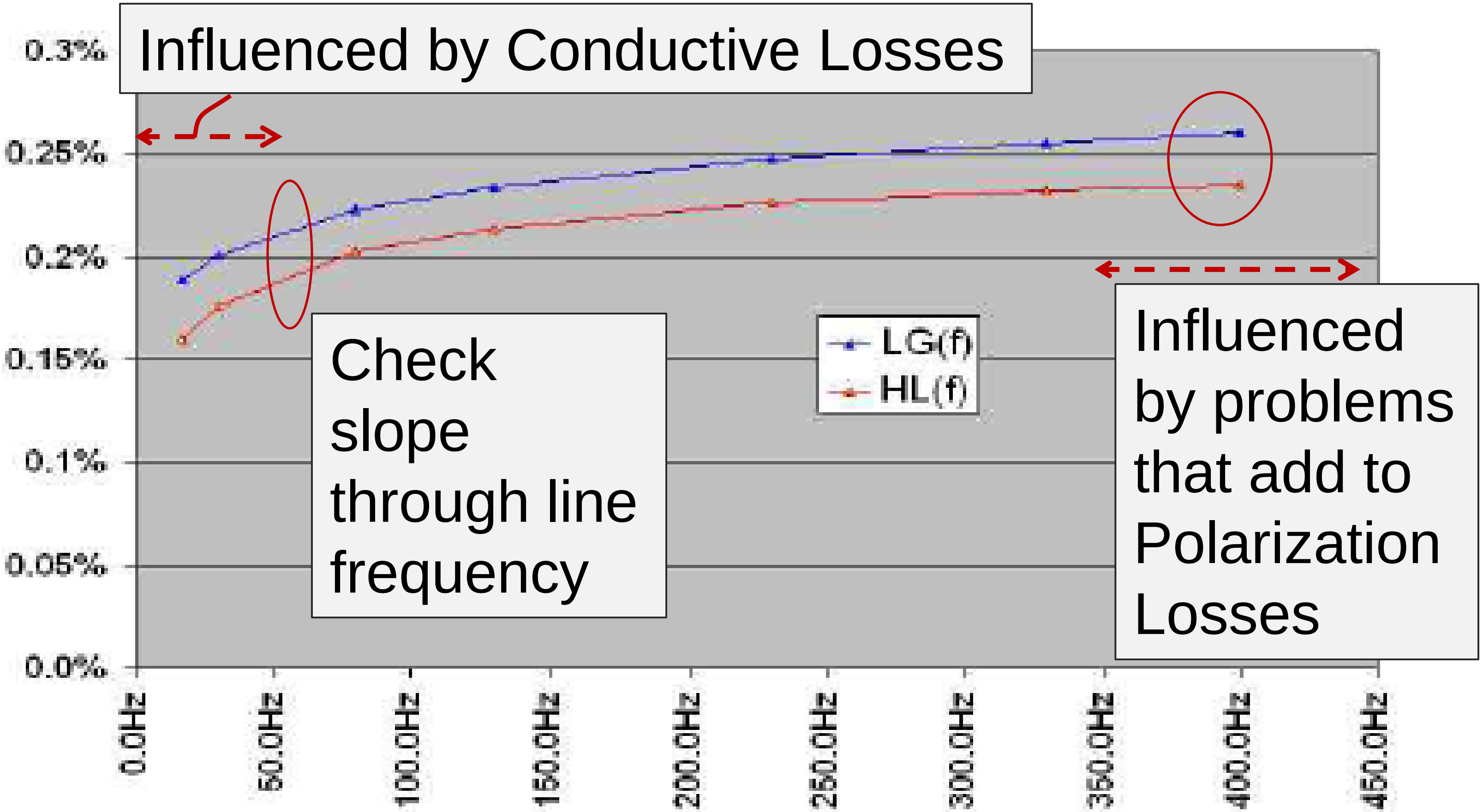
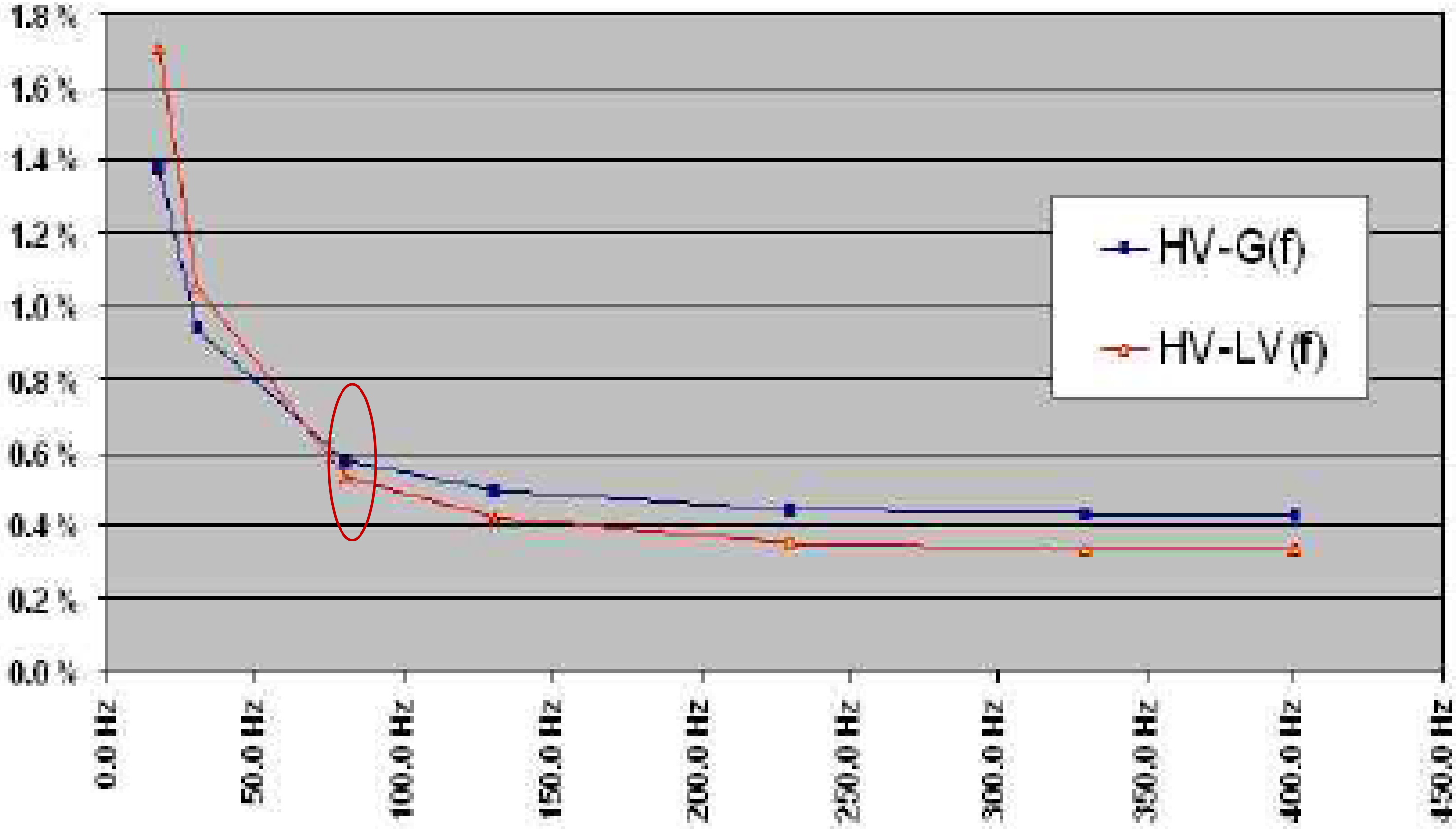
Increasing Conductive Losses at Multiple Frequencies



Multiple Frequency Insulation Test on a Healthy Transformer



Transformer with High Moisture Content



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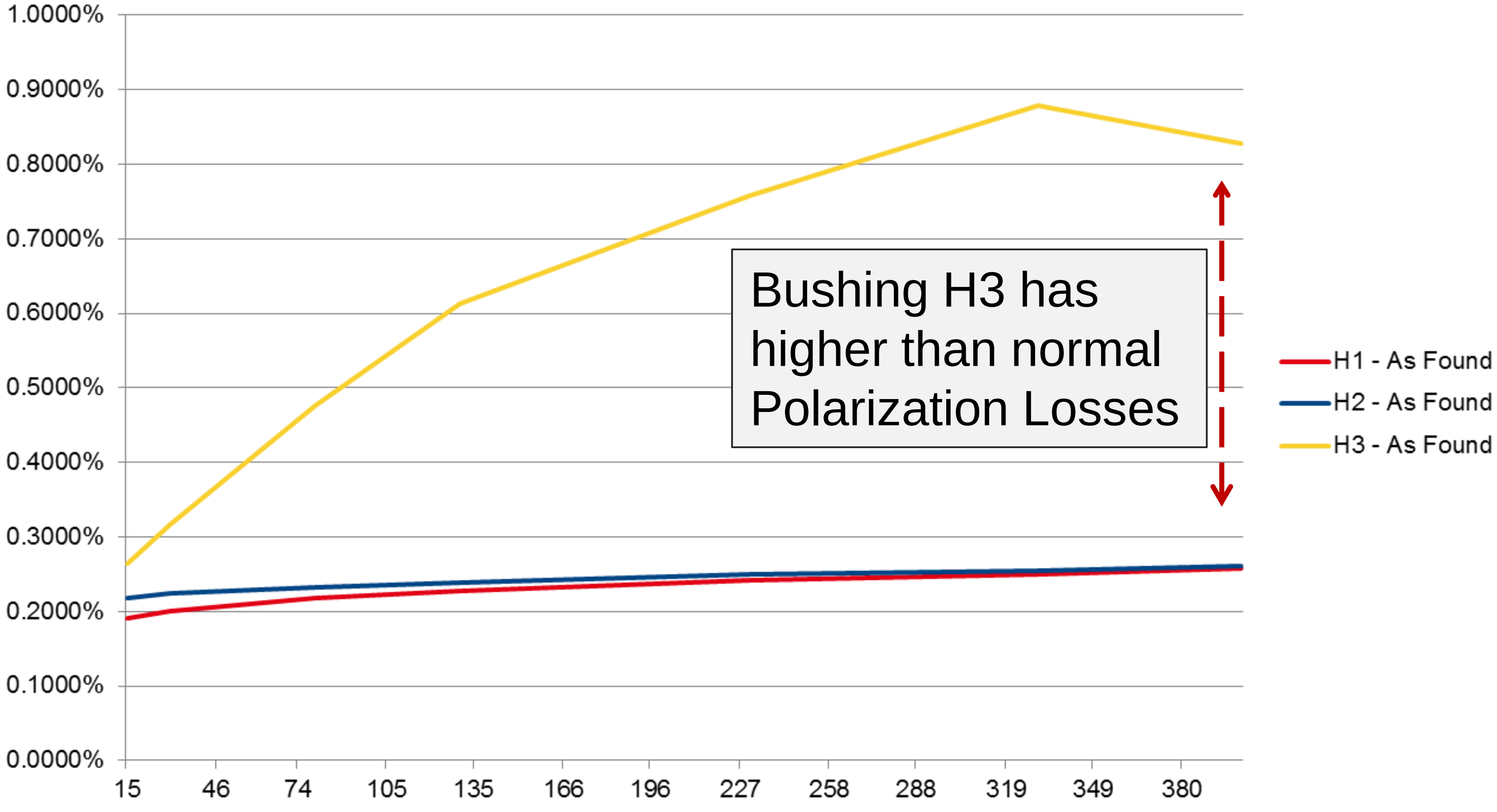
230 kV ABB O+C bushings – High Polarization Losses



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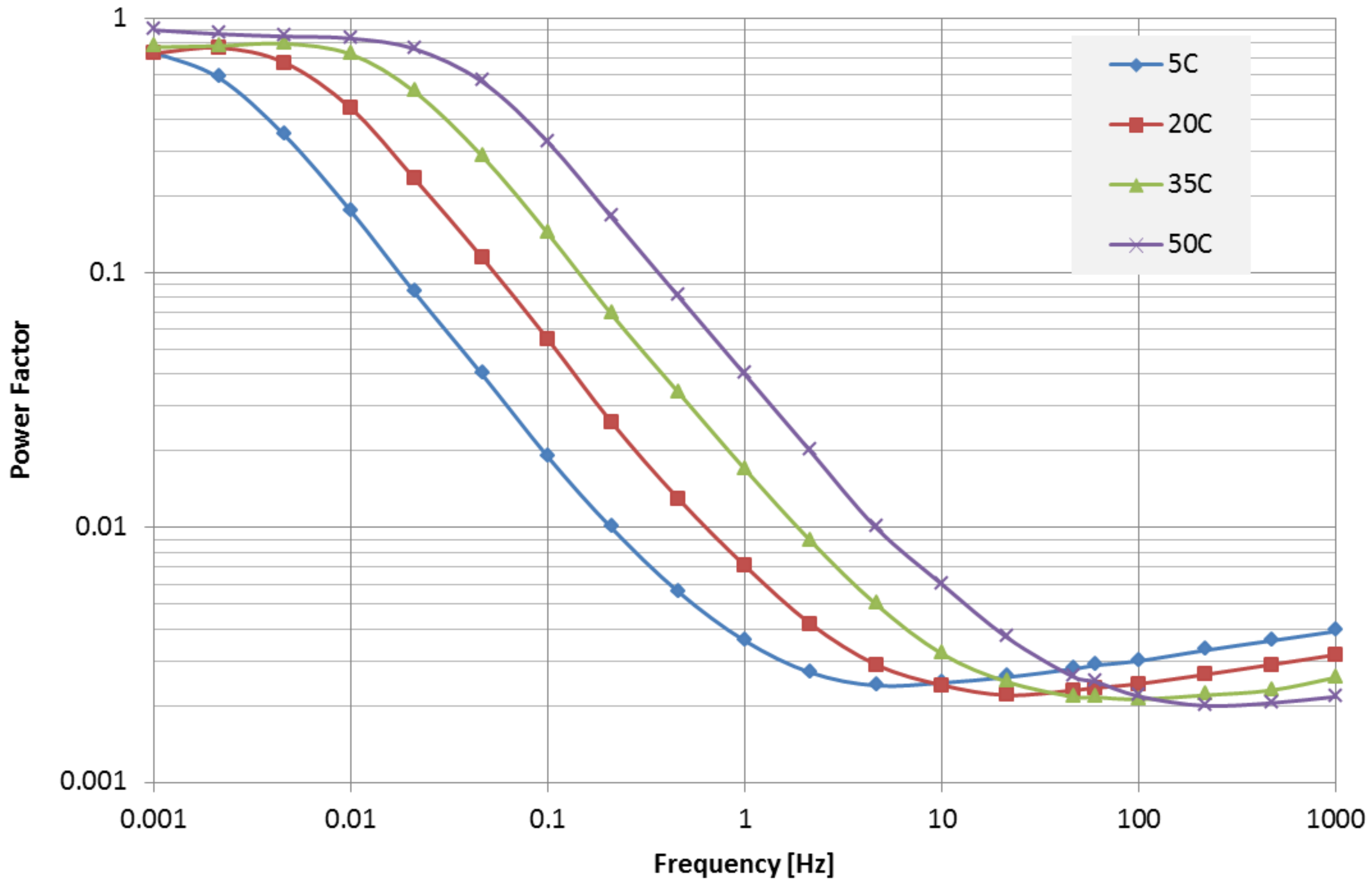
Loose Top Terminal

INDIVIDUAL TEMPERATURE CORRECTION (ITC)

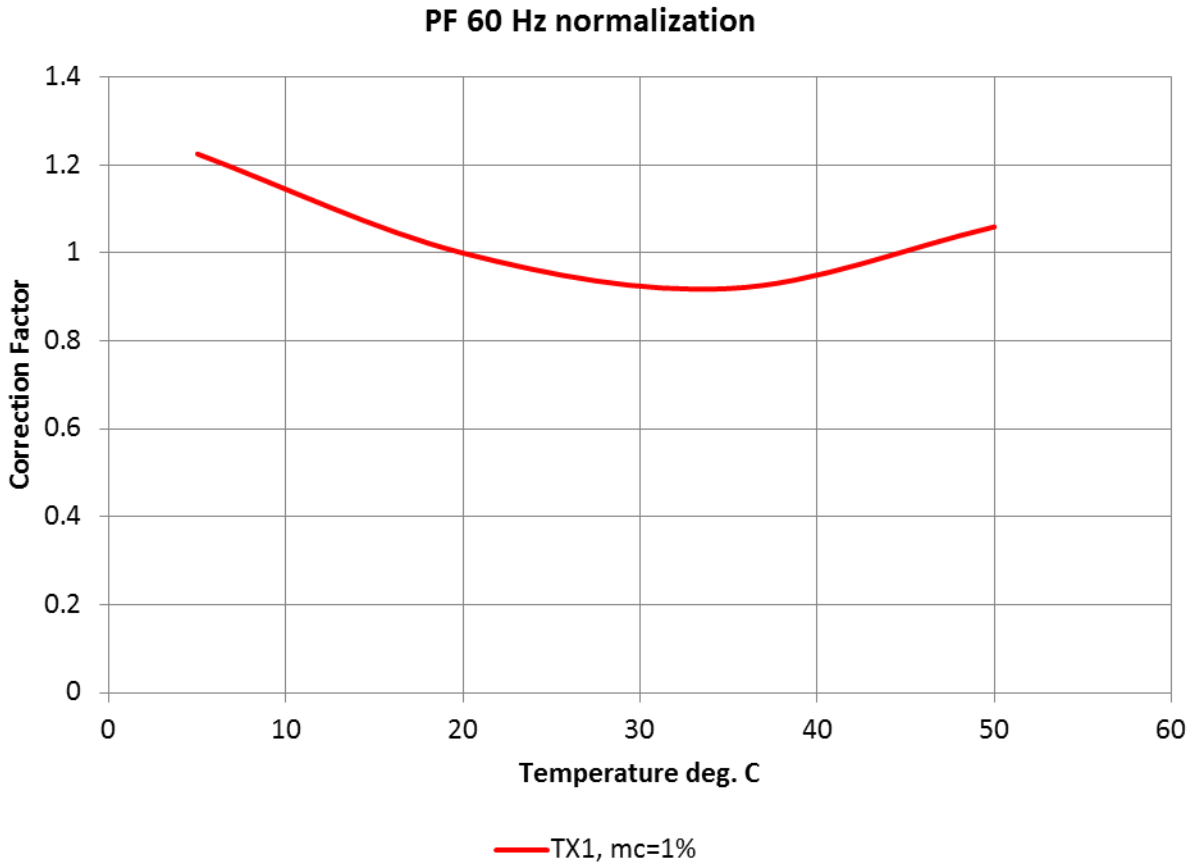
Individual Temperature Correction

- Using the frequency response to estimate temperature dependence

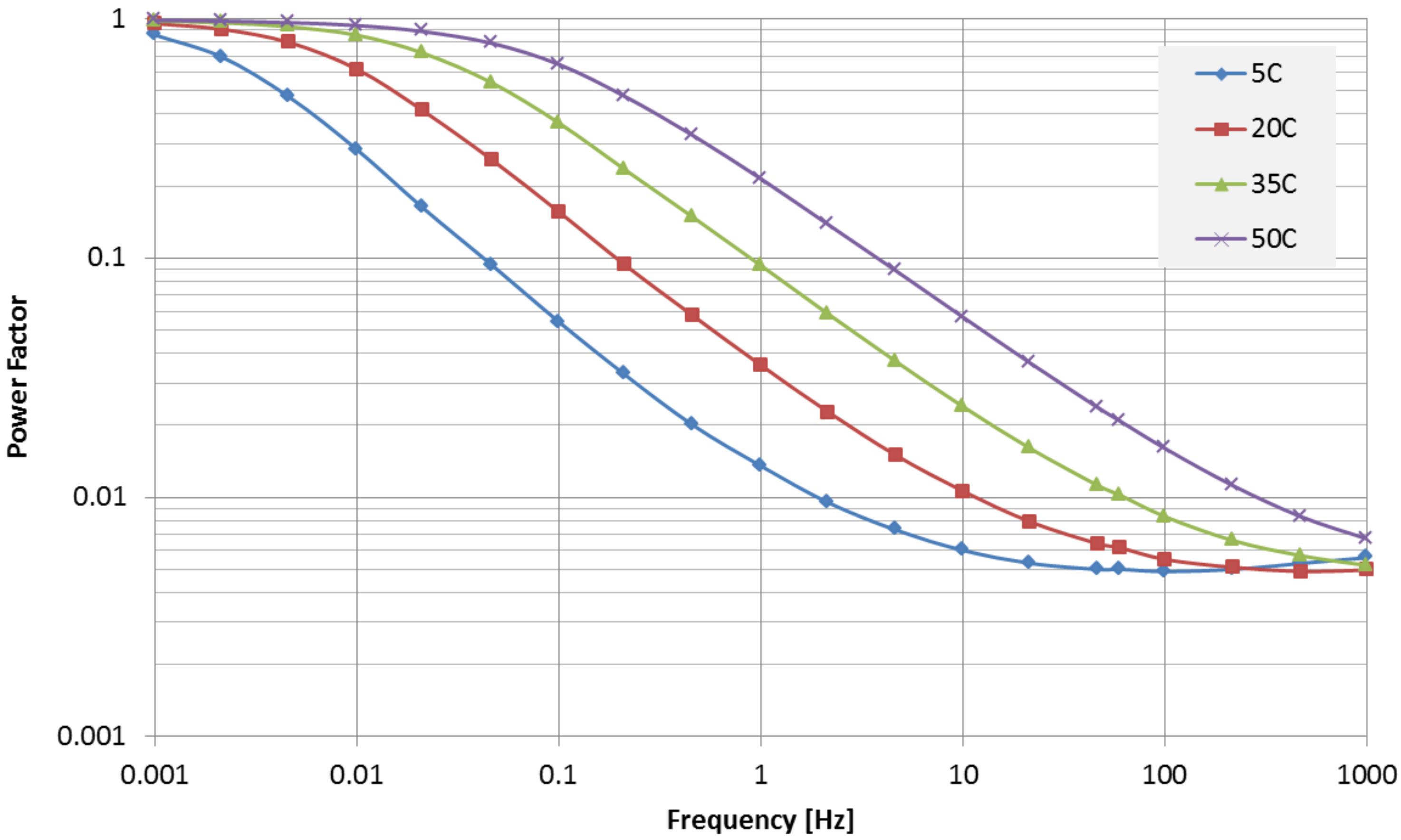
DFR measurements for a Sample with 1% Moisture Content



Correction Factors for PF for the Sample with 1% Moisture Concentration



DFR measurements for a Sample with 3.5% Moisture Content



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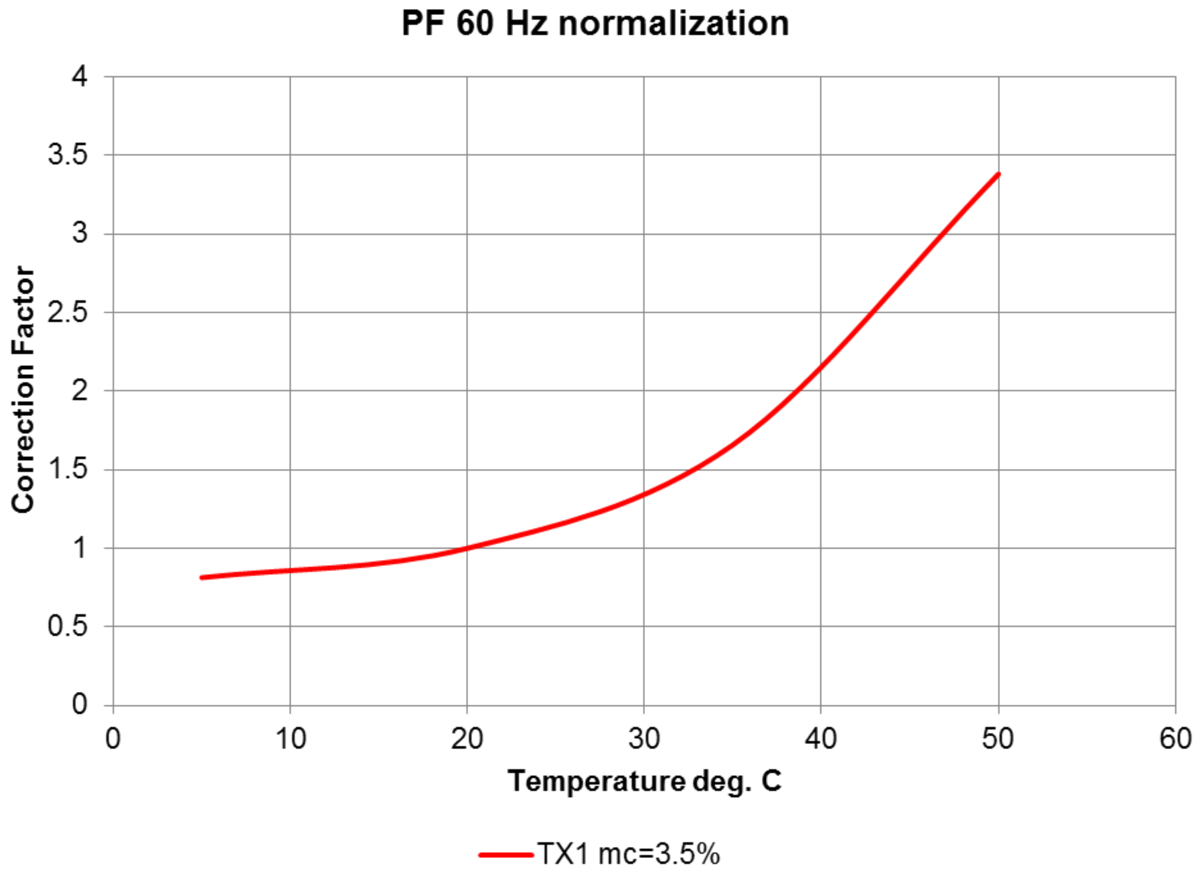
Correction Factors for PF for the Sample with 3.5% Moisture Concentration



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Individual Temperature Compensation

- Generic correction factors were available in IEEE standard C57.12.90-2006, section 10.10.5 but were removed in C57.12.90-2010 with the following note:
- *Note 3.b) Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases.*

Individual Temperature Correction

- Able to correct to any temperature (5 – 50 °C)

- Can be used as a diagnostic indicator. The temperature correction of an asset should not change appreciably with time if the asset's condition remains relatively unchanged.

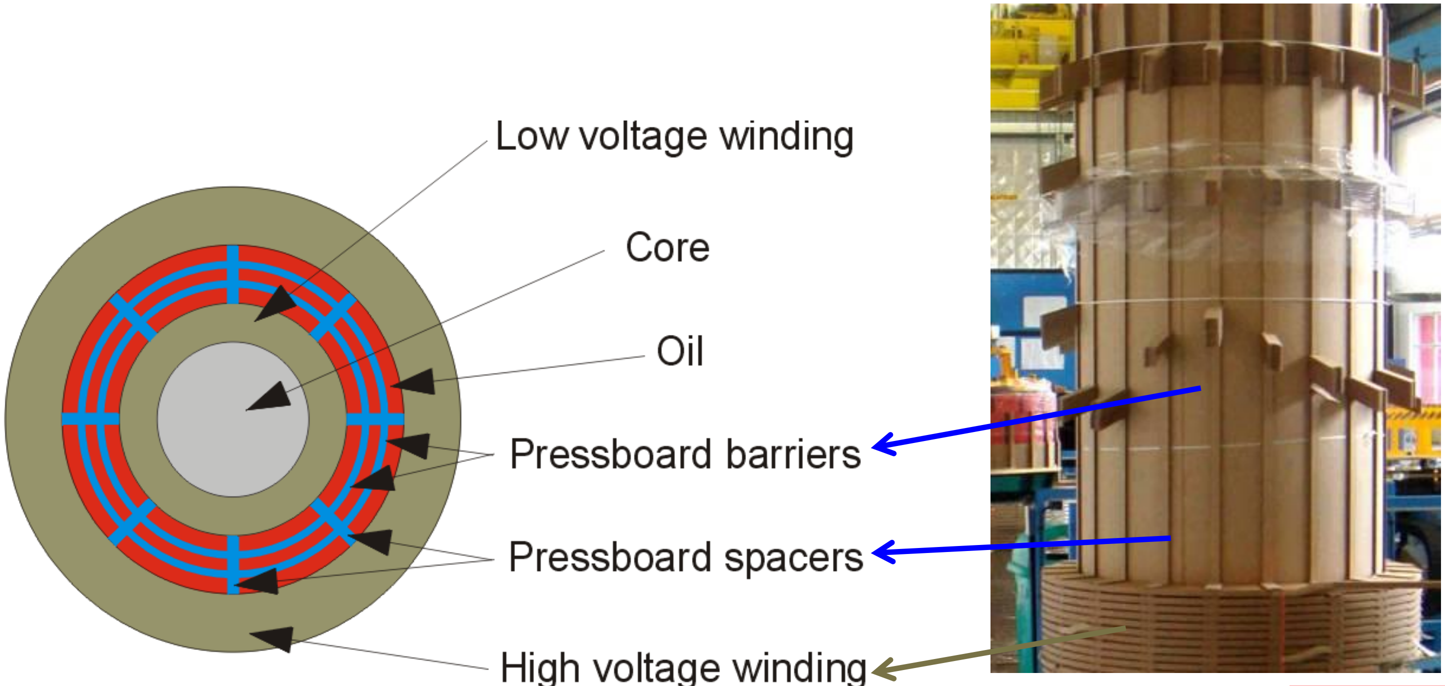
- Dr. Diego Robalino, "Individual Temperature Compensation – Benefits of Dielectric Response Measurements", Transformers Magazine, Vol 2 Issue 3, July 2015

DIELECTRIC FREQUENCY RESPONSE (DFR)

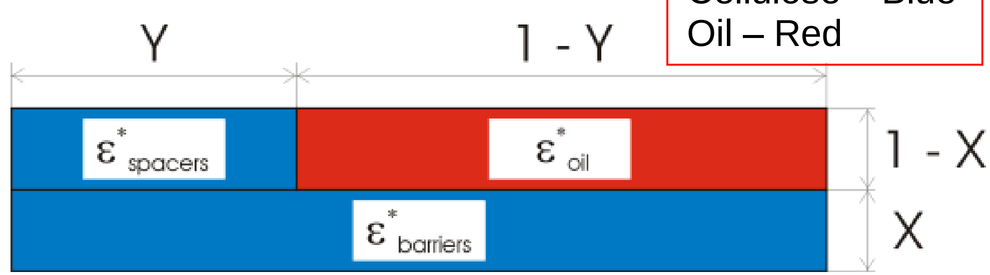
FDS/DFR moisture assessment

- Measure tan delta from 1 kHz to 1 mHz (20 C)
- Analysis is performed by software
- Confirm insulation temperature (winding/top-oil temperature)
- Software 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

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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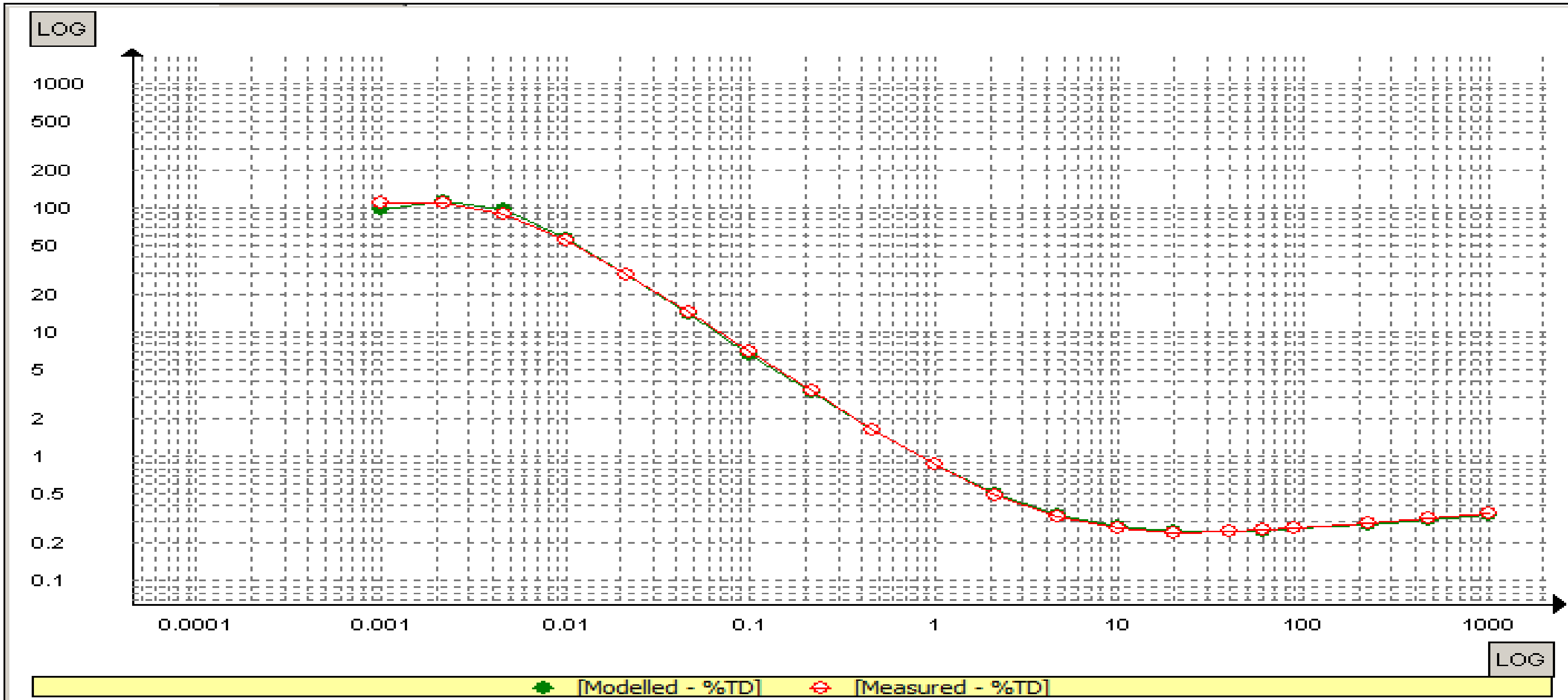
DFR measurement and moisture assessment



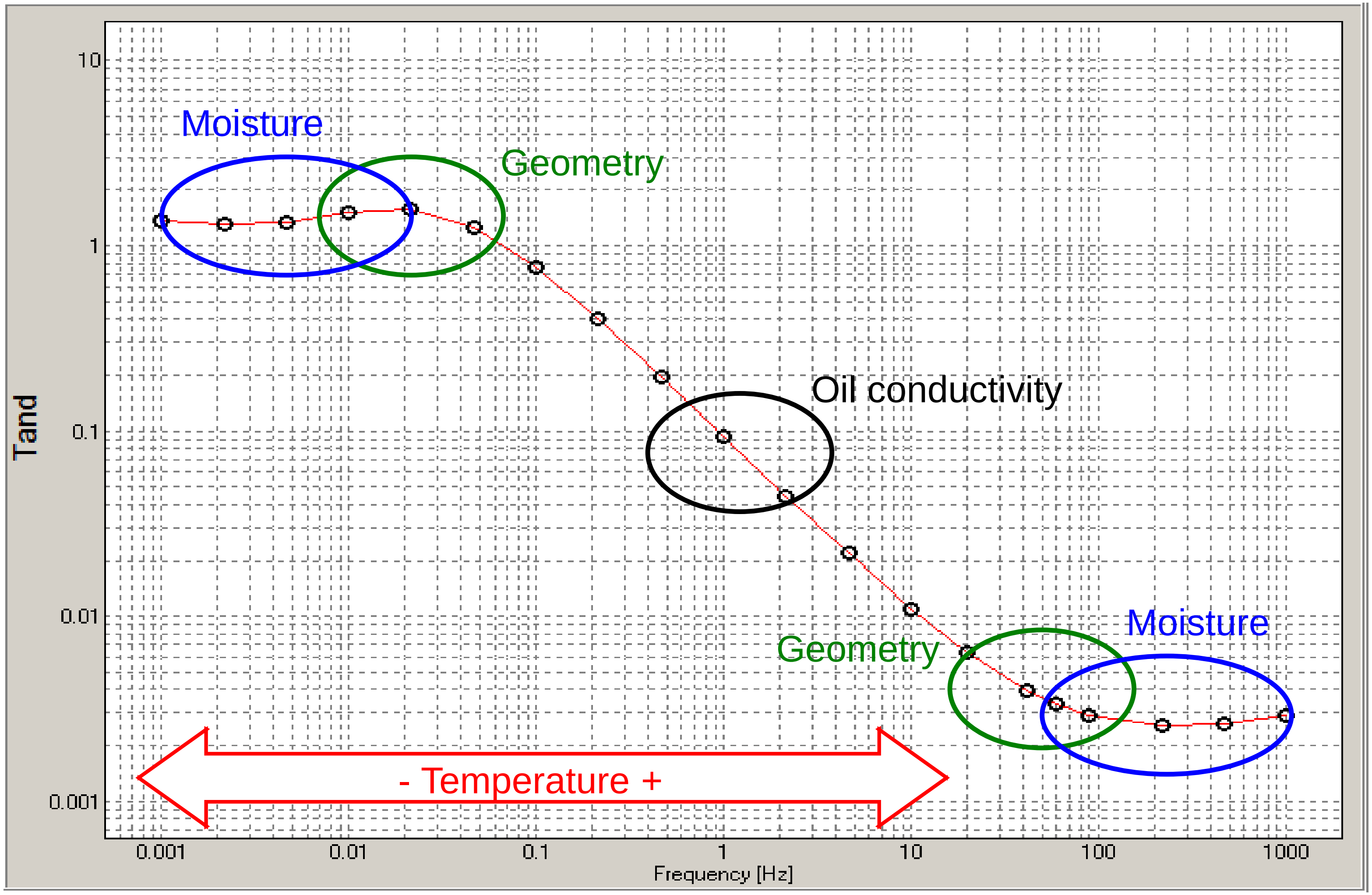
Results @ 50Hz, 24°C

Capacitance pF	%TD
6125	0.255

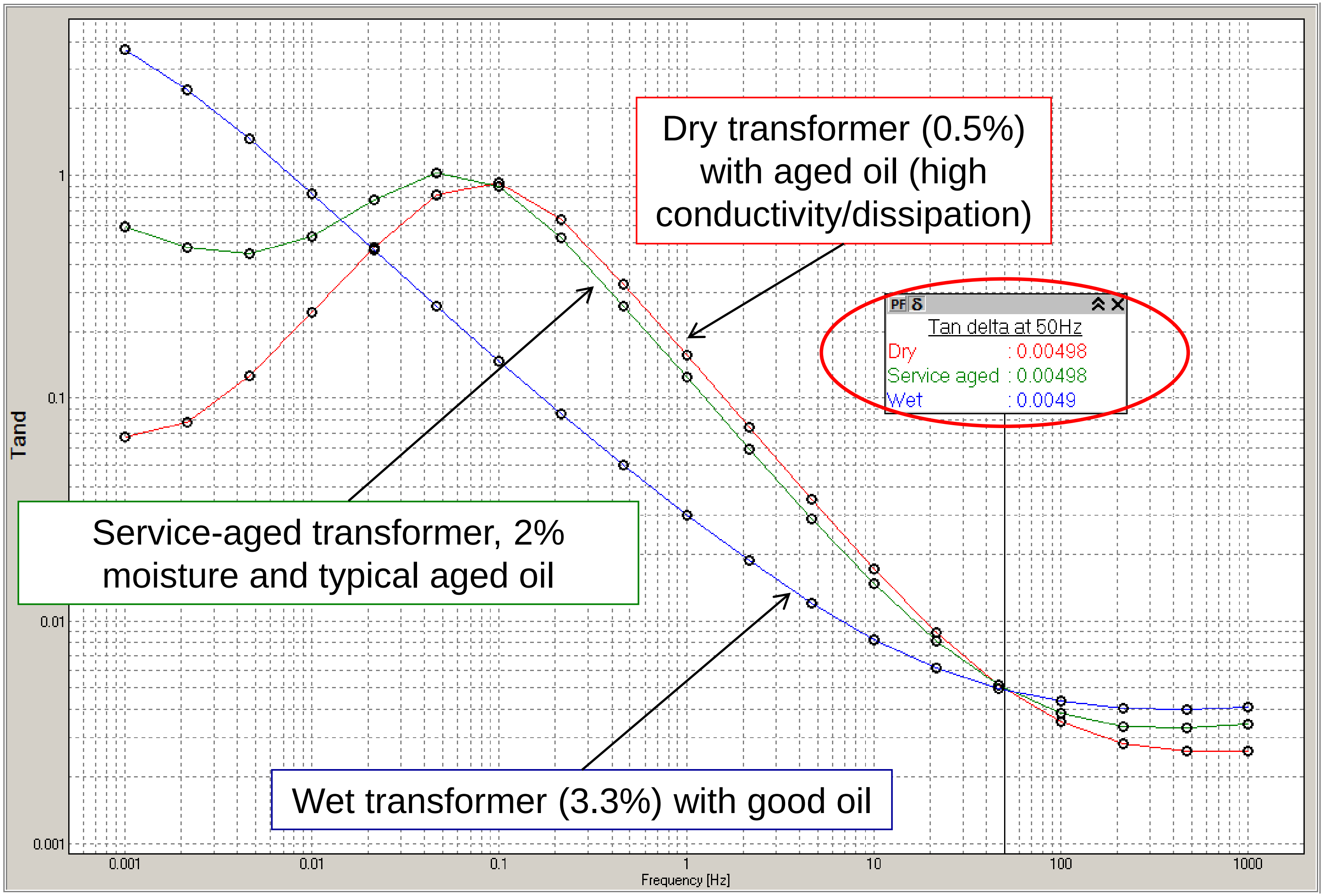
Analysis results

%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

What affects the frequency response?



DFR - Investigating 0.5% tan delta values



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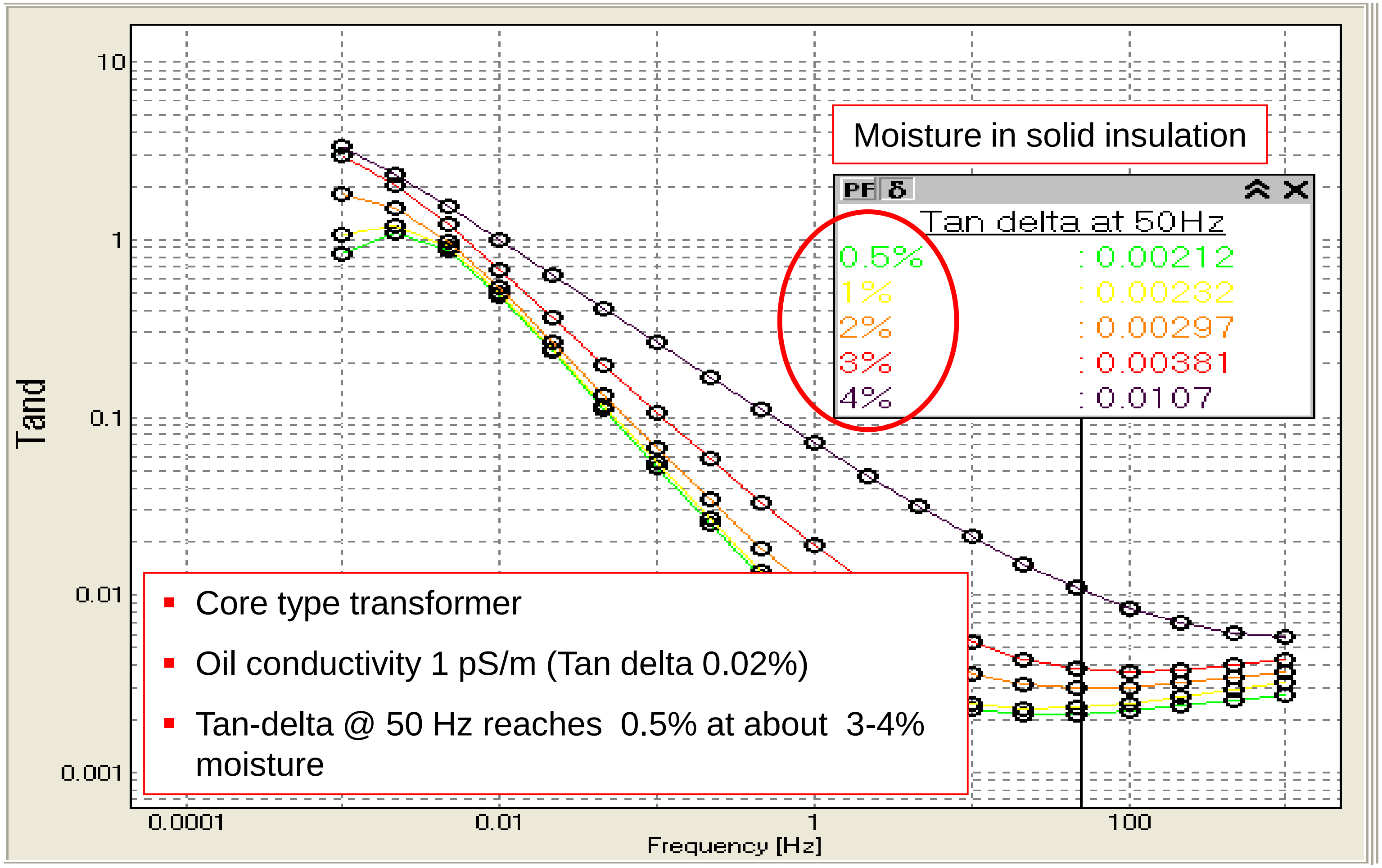
Tan delta vs moisture @ 20 C



- Core type transformer
- Oil conductivity 1 pS/m (Tan delta 0.02%)
- Tan-delta @ 50 Hz reaches 0.5% at about 3-4% moisture

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**

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

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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SUMMARY

Summary

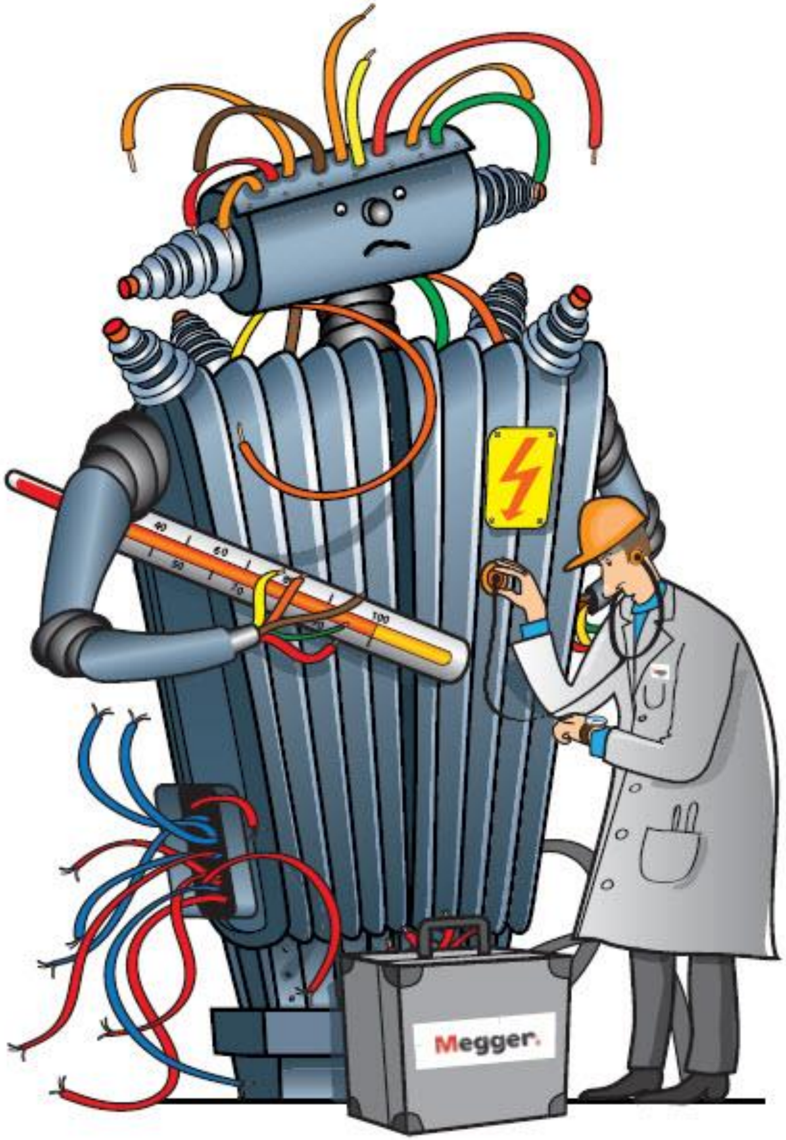
- A traditional power factor test is not acutely sensitive to changing levels of contamination
- Power Factor is sensitive to temperature
- Trending is the best approach for analyzing traditional P.F. measurements
- Trending success relies on representative test results, e.g., properly corrected to a 20°C base.
- Individual Temperature Correction of dielectric properties can be performed in both frequency domain (tan delta) and time domain (e.g. Insulation Resistance)

Summary

- To push past the limitations of a traditional power factor measurement, you can:
  - Segment further (in some cases) and perform additional tests (using the core ground, DETC, and/or cross-check methods)
  - Perform power factor measurements at multiple frequencies.
- DFR (Dielectric Frequency Response)
  - Narrow Band (1 – 500 Hz)
  - Wide Band (1 mHz – 1 kHz)
  - Enables determination of the ITC (individual temperature correction)

Summary

- Narrow Band DFR (multiple frequency insulation test)
  - Earlier detection of problems
  - Low frequencies – very sensitive to conductive losses
  - Higher frequencies – sensitive to problems that increase normal polarization losses
- DFR
  - Provides moisture in the solid insulation
  - Provides oil conductivity



Thank you for your attention!

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