Dielectric Spectroscopy of Solid Insulators

OMICRON Lab Webinar Series 2020

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Agenda

• Theory and measurement methods

• Introduction dielectric sample holder – DSH 100

• Measurement example using the DSH 100
Dielectric Spectroscopy of Solid Insulators

Theory and measurement methods
Dielectric Analysis Basics
Dielectric Material Analysis: Definitions

- There are lot of terms used for the description of a dielectric material:

  - **Permittivity** \( \varepsilon'_r \)
  - **Dissipation Factor** \( \tan(\delta) \)
  - **Dielectric Losses** \( \varepsilon''_r \)
  - **Dielectric Constant**
  - **Permeability**
Permittivity $\varepsilon$

“Permittivity is a measure of how an electric field effects and is effected by a dielectric material.” (in simple words)

- $\varepsilon$ - Permittivity of material
  - Describes the interaction of a material with an external electrical field

- $\varepsilon_0$ - Permittivity of space
  - Constant value $8.85\times10^{-12}$ F/m
  - Describes the electrical field generated in vacuum
Relative Permittivity $\varepsilon_r$

- The absolute material permittivity $\varepsilon_r$ is relative to the permittivity of free space $\varepsilon_0$

\[
\kappa = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon' - j\varepsilon''
\]

- $\varepsilon_r'$ indicates how much energy from an external electric field is stored in a dielectric material
- $\varepsilon_r''$ indicates the losses within the dielectric material when an external electric field is applied.
- $\varepsilon_r''$ is usually much smaller than $\varepsilon_r'$ and includes the effects of both dielectric loss and conductivity.
Dielectric Losses $\tan(\delta)$

- The ratio of lost energy ($\varepsilon_r''$) to stored energy ($\varepsilon_r'$) is the relative losses of a dielectric material

$$\tan(\delta) = D = \frac{\varepsilon_r''}{\varepsilon_r'} = \frac{1}{Q} = \frac{\text{Energy lost per cycle}}{\text{Energy stored per cycle}}$$

- Q is the quality factor
- Used terms for the relative losses of a dielectric material are:
  - Dissipation factor D
  - Dielectric losses $\tan(\delta)$
Dielectric Spectroscopy Techniques

• The measurement technique for dielectric material analysis depends on the frequency range to measure.

• For a frequency range from $10^{-6}$ Hz to $10^8$ Hz the following two measurement techniques can be used:
  
  - Time Domain Spectroscopy
  - Frequency Domain Spectroscopy
  - etc.

10^{-6} 10^{-4} 10^0 10^4 10^8

Time Domain

Frequency Domain

AC-bridges
Frequency Domain Spectroscopy (FDS)

FDS Principle:
- Measures $\tan(\delta)$ at different frequencies:
  - Apply sinusoidal voltage of different frequencies $f_1, f_2, ...$ to a dielectric material e.g. located in a parallel electrodes test cell
  - Determine $\tan(\delta)$ at the frequencies $f_1, f_2, ...$

\[
\tan(\delta, f) = \frac{I_R(f)}{I_C(f)}
\]
Frequency Domain Spectroscopy (FDS)

• Advantage of FDS
  − Fast and accurate at high frequencies
  − Resistant to disturbances

• Disadvantage of FDS
  − Very slow at low frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Duration of 1 sine wave</th>
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<tbody>
<tr>
<td>5000 Hz</td>
<td>0,2 ms</td>
</tr>
<tr>
<td>1000 Hz</td>
<td>1 ms</td>
</tr>
<tr>
<td>50 Hz</td>
<td>20 ms</td>
</tr>
<tr>
<td>1 Hz</td>
<td>1 s</td>
</tr>
<tr>
<td>0.1 Hz</td>
<td>10 s</td>
</tr>
<tr>
<td>10 mHz</td>
<td>100 s</td>
</tr>
<tr>
<td>1 mHz</td>
<td>16,7 min</td>
</tr>
<tr>
<td>0.1 mHz</td>
<td>2,7 h</td>
</tr>
<tr>
<td>10 µHz</td>
<td>27 h</td>
</tr>
</tbody>
</table>
Time Domain Spectroscopy

- The time domain spectroscopy used in the SPECTANO 100 is called **PDC** measurement (Polarization Depolarization Current)

- **PDC Principle**
  - Apply a voltage step to a dielectric material e.g. located in a parallel electrodes test cell
  - Measure the charge current at times $t_1$, $t_2$, ...
  - Calculate the dielectric properties like $\varepsilon$, $c$, tan($\delta$) at the corresponding $f_1 = \frac{1}{t_1}$; $f_2 = \frac{1}{t_2}$ ...
    using the Fourier transformation
Time Domain Spectroscopy

- **Advantage of PDC**
  - Fast and accurate at low frequencies

- **Disadvantage of PDC**
  - Inaccurate at high frequencies

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
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<tr>
<td>PDC</td>
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<td>☹ Inaccurate at high frequencies</td>
</tr>
<tr>
<td>FDS</td>
<td>☻ Fast and accurate at high frequencies</td>
<td>☹ Very slow at low frequencies</td>
</tr>
</tbody>
</table>
Combination of FDS and PDC

Fourier Transformation

Current in nA

Time in s

1000

Frequency in Hz

$tan(\delta)$

1000

$tan(\delta)$

0,001

Frequency in Hz

0,001

0,1

1

1

1
Dielectric Polarization

- When a dielectric material is placed in an external electrical field charged particles are displaced. This process is called dielectric polarization.
Polarization processes

- Depending on the frequency different polarization types occur

\[ E = E_0 \cos(\omega t) \]

displayed in the time domain \( f = \frac{1}{t} \)
Why is dielectric material analysis in comparison to common analysis methods as $\tan(\delta)$ 50 Hz so important?
Our customer said, we have bad materials!

I will check the probe with our best 50 Hz Analyzer... and will compare it with good and bad materials
Tan(δ) 50 Hz Analysis = Common “type” of insulation material measurement

\[ \tan(\delta), \ C \text{ at 50 Hz:} \]

- Bad material
- Good material
- Probe

I will control it again!

NO, NO, NO! I can’t find the error!!
What is the problem of Professor X?
Importance of Dielectric Material Analysis
Importance of Dielectric Material Analysis (cont.)
Importance of Dielectric Material Analysis (cont.)

Dielectric response: \((\tan(\delta), C, \varepsilon \text{ at kHz...}\mu\text{Hz})\)

- Separation of effects due to large frequency range
- Detailed analysis possible

- **red**: bad material = aged
- **blue**: good material = normal (dry)
- **green**: probe = wet and thus inaccurate/faulty
Factors influencing the dielectric response

Possible influence factors:

- Temperature
- Humidity or moisture
- Homogeneity
- Conductivity e.g. oil
- Aging byproducts
- Viscosity e.g. during curing
- Structure

⚠️ kind of influences depend on material
Typical Dielectric Material Curves

Pressboard disk before & after pressing with 10kg weights for 2 month

Epoxy resin curing process
Why are C and $\varepsilon$ dielectric material properties?

Tan$\delta$ for new and aged pressboard with similar moisture content at 20°C

Permittivity of aged pressboard with different moisture content at 20°C
Importance of dielectric analysis

• To detect aging or changes of dielectric material structure / composition before material is used in the field

• Aging or changes of the dielectric material can lead into
  - Wrong electrical behavior
  - Changes of electrical specification
  - Reduction of dielectric strength
  - Reduction of longevity
  - Avoid short circuits e.g. in high voltage equipment and thus faster aging
  - Reduction of humidity or temperature stability
Dielectric Material Analysis: Applications

Measures dielectric parameters like losses (tanδ), relative permittivity (ε) or capacitance (C) to characterize easily

- Nanomaterial and material composites
- Dielectrics used as insulations in cables and high voltage assets
- Polymers, epoxy, insulation paper/cellulose, glasses or thin films
- Insulation liquids like mineral oil or silicone
Dielectric Spectroscopy of Solid Insulators

Introduction dielectric sample holder – DSH 100
Typical Test Cell Types

- The test cell type for the dielectric material analysis depends on
  - The used dielectric spectroscopy techniques
  - Material under test (liquid, powder, solid, granulate...)

Parallel Plate with guard ring

Transmission Line

Coaxial Probe
Typical Test Cell Types

TC12 Transformer Oil Test Cell (cylindrical) by OMICRON electronics

Disc electrode with guard ring by TU Munich
DSH 100 – Dielectric Sample Holder for solid material

- Cooperation project with the **Tony Davies High Voltage Laboratory University of Southampton**

- Test cell type
  - Disc electrode with guard ring
  - Shielding mechanism included
  - Disposable electrodes (usable for curing processes)
  - Easy adjustment of air gap for air reference measurement
  - Usable for voltages $\leq 200 \text{ V}_{\text{peak}} \ (\text{AC} + \text{DC})$
  - Usable frequency range 5 $\mu$Hz to 5 MHz
  - Option: Temperature control system
Sample Holder DSH100 – Features

- Housing, connection & environmental control
  - Shielding for precise measurements
  - Triaxial connection for
    - Low current (pA)
    - Capacitances down to 10 pF
  - Temperature control
    - Heating pad
    - PT-100 temperature sensor
Sample Holder DSH100 – Features

• Electrical Parameters

Maximum Operation Voltage (AC/DC) ≤ 200 V\text{peak}

Maximum current (AC/DC) ≤ 50 mA\text{peak}

Usable frequency range 5 \mu Hz to 5 MHz

Sample thickness 0.1 mm to 20 mm

Sample size 50 mm x 50 mm to 70 mm x 70 mm
Sample Holder DSH100 – Features

• Safety interlock mechanism
Sample Holder DSH100 – Features

• Tensioner to control pressure

• Spring force:10N, 50N and 100N
• Ensures proper electrical contact
• Constant force (scaling)
• Reproduceable results
• Exchangeable design
Sample Holder DSH100 – Features

- Electrode design
- Exchangeable and disposable electrodes with guard ring
- Thin multilayer Printed Circuit Board (PCB) with gold coating (1.55mm thick)
- Electrode material allows deformation for proper contact to non-flat, rigid samples
- Designed according to IEC 250 and ASTM D150-11 standards

Top/Input electrode: Ø 70 mm
Bottom/Measurement electrode with guard ring: Ø 49 mm
Guard ring width / gap: 9.5 mm / 1 mm
Sample Holder DSH100 – Features

- Electrode design

Exchangeable and cost-effective
Sample Holder DSH100 – Features

- Spacer

Spacer for air-reference measurement thickness: 0.8 mm / 1 mm / 1.55 mm
Sample Holder DSH100 – Features

- Option: Heating pad and temperature sensor
Sample Holder DSH100 – Features

• Environmental Conditions
  Operating temperature: -55 °C to +200 °C
  Operating relative humidity: ≤ 95 % non-condensing
  Maximum altitude: 2000 m

• General
  Dimensions (w x h x d) 165 mm x 108 mm x 118 mm
  Weight 2.5 kg
  Supports measurements in accordance with:
  ASTM D150
  IEC 62631-2-1 (2018)
  IEC 62631-3-1 (2016)

  Triaxial connectors: LEMO plug
Sample Holder DSH100

- Factors leading to a reduced accuracy

Accurate dielectric measurement results requires:

- Accurate dielectric analyzer
- Unique and planar sample surface
- Accurate sample holder with planar, parallel electrodes
Sample Holder DSH100

- Factors leading to a reduced accuracy
  - Electrical contact: Reasons for poor electrical contact (air pockets)
  - Sample and electrode surface
    - Uneven sample or electrode surface
    - Scratches or contaminations on the sample or electrode surface like finger-prints, dust or oxide layers
  - Sample holder design
    - Tilting of the upper electrode (usually mounted with a small fixing point)
    - Deviations of the micrometer or sample thickness
Sample Holder DSH100

• Factors leading to a reduced accuracy
  
• Stray Capacitances

Disk electrode without guard ring

\[ C_{\text{measured}} = C_m + C_s \]

Disk electrode with guard ring

• Sample deformation
Sample Holder DSH100

• Working with dielectric material:
Dielectric Spectroscopy of Solid Insulators

Measurement example using the DSH 100
Measurement example using the DSH 100

- Measurement set up:
Thank you for your attention!

Feel free to ask questions via the Q&A function...

If time runs out, please send us an e-mail and we will follow up.
You can contact us at: info@omicron-lab.com