ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

LIMES
LABORATORY OF INNOVATIVE MATERIALS FOR ELECTRICAL SYSTEMS

Dielectric spectroscopy technique for non-destructive cable condition monitoring: theory and applications

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Co-financed by the Connecting Europe Facility of the European Union

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DIPARTIMENTO DI INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

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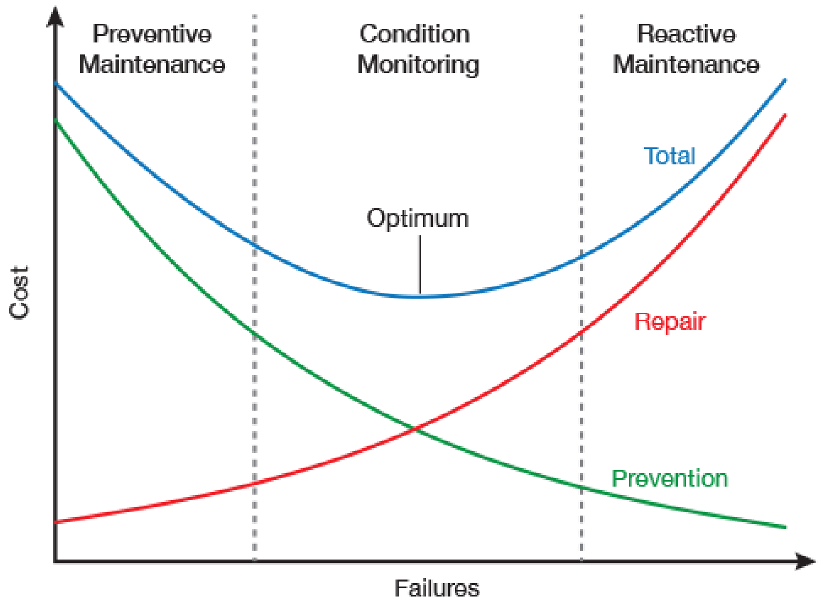
Why condition monitoring?

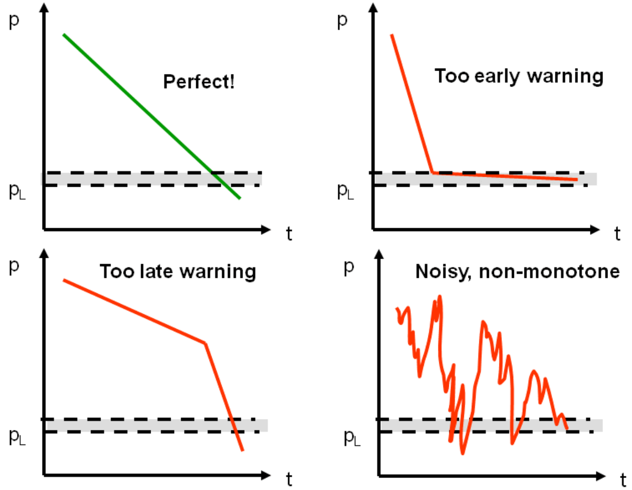
- Condition monitoring can be described as "assessing the current state and estimating the future state of a system by means of measurements and calculations".
- The results of condition monitoring can be used to take corrective actions, to plan the availability and maintenance, and to optimize the system performance.
- The main reasons to apply condition monitoring are:
  - Prevention of damage.
  - Increasing availability.
  - Increasing reliability.
  - Changing from periodic maintenance to condition dependent maintenance.
  - Reduction of production loss.
  - Better operator process knowledge through more information and insight.

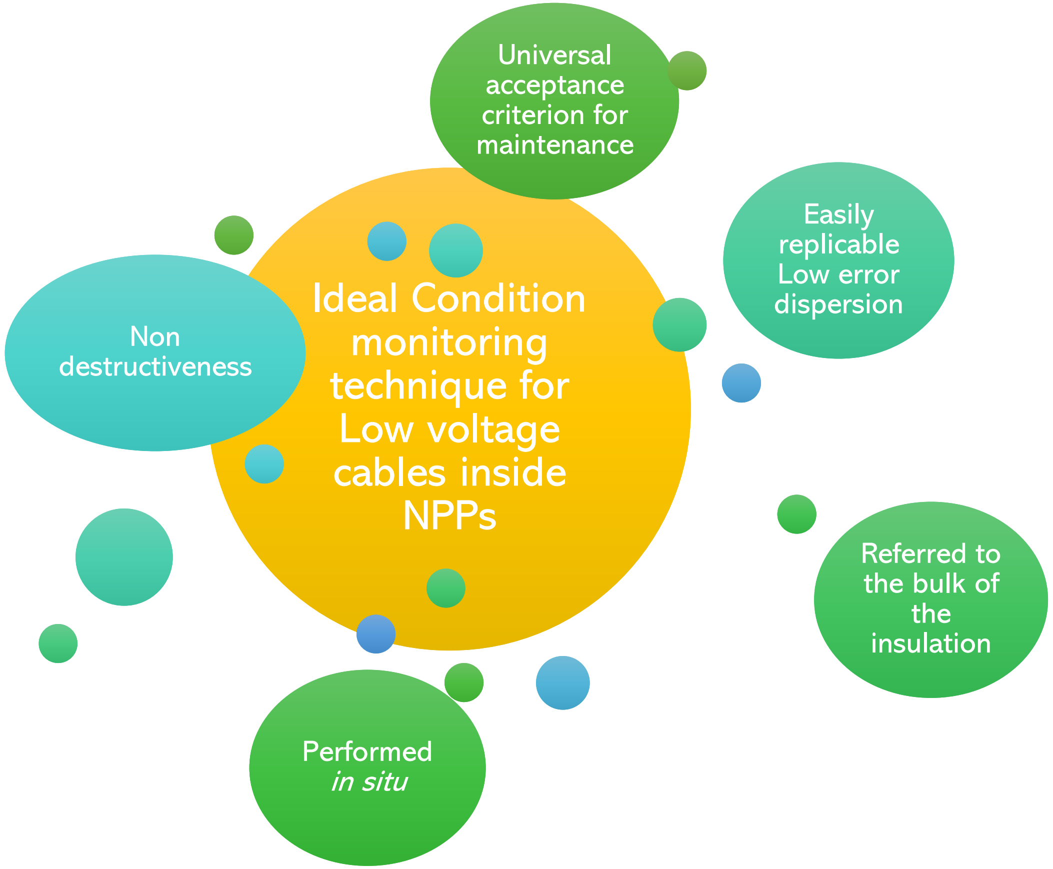


T. Álvarez Tejedor, et al. "Modern Gas Turbine Systems", 2013

Why condition monitoring?

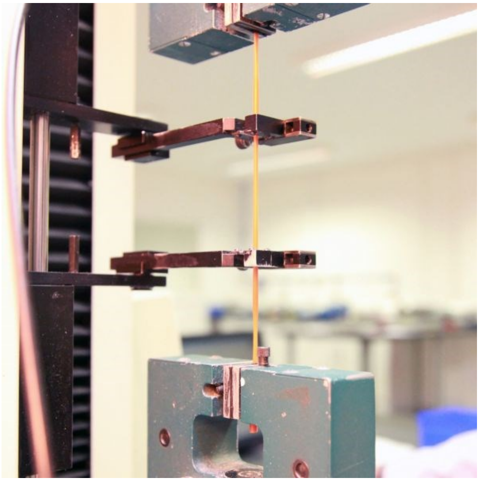
- Condition monitoring can be described as "assessing the current state and estimating the future state of a system by means of measurements and calculations".
- Desidered property characteristics
  - Property must be related to system aging.
  - Monotonic variation of the property with time
  - Avoid abrupt variation of the property with time





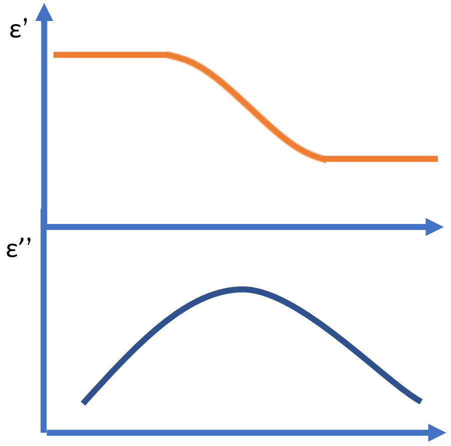
S. W. Glass, L. S. Fifield, G. Dib, J. R. Tedeschi, A. M. Jones, and T. S. Hartman, "State of the Art Assessment of NDE Techniques for Aging Cable Management in Nuclear Power Plants FY2015," PNNL--24649, M2LW--15OR0404024, 1242348, Sep. 2015. doi: 10.2172/1242348.

Elongation-at-break and dielectric spectroscopy



From basec.org.uk

PROs	CONs
Method used over many years	Not representative of the entire cable insulation (little testing cable portion) and strictly related to local defects
Very good correlation with polymer degradation level	It can be affected by huge error displacements.
It guarantees minimum mechanical bending properties	It does not consider different polymeric materials



PROs	CONs
Nondestructive technique	Not able to localize aged spots
Very good correlation with polymer degradation level	No universal acceptance criterion yet defined
Easily replicable with low error dispersion	
Referred to the bulk of the insulation	
Performable in situ (measure from cable terminations)	

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E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

Polarization in solids

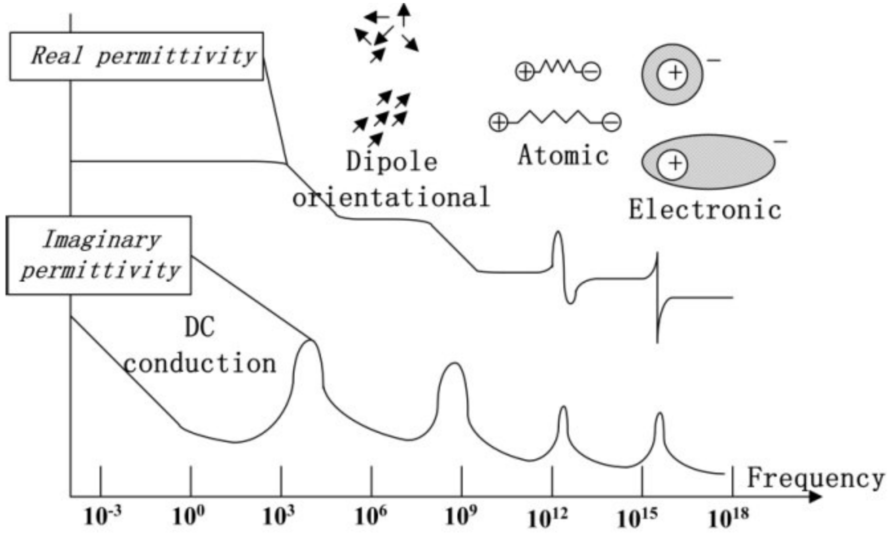
- Polarization is defined as the response of an insulating material **(dielectric)** to an applied electric field.
- There are four different polarization mechanisms:
  - Electronic polarization (10^{18}-10^{13} Hz)

    It consists of the desplacement of the electronic cloud around the atomic nuclei
  - Atomic polarization (10^{13}-10^{12} Hz)

    The applied electric field changes the localization of the atomic nuclei inside a molecule
  - Dipolar polarization (10^{10}-10^{2} Hz)

    It occurs on materials with molecules with permanent dipolar momentum. Dipoles orient themselves in the direction of the applied electric field.
  - Interfacial polarization (Maxwell-Wagner-Sillars) (<10 Hz)

    This is linked to space charges accumulated next to material interfaces e.g., crystalline and amorphous phases, additives, fillers etc.



Polarization in solids

DIPARTIMENTO DI INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

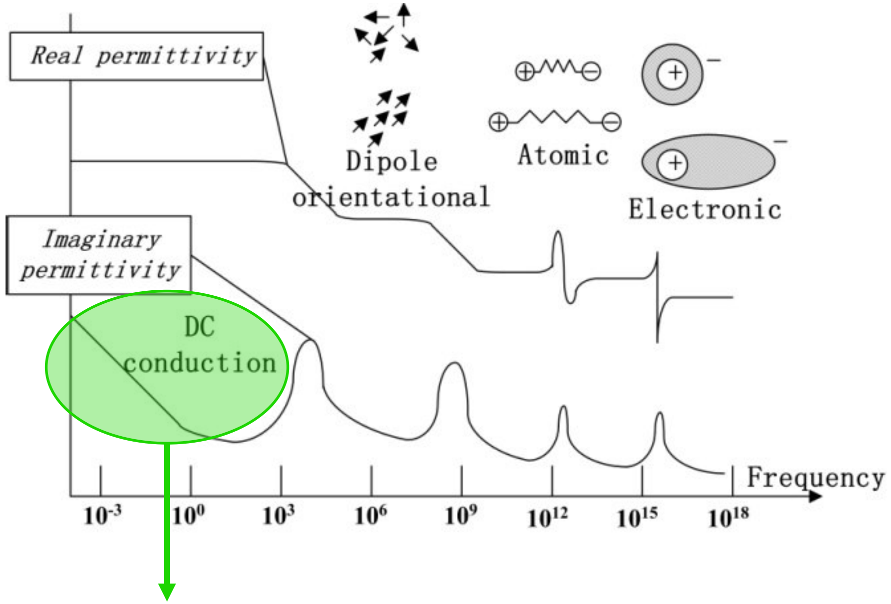
- Polarization is defined as the response of an insulating material **(dielectric)** to an applied electric field.
- The quantity which measures the intensity of polarization is the **complex permittivity ε**

$$\dot{\boldsymbol{\varepsilon}}(\boldsymbol{\omega}) = \boldsymbol{\varepsilon}'(\boldsymbol{\omega}) - \boldsymbol{j} \cdot \boldsymbol{\varepsilon}''(\boldsymbol{\omega})$$

where ε' is linked to the energy stored in the material

ε'' represents the dielectric losses of the material

ω is the angular frequency of the applied electric field



Quasi-DC conduction

The permittivity trend is lead by conduction phenomena which hide the contribution of dielectric losses.

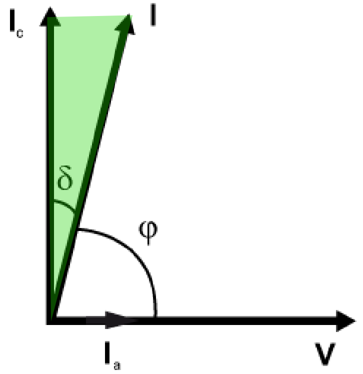
Polarization in solids

- One more common quantity, linked to the dielectric losses, is the dissipation factor tanδ.

$$\tan\boldsymbol{\delta} = \frac{\sigma/\omega + \varepsilon''}{\varepsilon'} \sim \frac{\varepsilon''}{\varepsilon'} \text{ (at high frequencies)}$$

where σ is the material conductivity

- This measures the quantity of energy dissipated by the dielectric system due to polarization mechanisms and conduction losses because of the not-infinite resistance of the insulating material
- In the case of perfect dielectrics, current is π/2 leading with respect to the applied voltage. In real dielectrics, the phase displacement is not exactly π/2 but there is an angular deviation (δ), whose tangent (tanδ) is defined as dissipation factor.



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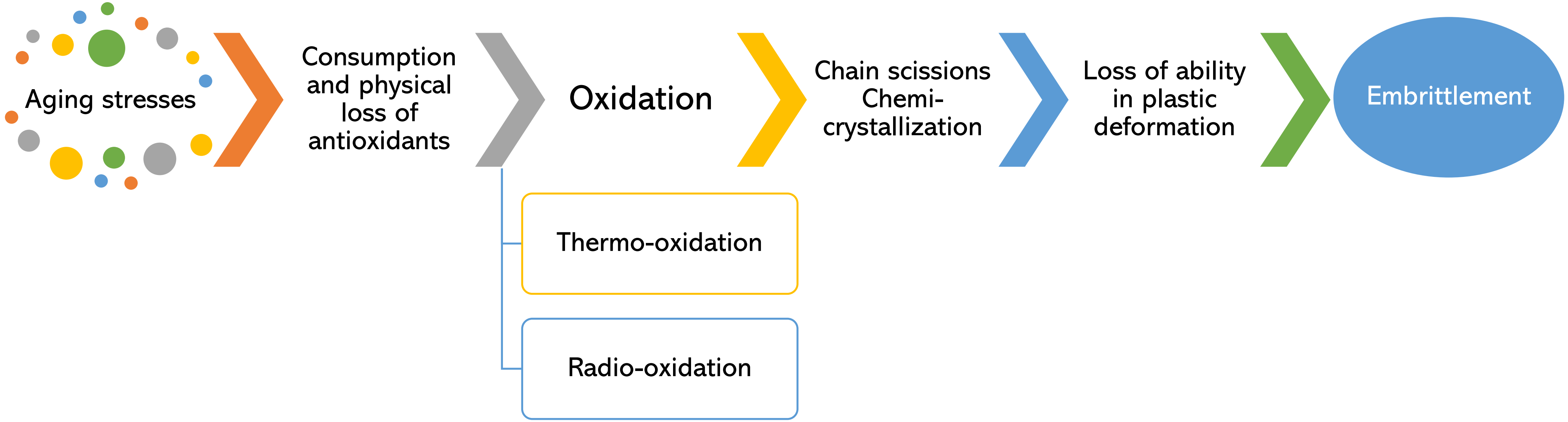
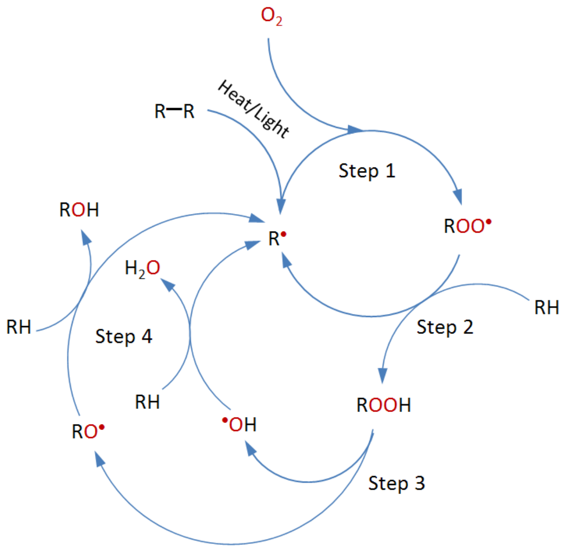
Polymer aging

DIPARTIMENTO DI INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

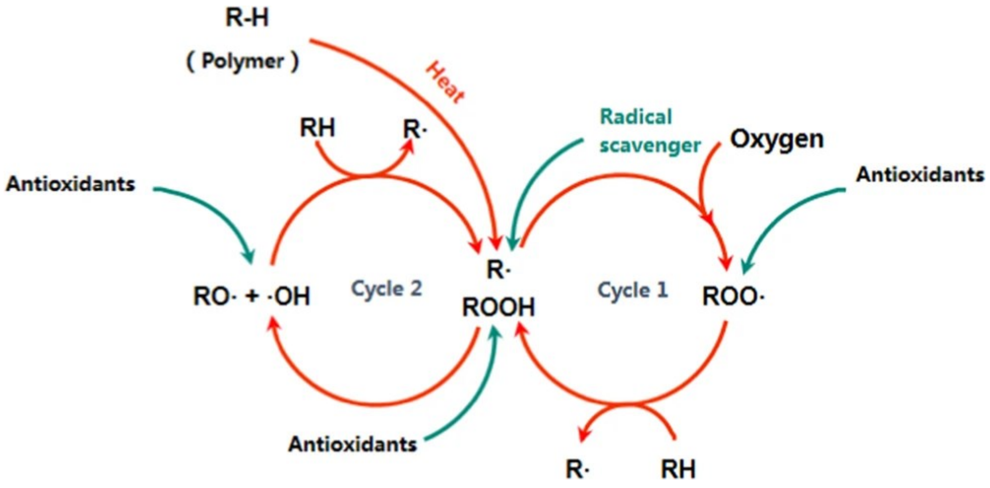
Polymer aging



Polymer aging



Oxidation without antioxidants



Oxidation with antioxidants

Li, J., Zhou, C., Xu, S. *et al.* Investigation of hindered phenol antioxidant effects on the aging performance of cross-linked LDPE in the presence of copper. *Sci Rep* **10,** 10189 (2020). https://doi.org/10.1038/s41598-020-67131-1

Polymer aging

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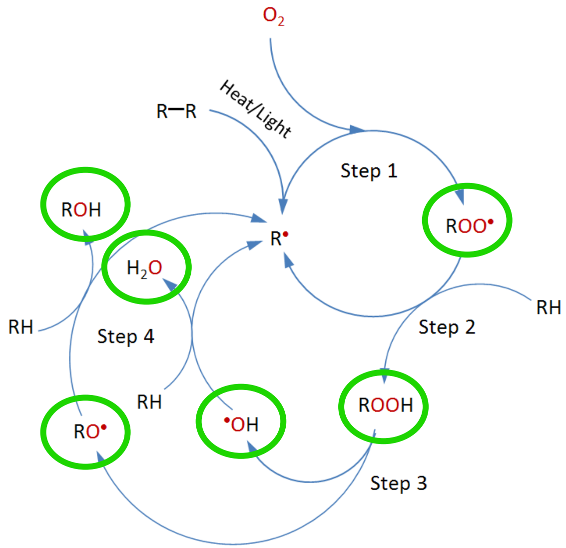
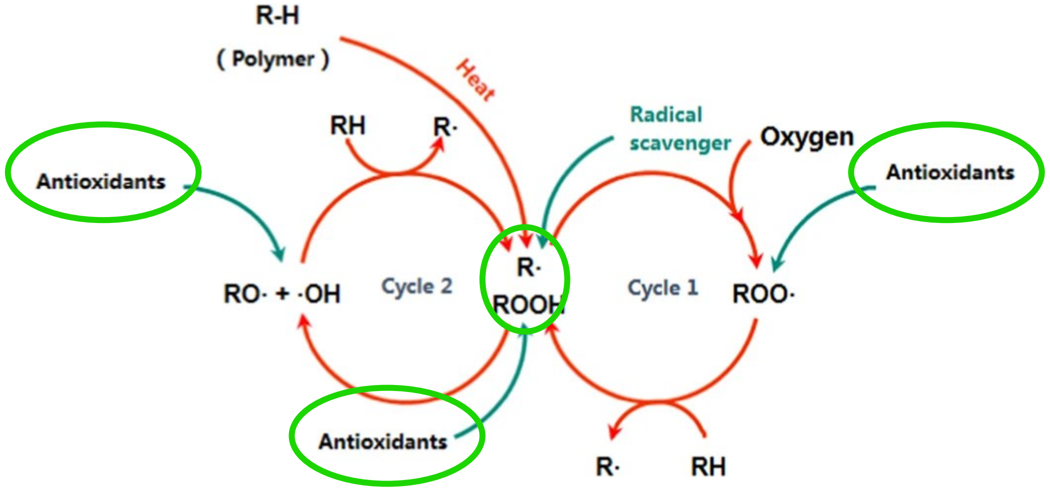


Oxidation without antioxidants

Polar species

↓

Dipolar polarization



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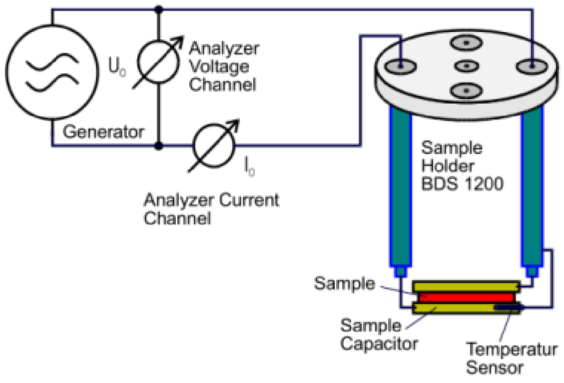
Dielectric analyzer

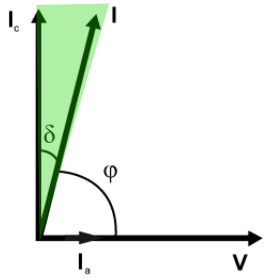
Device:
Novocontrol Alpha Dielectric Analyzer V2.2

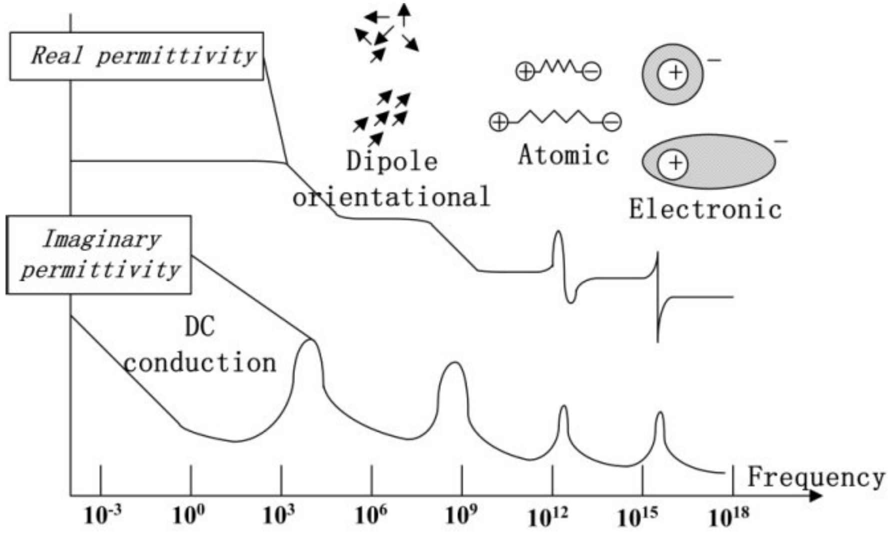


Tests parameters:

- V_{rms} = 3 Volts
- Temperature: -100 - +150 °C
- Frequency range = 10^{-2}-10^{6} Hz
  - Dipolar polarization
  - Interfacial polarization
  - Quasi-DC conduction

Complex permittivity	Loss angle
$\varepsilon(\omega) = \varepsilon'(\omega) - j\,\varepsilon''(\omega)$	$\delta = 90° - \phi$
Loss factor	
$\tan(\delta) = \frac{\sigma/\omega + \varepsilon''}{\varepsilon'}$	σ conductivity





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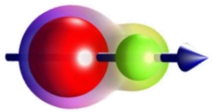
Dielectric analyzer

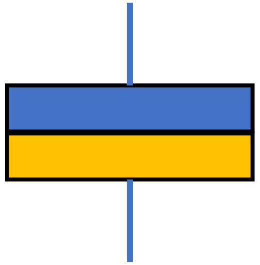
High frequency (10^2-10^6 Hz)

- Dipolar polarization - Dipolar species e.g., antioxidant degradation products and oxidized polymer chains



Low frequency (10^{-2}-10^2 Hz)

- MWS polarization - Interfaces between different materials and polymer matrix/additives
- Q-DC conduction – Radicals and/or free ions which can migrate under the electric field



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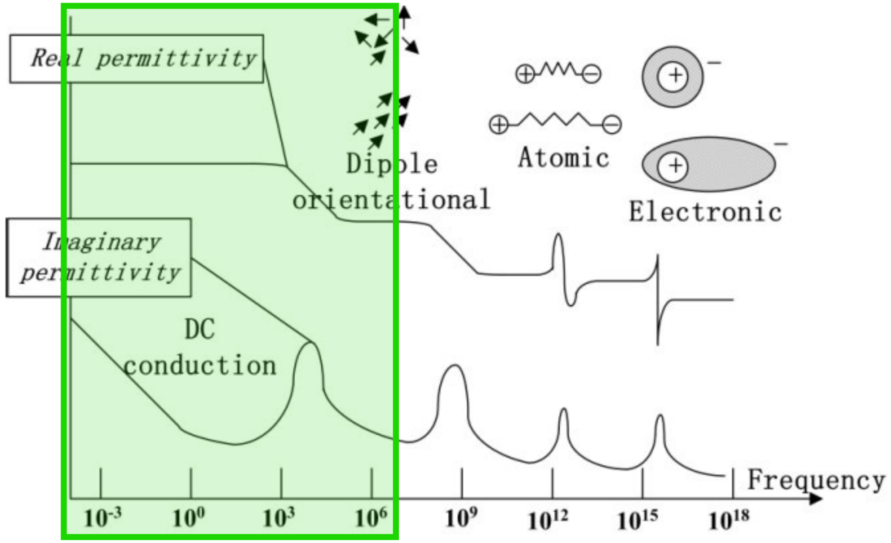
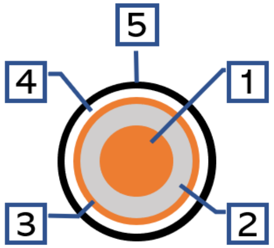
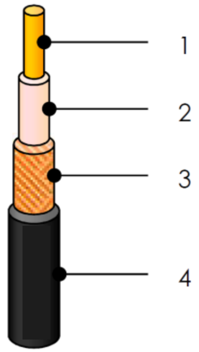


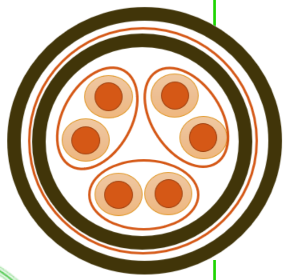
Cable specimens



Coaxial cable geometry

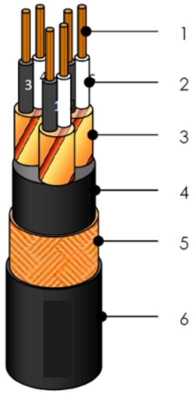
1. Inner conductor – Copper (the innermost);
2. Primary insulation – XLPE Compound #1
3. Polymeric film;
4. Shielding – Copper wire braid;
5. Outer sheath – Low Smoke Zero Halogen.





Twisted pair cable geometry

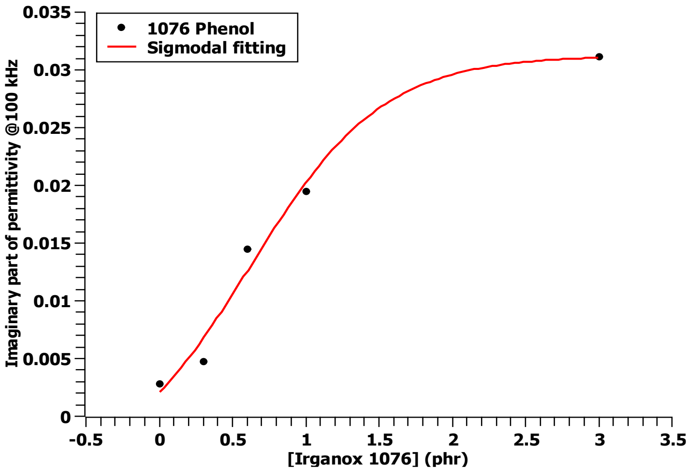
1. Inner conductor – Copper (the innermost);
2. Primary insulation – XLPE Compound #1 (non filled), #2 (filled), EVA-EPDM
3. Shielding – Copper foil;
4. Sheath – Low Smoke Zero Halogen
5. Shielding – Copper wire braid;
6. Outer sheath – Low Smoke Zero Halogen.

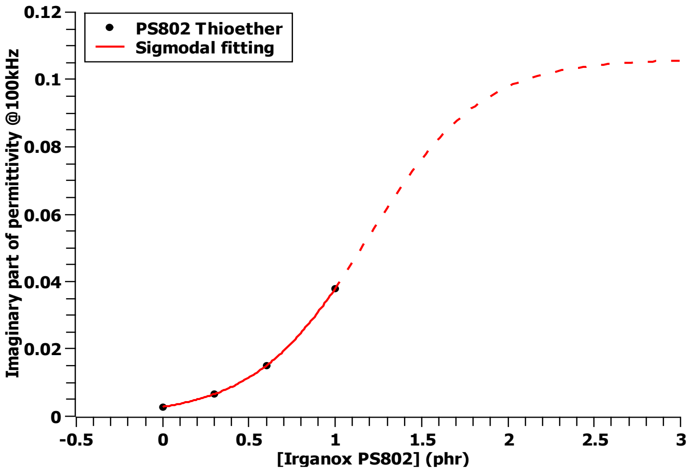


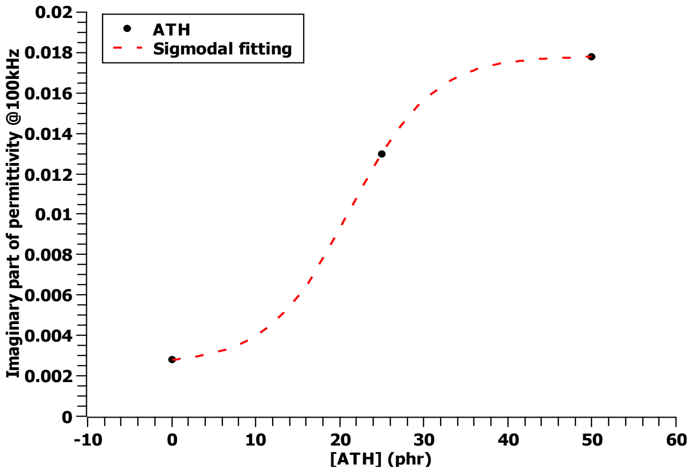
Silane XLPE

- Compound #1
  - Phenol-based antioxidant (1 phr)
  - Thioether-based antioxidant (1 phr)
- Compound #2
  - Phenol-based antioxidant (1 phr)
  - Thioether-based antioxidant (1 phr)
  - Flame retardants – ATH (50 phr)

Impact of additives on dielectric response







- Considered additives are strong dipolar species.
- High frequency dielectric response is relatable to dipolar properties of the analyzed materials.
- The increase of the HF dielectric response is found to follow the additive content for low concentrations.
- At high concentrations, the variation of the dielectric property with additive concentration is more and more reduced. They may agglomerate, shifting their dielectric response towards lower frequencies.

S. V. Suraci and D. Fabiani, "Quantitative investigation and modelling of the electrical response of XLPE insulation with different filler content," in *2020 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, East Rutherford, NJ, USA, Oct. 2020, pp. 439–442. doi: 10.1109/CEIDP49254.2020.9437470.

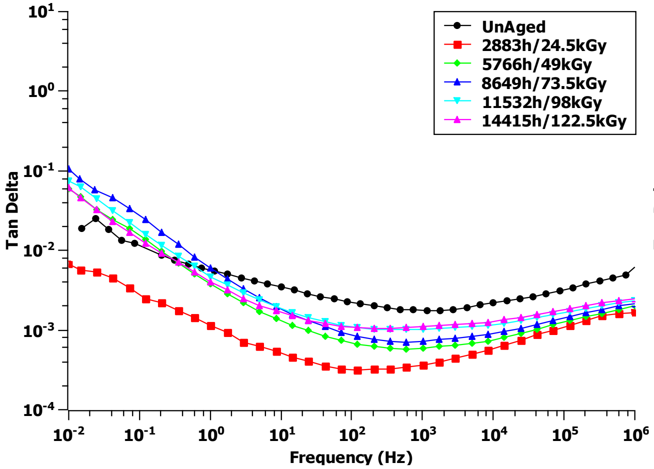
Accelerated aging conditions

Low dose rate aging	Medium dose rate aging	High dose rate aging	Combined aging
8 Gy/h	60 Gy/h	400 Gy/h	6 Gy/h
47 °C	47 °C	21 °C	87 °C
2883 h – 24 kGy	864 h – 51.2 kGy	167 h – 66.8 kGy	2883 h – 24 kGy
14415 h–115 kGy	4811 h – 286 kGy	835 h – 334 kGy	14415 h–115 kGy

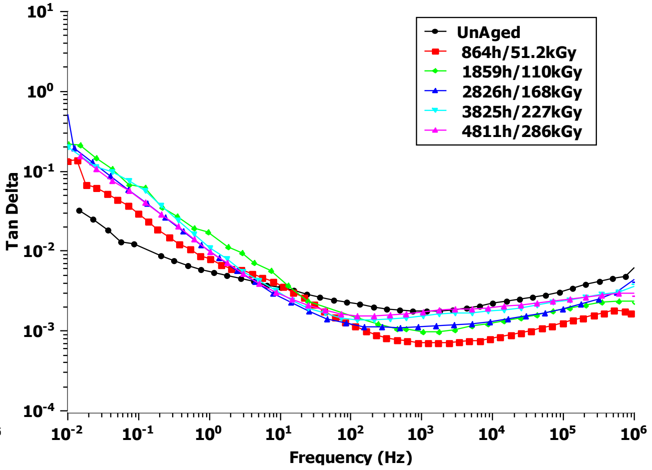
Increasing Dose Rate

Dielectric spectroscopy on cables

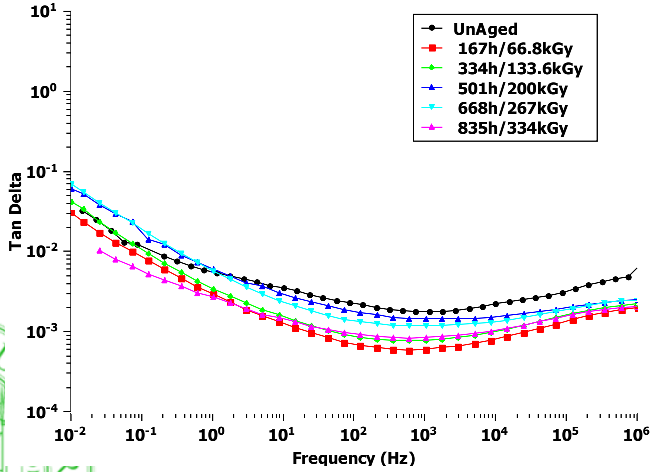
Low dose rate aging



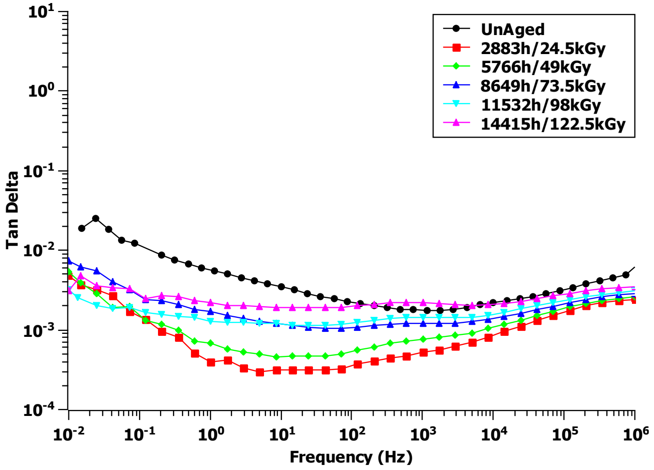
Medium dose rate aging



High dose rate aging



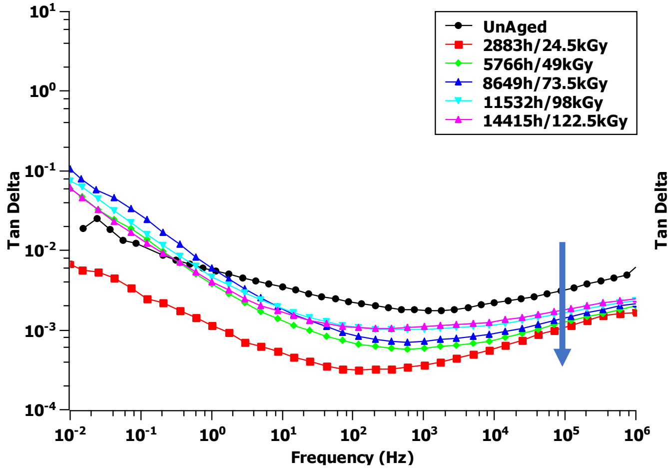
Combined aging



- Trend over frequency characterized by
  - One peak at high frequency (10^6 Hz)
    - → Related to dipolar polarization
  - Linear increase lowering the frequencies (10 – 0.1 Hz)
    - → Q-DC conduction phenomenon
    - → Interfacial polarization

Dielectric spectroscopy on cables

Low dose rate aging



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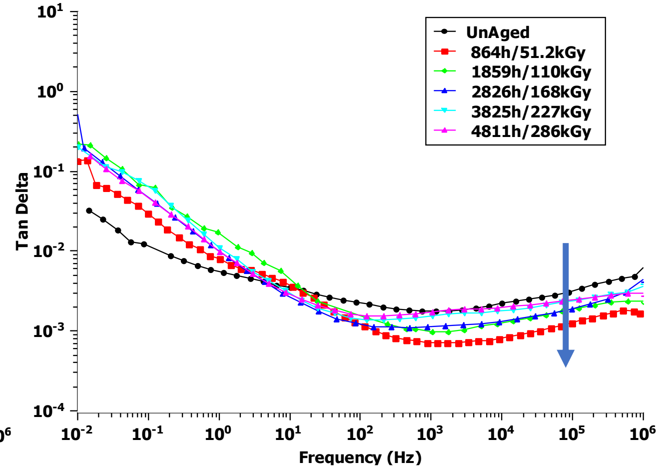

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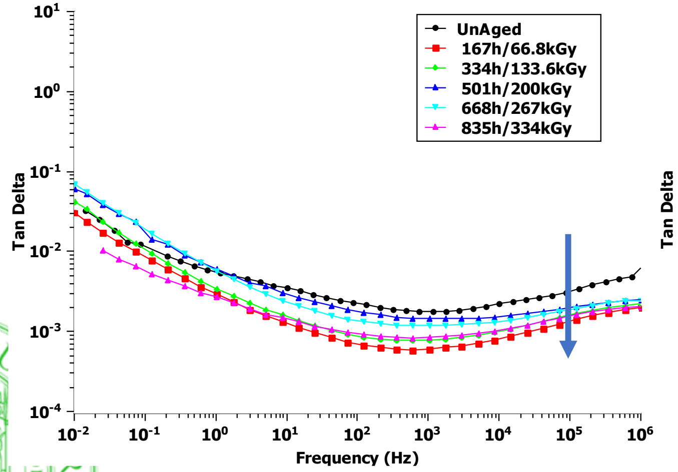

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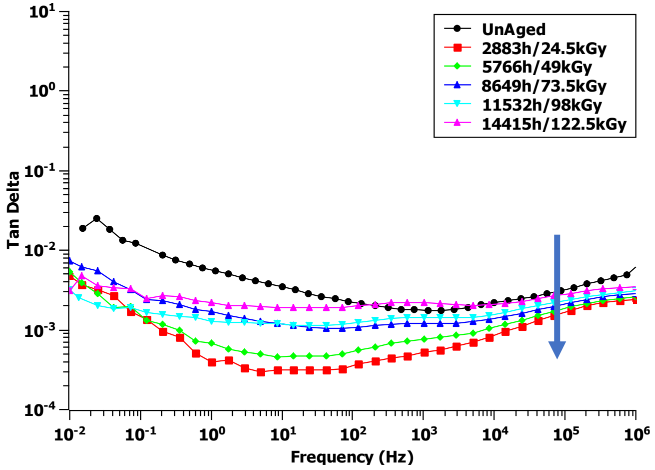

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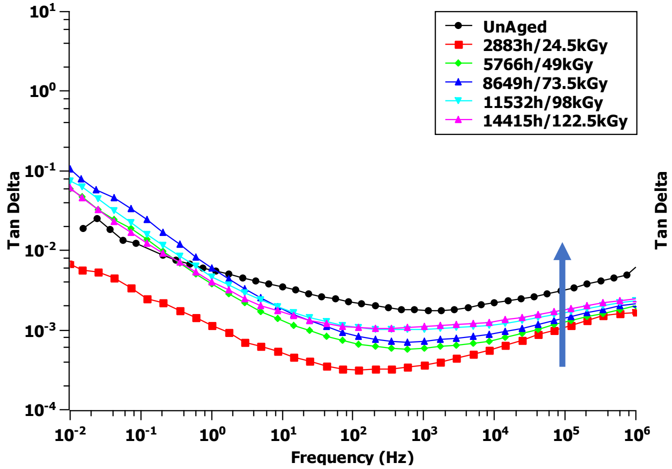
Dielectric spectroscopy on cables

Low dose rate aging



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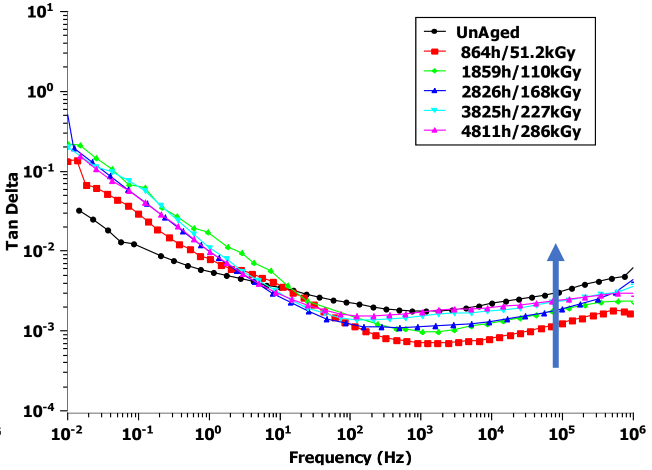

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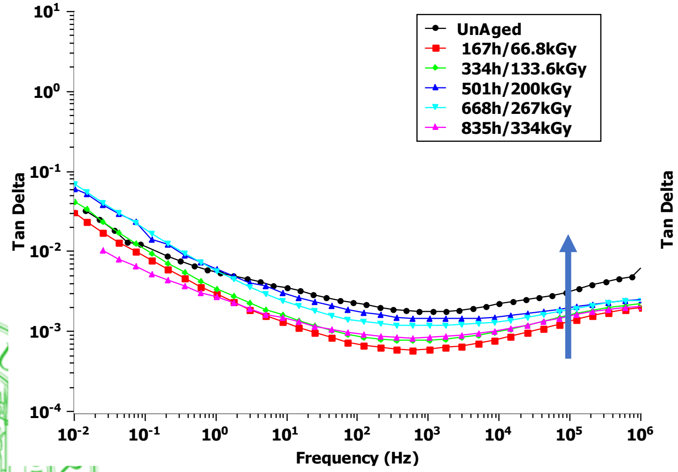
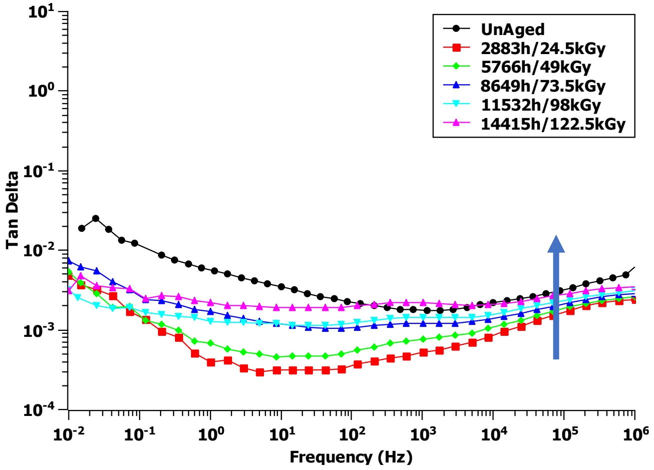


Combined aging



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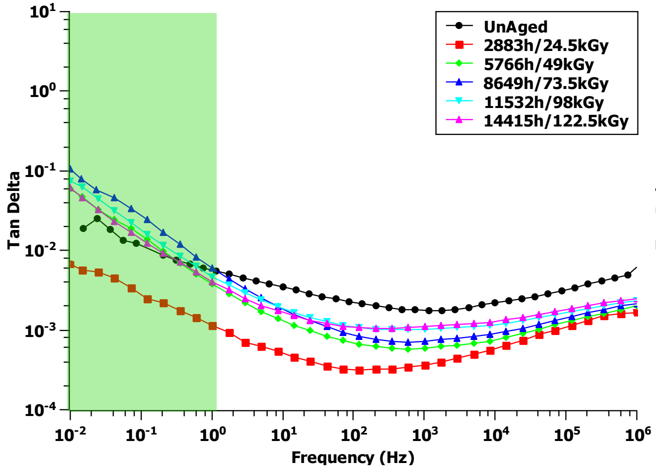
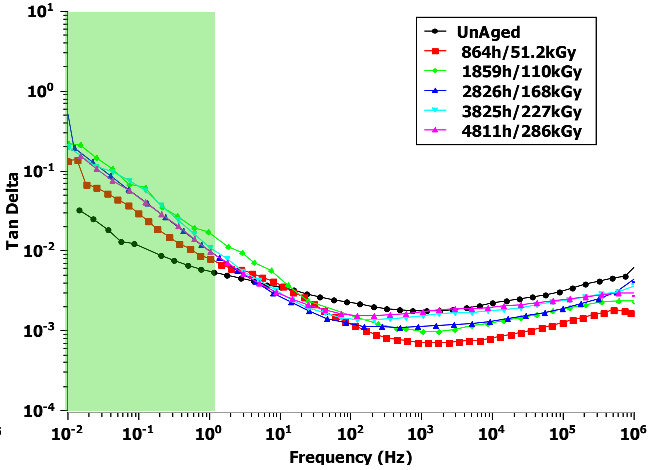
Dielectric spectroscopy on cables

Low dose rate aging



Medium dose rate aging



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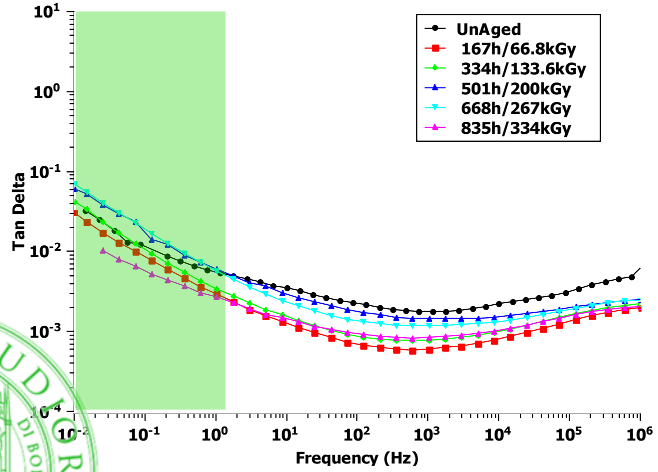
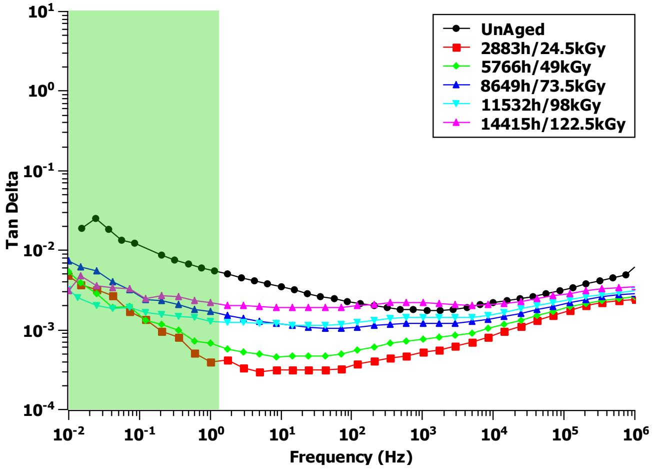


Combined aging



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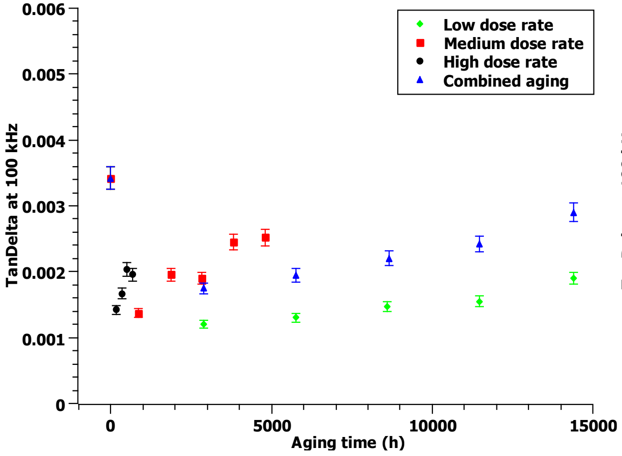
Low frequency dielectric response:

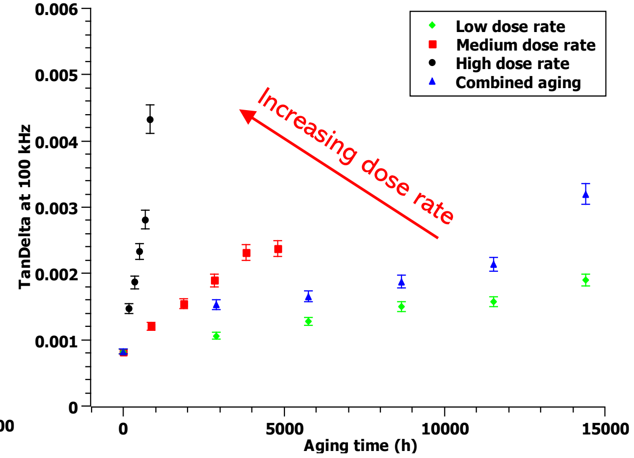
- Non monotonic increase of the property
- Overlapping of the different curves

Dielectric spectroscopy on cables

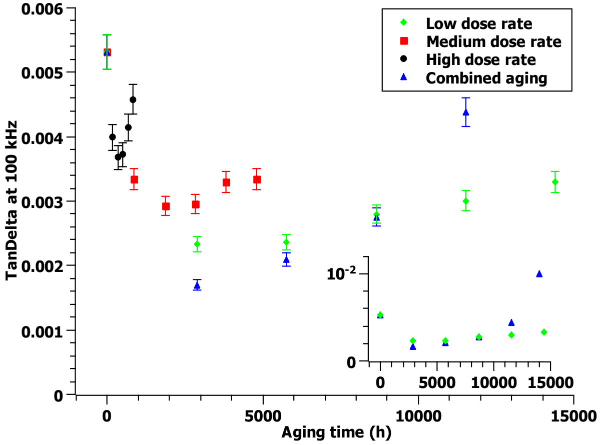
Coaxial cable



Twisted pair non filled cable



Twisted pair filled cable



- Dielectric loss slope with aging time is different among different aging conditions
- Harsher the aging conditions, steeper the slope
- Dielectric losses follow a monotonic increase with aging.
- Combined aging depicts similar trend as LDR but with higher dielectric losses.

Dielectric property at 100 kHz is a suitable aging marker for cable aging evaluation.

S. V. Suraci, D. Fabiani, S. Roland, and X. Colin, “Multi scale aging assessment of low-voltage cables subjected to radio-chemical aging: Towards an electrical diagnostic technique,” *Polymer Testing*, p. 107352, Oct. 2021, doi: 10.1016/j.polymertesting.2021.107352.

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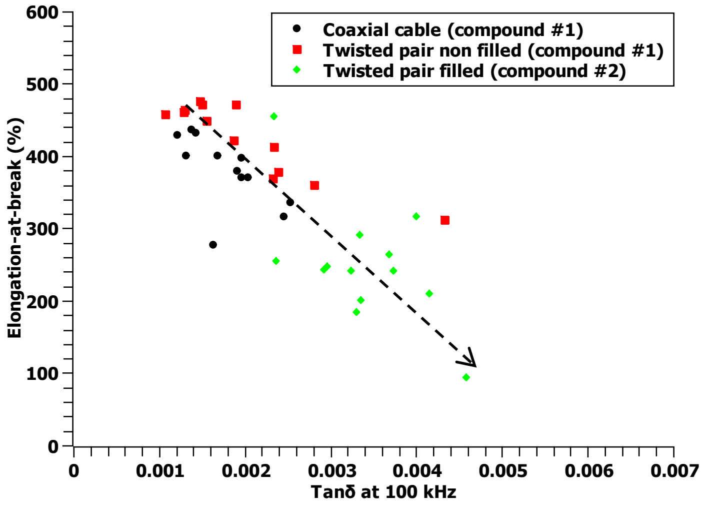
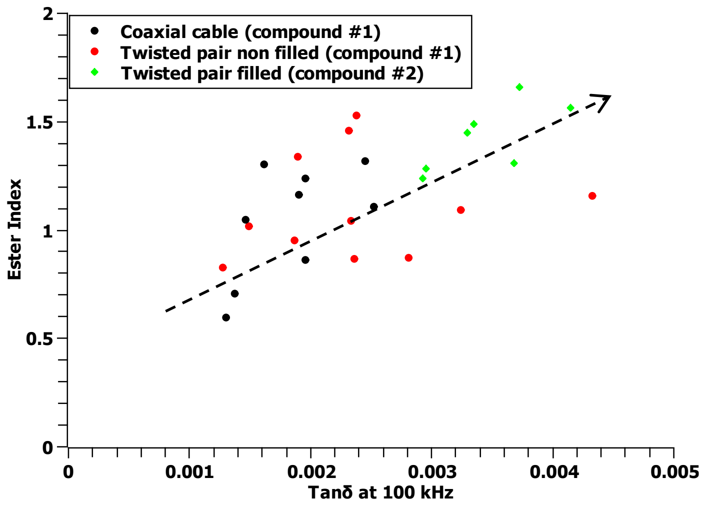
E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

Correlation with other CMTs





Elongation-at-break

- The decay of EaB values corresponds to the increase of the dielectric losses (tanδ) for all the analyzed conditions

Ester index

- The raise of ester index values corresponds to the increase of the dielectric losses (tanδ) for all the analyzed conditions

Effect of fillers

- The presence of fillers (ATH) shifts the experimental data towards a different path of the same trend line.
  - Copious dipolar species → Higher tanδ values
  - Reduction of the mechanical resistance

- Consistent correlation between tanδ at 100 kHz and:
  - the decay of EaB
  - the arising of oxidized species during aging (by EI)

S. V. Suraci, D. Fabiani, S. Roland, and X. Colin, “Multi scale aging assessment of low-voltage cables subjected to radio-chemical aging: Towards an electrical diagnostic technique,” *Polymer Testing*, p. 107352, Oct. 2021, doi: 10.1016/j.polymertesting.2021.107352.

DIPARTIMENTO DI INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

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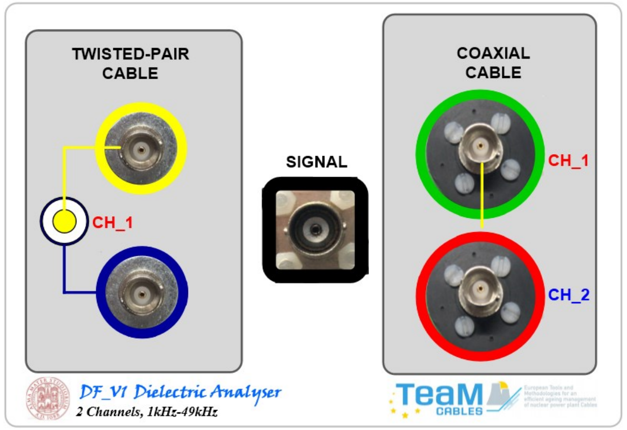
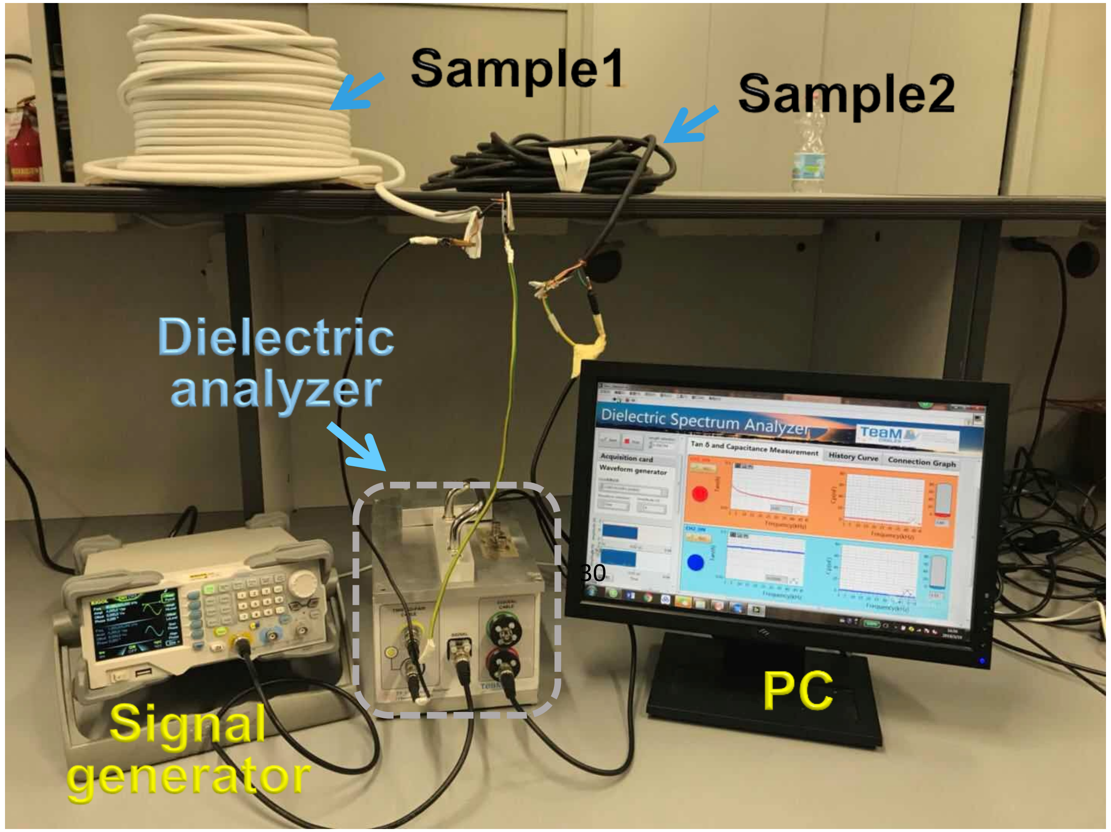
How to measure dielectric properties on site?

Technical indicators:

Voltage: 0.1 ~ 10 V;
Frequency: 1 ~ 200 kHz;
Capactance: 0.6 ~ 75 nF;
Two channels.



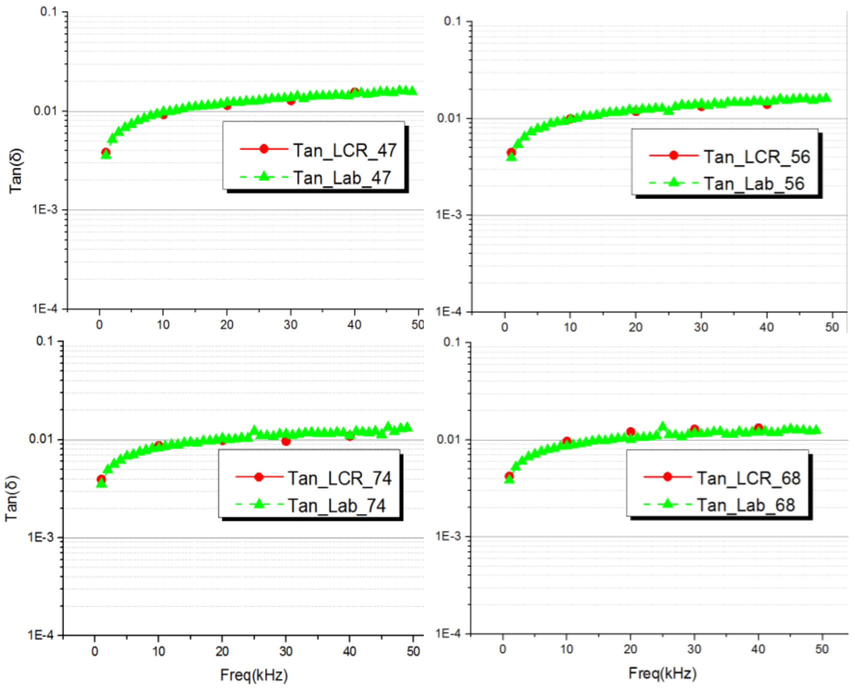


Picture of the experimental setup

Validation and sensitivity analysis of the portable device

Validation

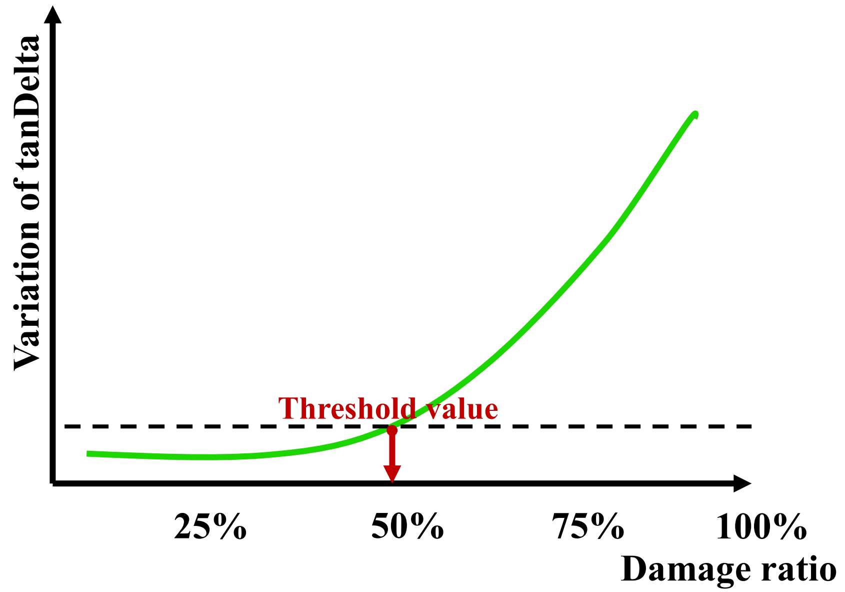
Sample capacitance are tested through both lab-scale dielectric analyzer and portable device.



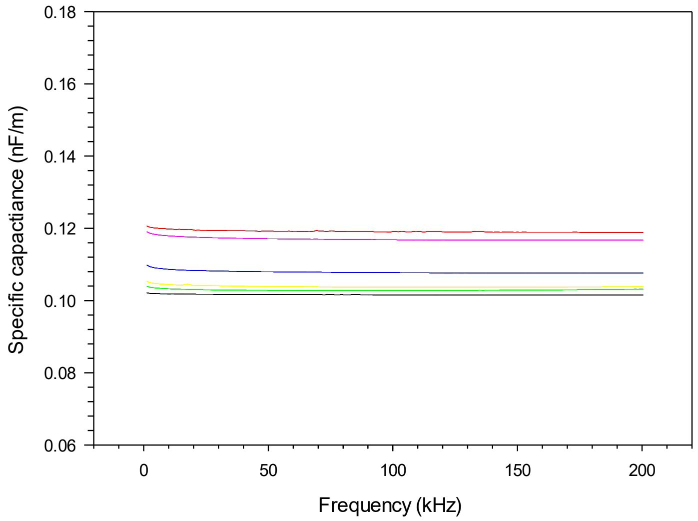
Sensitivity analysis

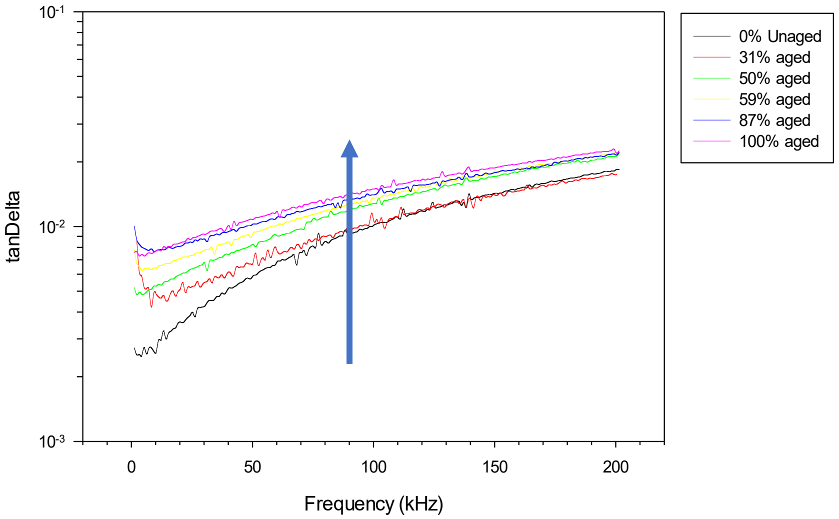
Cables with increasing lengths, e.g., from 1m to 20m, were locally aged under the same aging conditions.

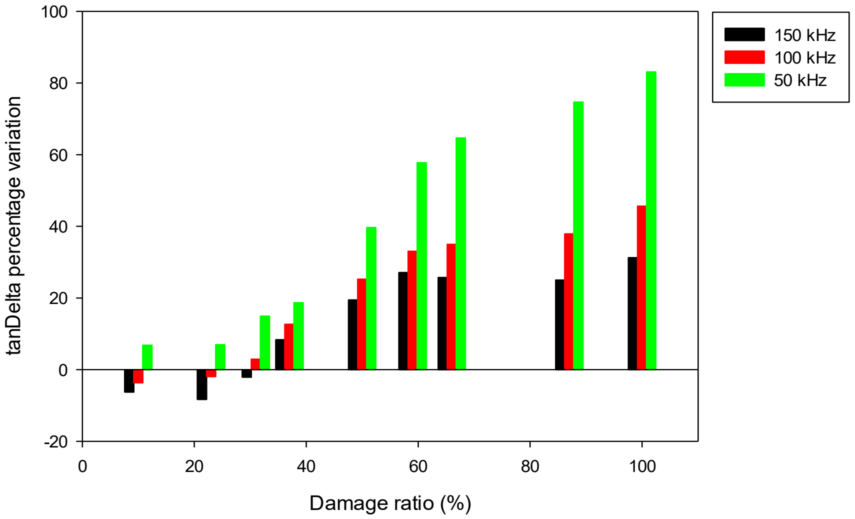
$$\text{Damage ratio} = \frac{\text{aged cable lenght (m)}}{\text{total cable lenght (m)}}$$



Sensitivity analysis of the portable device







- Very little variations of the specific capacitance (0.1-0.12 nF/m) – Non monotonic increase
  → Measure/Device uncertainties
- tanδ depicts
  → Monotonic increase of the property
  → Increase up to 1 order of magnitude
  As the damage ratio increases, the value of tanδ raises

tanδ follows the dilution and concentration of aged sections

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Conclusions

- Radio-chemical aging modifies physical-chemical and electrical properties of XLPE-based polymer used as insulator for low-voltage cables.
- Additives and fillers significantly affect polymer properties and its response to aging.
- Dielectric spectroscopy showed to coherently follow the polymer changes caused by aging, suggesting its suitability as a nondestructive condition monitoring technique for LV cables.
- DS successfully correlated with mechanical and various physical-chemical analyses

  → ability to **follow aging development**, throughout the various aging phases (antioxidant consumption, arising new degradation species, …).

  → tanδ at high frequency (100 kHz) proposed to be used as an aging marker.

- Developed portable device allows the evaluation of electrical properties in the frequencies of interest.

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DIELECTRIC SPECTROSCOPY TECHNIQUE FOR NON-DESTRUCTIVE CABLE CONDITION MONITORING: THEORY AND APPLICATIONS

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