Budapest University of Technology and Economics
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Measurement of dielectric response as a tool for insulation diagnosis and material characterization

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THE DIELECTRIC RESPONSE

The dielectric response I.

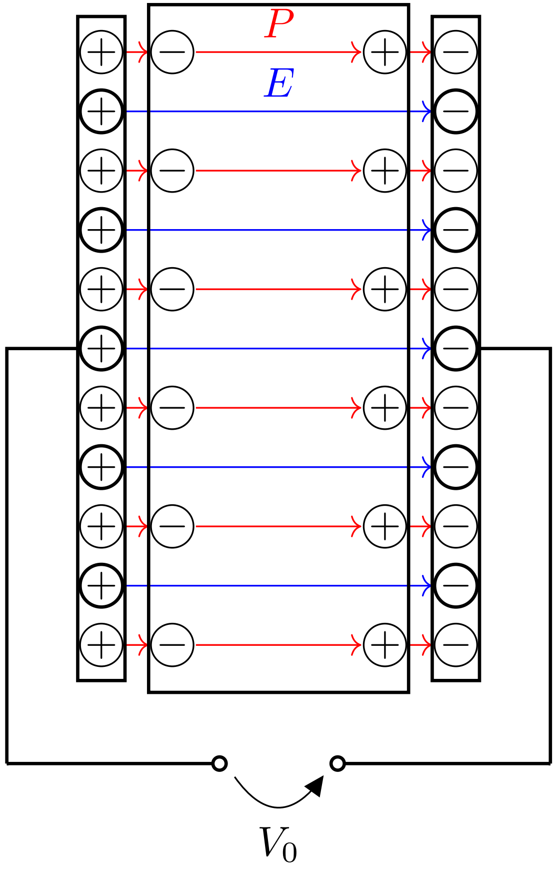
- Connecting a dielectric to a voltage source, in steady state conditions:

$$D = \varepsilon_0 E + P,$$

$$\sigma_0 = \sigma_e + \sigma_{pol}$$

- The time functions:

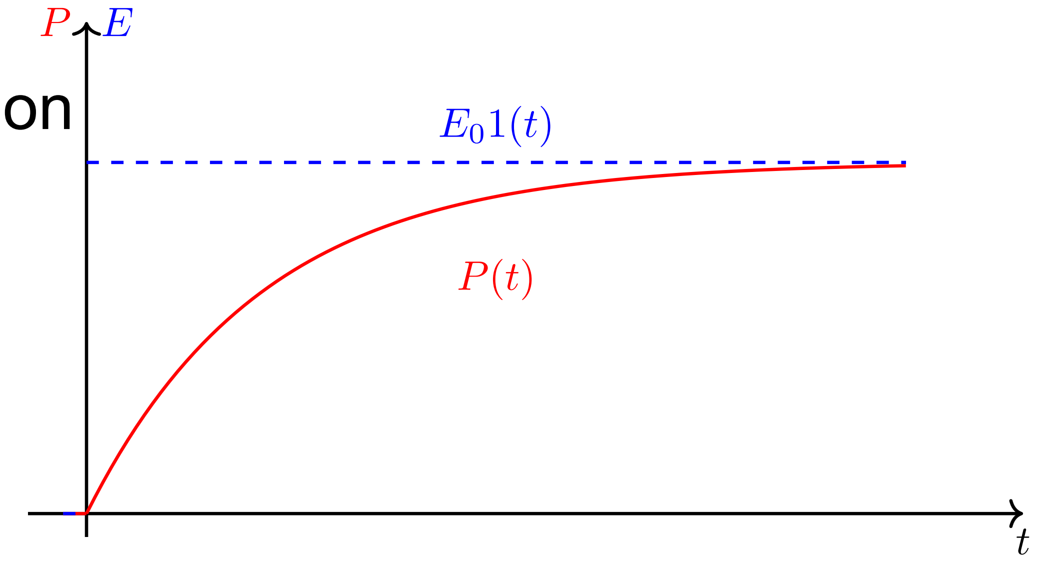
$$\sigma_0(t) = \sigma_e(t) + \sigma_{pol}(t)$$
$$D(t) = \varepsilon_0 E(t) + P(t).$$



The dielectric response II.

- Using step-voltage excitation, the polarization exhibits delayed response
- The dielectric response function *f(t)* can be introduced:

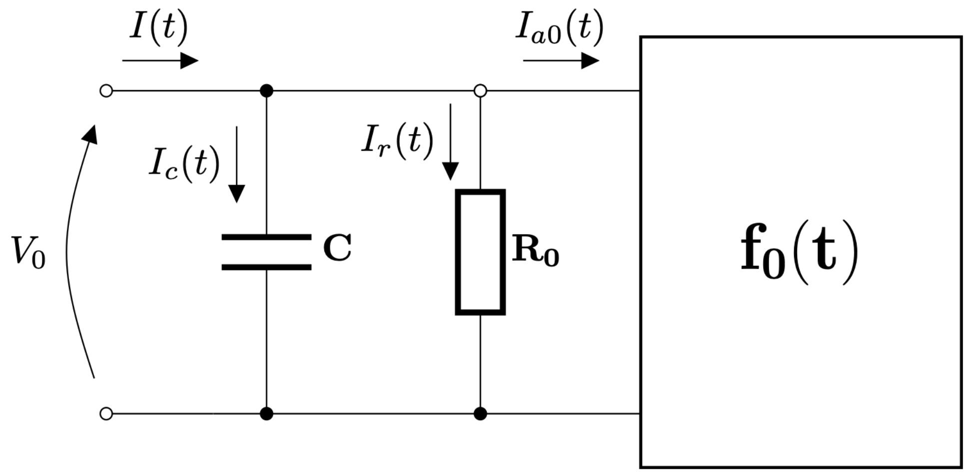
$$P(t) = \varepsilon_0 E_0 \delta(t) f(t)$$



- For general excitation: $P(t) = \varepsilon_0 \int_0^\infty f(\tau) E(t-\tau) d\tau.$
- For voltage step: $P(t) = \varepsilon_0 E_0 \int_0^t f(\tau) d\tau.$
- Physical interpretation $P(\infty) = \varepsilon_0 E_0 \int_0^\infty f(\tau) d\tau = P_0 = \varepsilon_0 \chi E_0$

The dielectric response III.

- The dielectric measurements can be modelled by a generalized circuit model

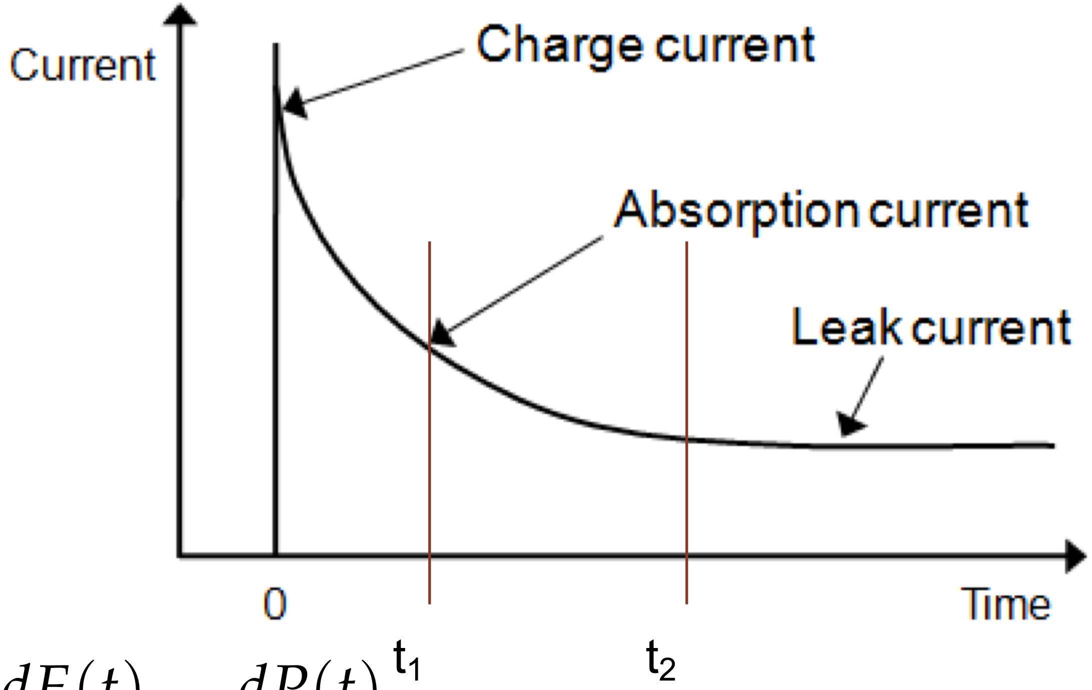


$$J(t) = \gamma E(t) + \frac{dD(t)}{dt} = \gamma E(t) + \frac{\varepsilon_0 dE(t)}{dt} + \frac{dP(t)}{dt}$$

MEASUREMENTS OF DIELECTRIC RESPONSE

Insulation resistance — Time domain

- DC voltage step
- Components of the current
- Dependence on the geometry of the insulation



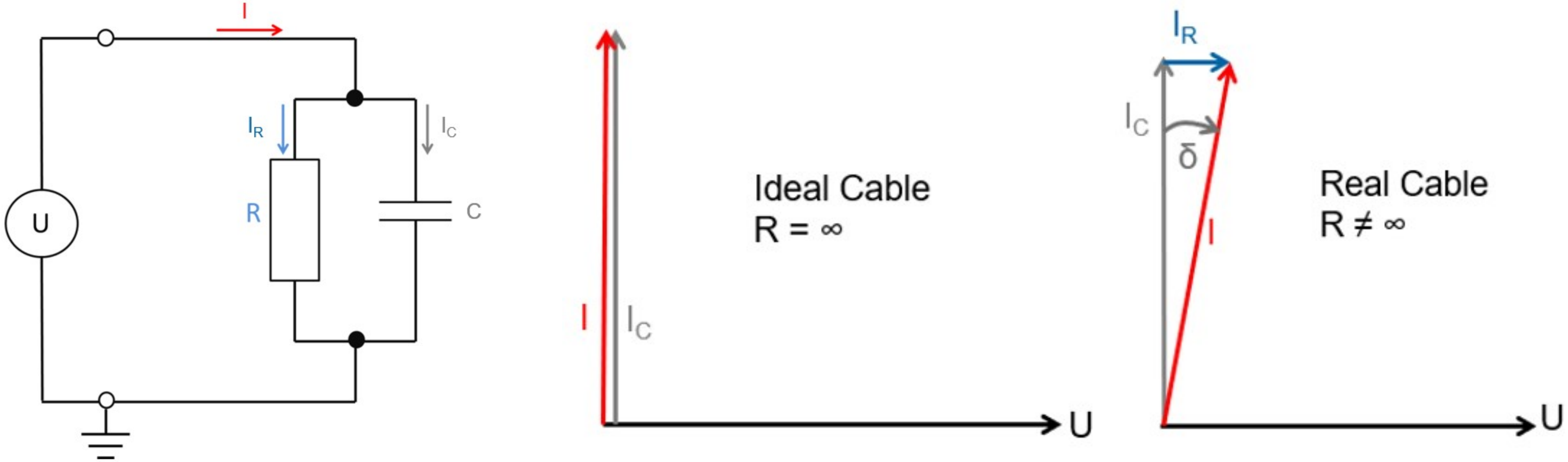
$$J(t) = \gamma E(t) + \frac{dD(t)}{dt} = \gamma E(t) + \frac{\varepsilon_0 dE(t)}{dt} + \frac{dP(t)}{dt}$$

- Polarisation Index (PI)= $I(t_1)/I(t_2)=R(t_2)/R(t_1)$, t_1=1 min, t_2=10 min
- Dielectric Absorption Rate (DAR)=$I(t_1)/I(t_2)=R(t_2)/R(t_1)$, t_1=15 sec, t_2=60 sec or t_1=30 sec, t_2=60

Tan delta (loss factor) — frequency domain

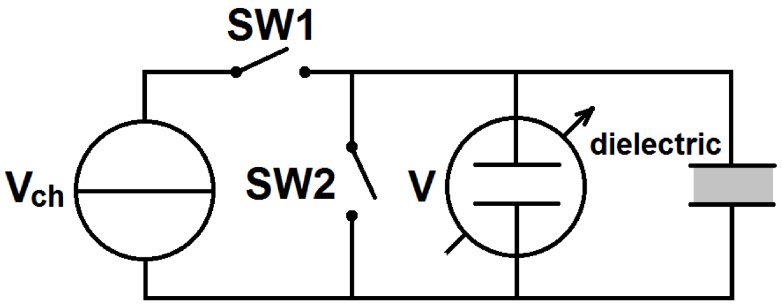
- Dissipation factor (D): tg δ=I_R/I_C
- Single frequency or D(f) (dielectric response in frequency domain)

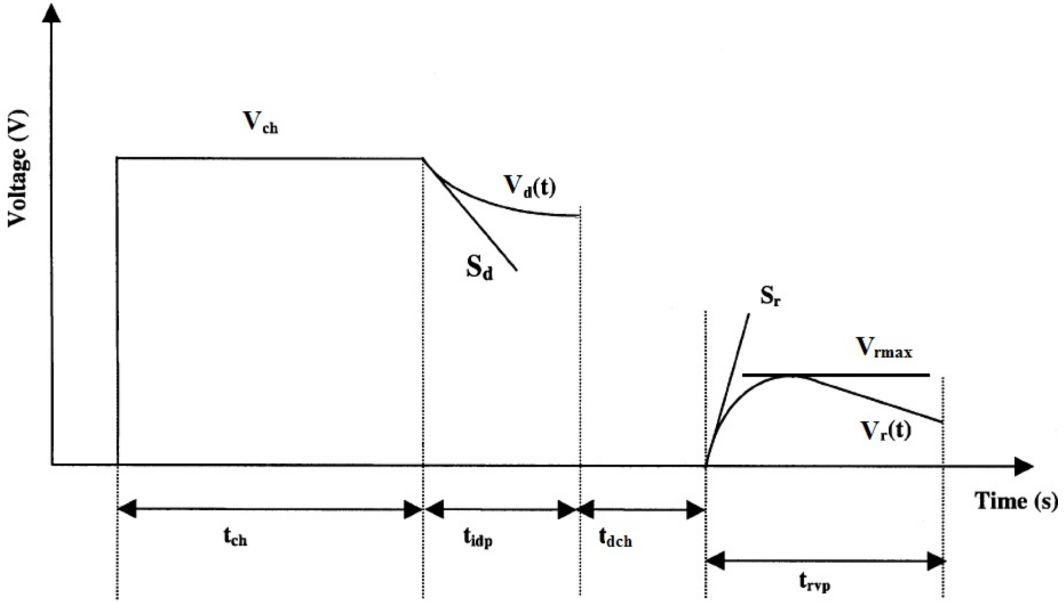
$$\tan\delta(\omega) = \frac{\varepsilon_r''(\omega)}{\varepsilon_r'(\omega)} = \frac{\varepsilon''(\omega) + \sigma_0 / \varepsilon_0\omega}{\varepsilon_r'(\omega)}$$



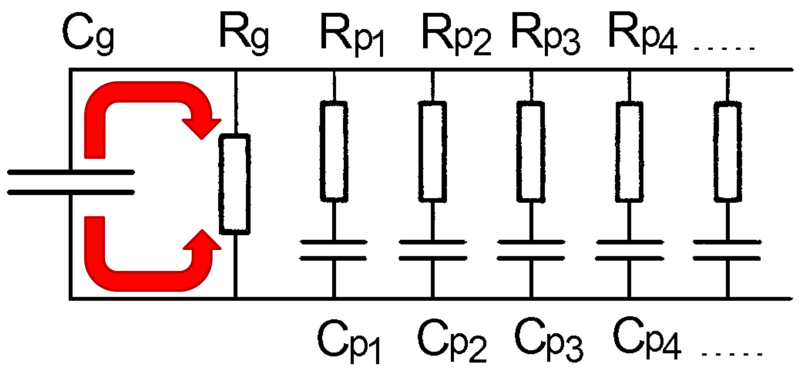
The Return Voltage Methods

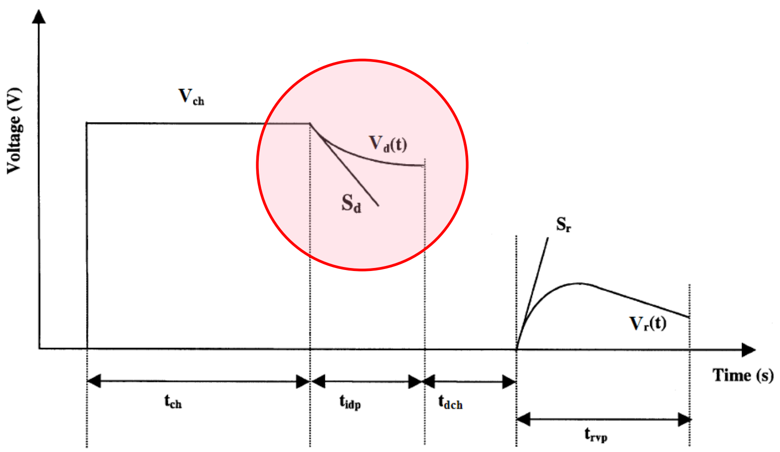
- The voltage response measurement is based on the measurement of the decay and the return voltage.
- The discharge voltage ($V_d(t)$) can be measured after the relatively charging period of the insulation.
- The return voltage ($V_r(t)$) can be measured after the shorting of a charged insulation.





The Decay Voltage



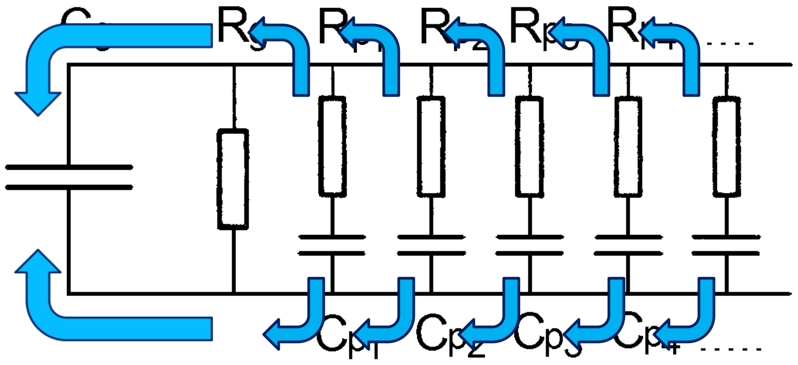


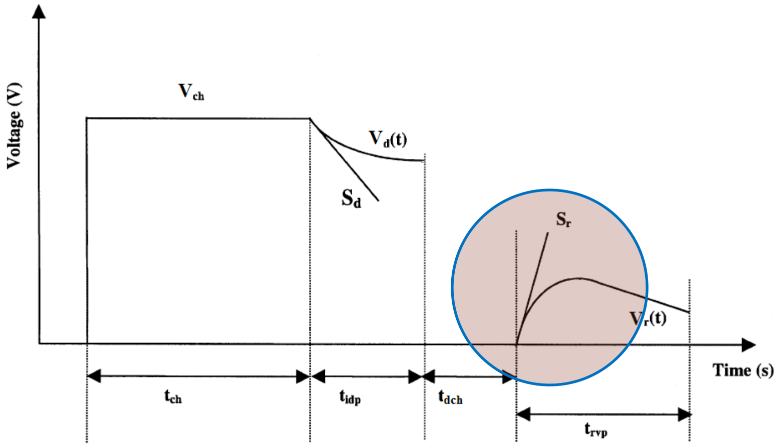
$$S_d = \gamma V_{ch} / \varepsilon_0$$

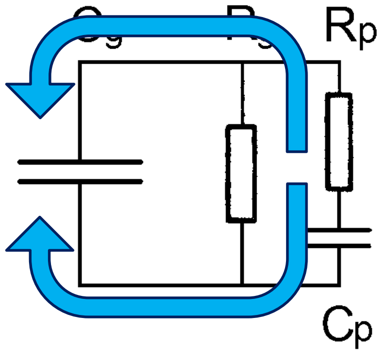
$$S_d = V_{ch} / \tau_g$$

$$\tau_g = R_g \cdot C_g$$

The Return Voltage







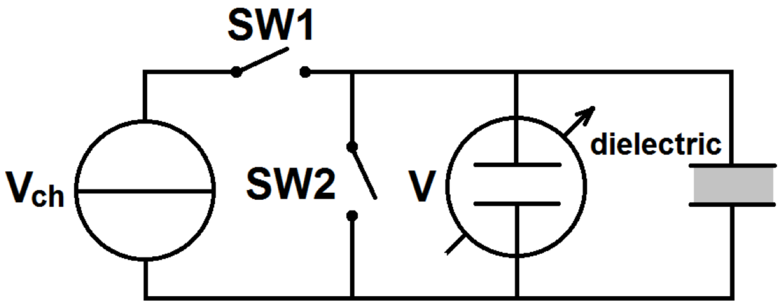
$$S_r = \beta V_{ch} / \varepsilon_0$$

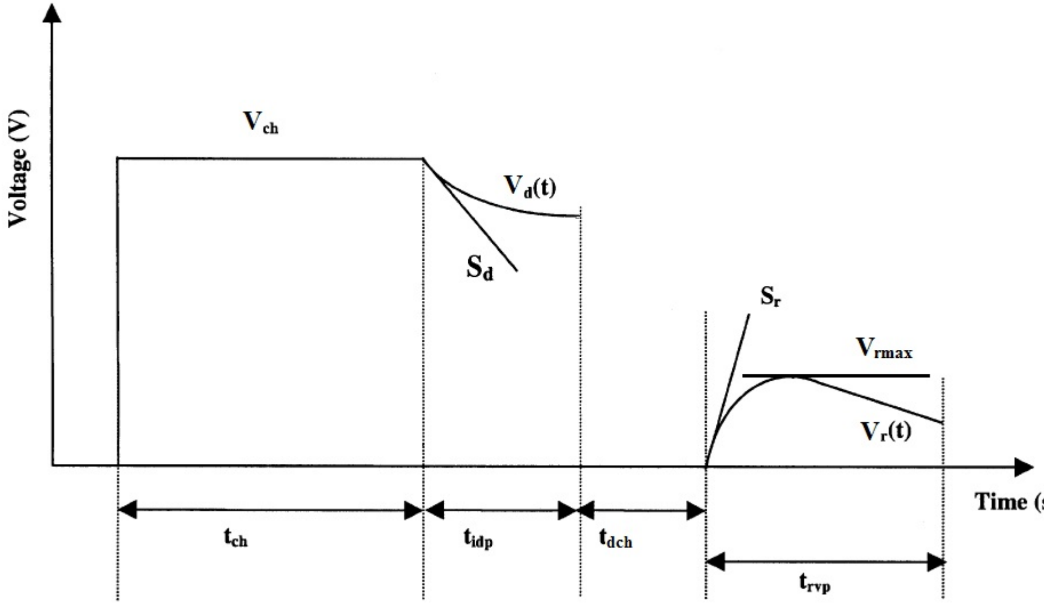
$$S_r = V_{ch} / \tau_r$$

$$\tau_r = R_p \cdot C_g$$

Evaluated Parameters

- Peak of return voltage (**V_{rmax}**)
- Slope of decay voltage (**S_d**)
- Slope of return voltage (**S_d**)
- **S_d: relating to the conductivity**
- **V_{rmax} and S_r: relating to polarization processes**



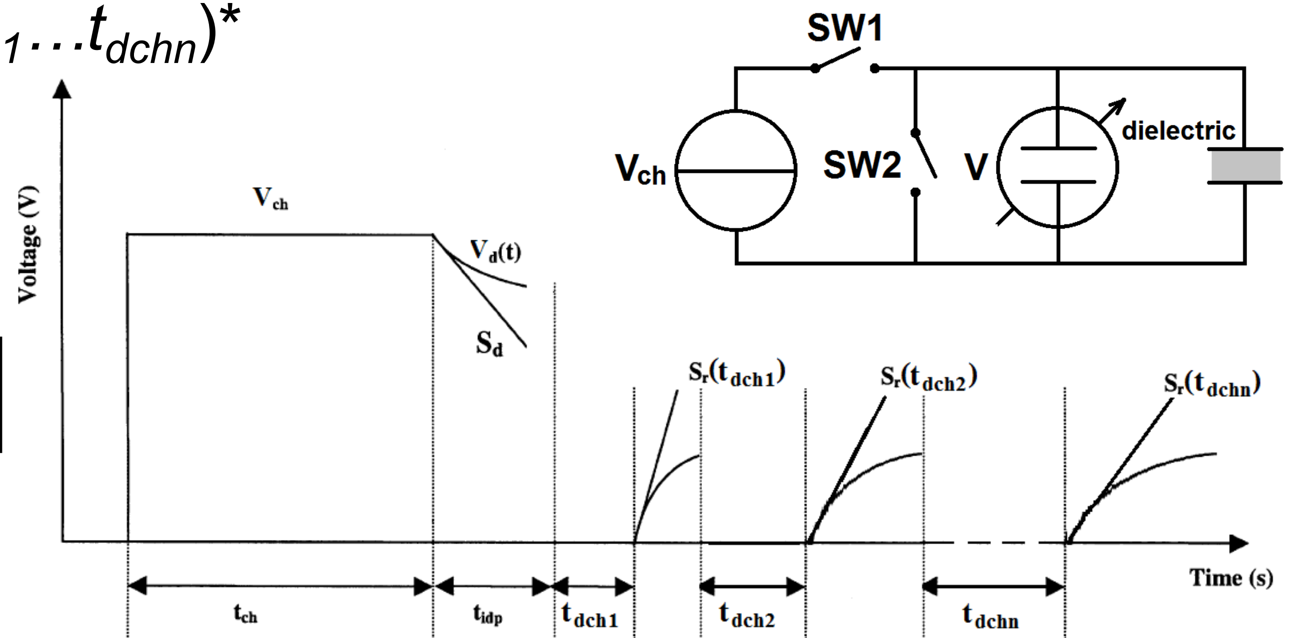


Extended voltage response method

- The **extended voltage response** measurement is based on the **measurement of decay and return voltages**.
- The decay voltage can be measured after a long charging time (t_{ch}) of the cable insulation disconnecting the voltage source
- The slopes of return voltages ($S_r(t_{dch1})\ldots S_r(t_{dchn})$) can be measured on the charged insulation after different shorting times ($t_{dch1}\ldots t_{dchn}$)*
- The relationship between the results and the dielectric characteristics can be expressed**:

$$S_d = \frac{V_{ch}}{dt}\bigg|_{t=t_{ch}} = -\frac{i_{pol}(t_{ch})}{C} = -\frac{V_{ch}}{\varepsilon_\infty}\left[\frac{\sigma_0}{\varepsilon_0} + f(t_{ch})\right]$$

$$S_r = \frac{V_{ch}}{\varepsilon_\infty}\left[f(t_{dch}) - f(t_{dch} + t_{ch})\right]$$

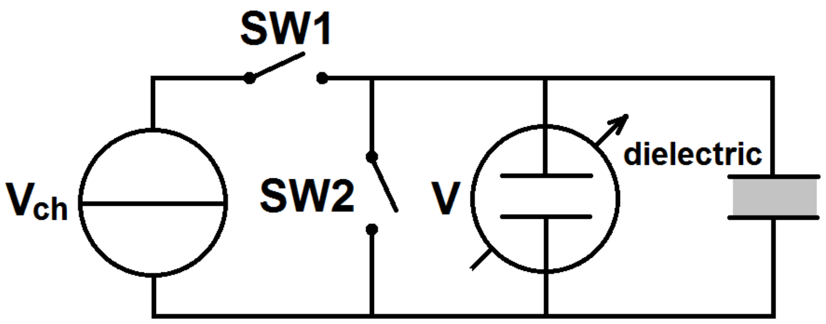


*Tamus Z Á, Csábi D and Csányi G M 2015 Journal of Physics: Conference Series 646 012043
**Tamus Z Á, 2019 Journal of Physics: Conference Series (inPress)

VOLTAGE RESPONSE FOR MATERIAL CHARACTERIZATION

Requirements of the measurement

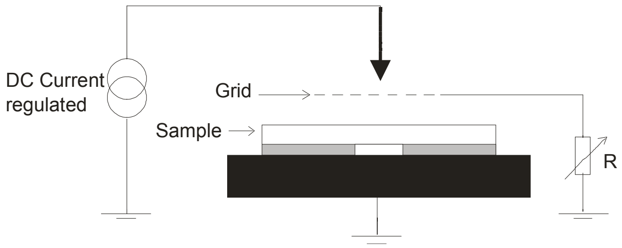
- The **capacitance of the equipment** has to be lower by two order of magnitude than that of the test object.
- The voltmeter has to be lossless but if the **input impedance** is higher by two order of magnitude than the resistivity of the test object.
- These requirements can be easily satisfied in case of testing high voltage equipment.
- But in case of material samples it is questionable.
- Critical elements
  - Voltmeter
  - SW1
  - SW2



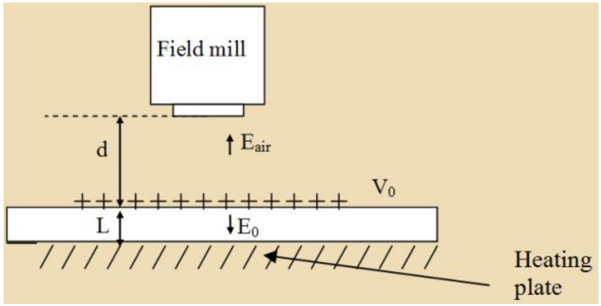
Application of ESVM for return voltage measurement

- Charging by corona discharge
- Neutralization by earthed and slightly alcohol wetted cotton

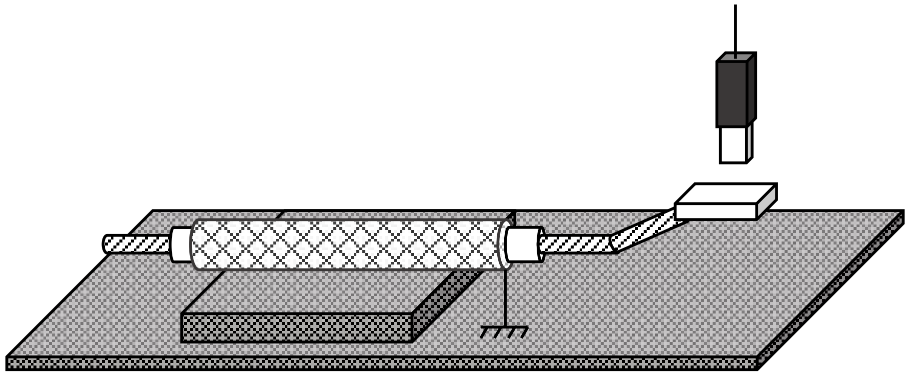
- Problem:
- Characterization requires accurate charging and discharging times



(a) Corona charging



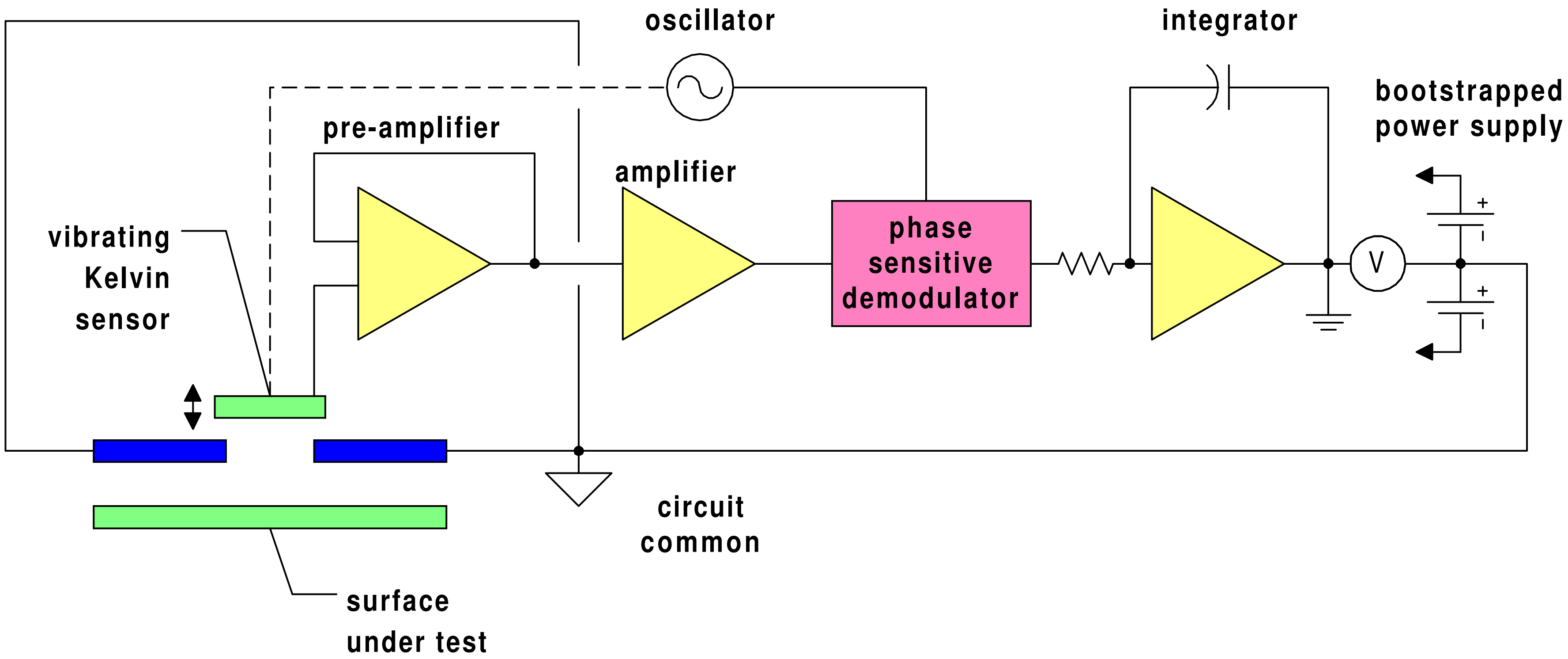
(b) Return voltage measurement



[10] Molinie P, Goldman M and Gatellet J 1995 Journal of Physics D: Applied Physics 28 1601–1610
[11] Molinie P 2005 IEEE Transactions on Dielectrics and Electrical Insulation 12 939–950 ISSN 1070-9878
[12] Moliní e P 2018 Proceedings of the 2018 Electrostatics Joint Conference

The electrostatic voltage follower

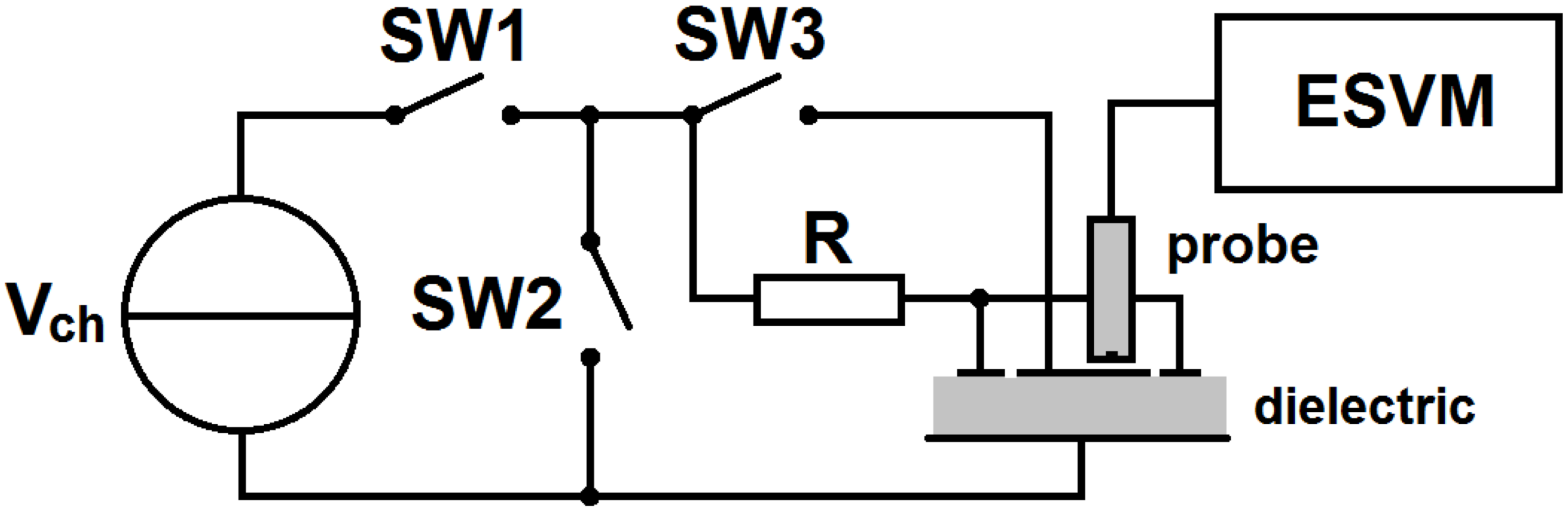
- Non-contact electrostatic voltmeter



Bartnikas R, McMahon E 1987 Engineering Dielectrics Volume IIB, Electrical Properties of Solid Insulating Materials: Measurement Techniques ASTM STP 926
Noras M A 2002 Trek application note

The arrangement

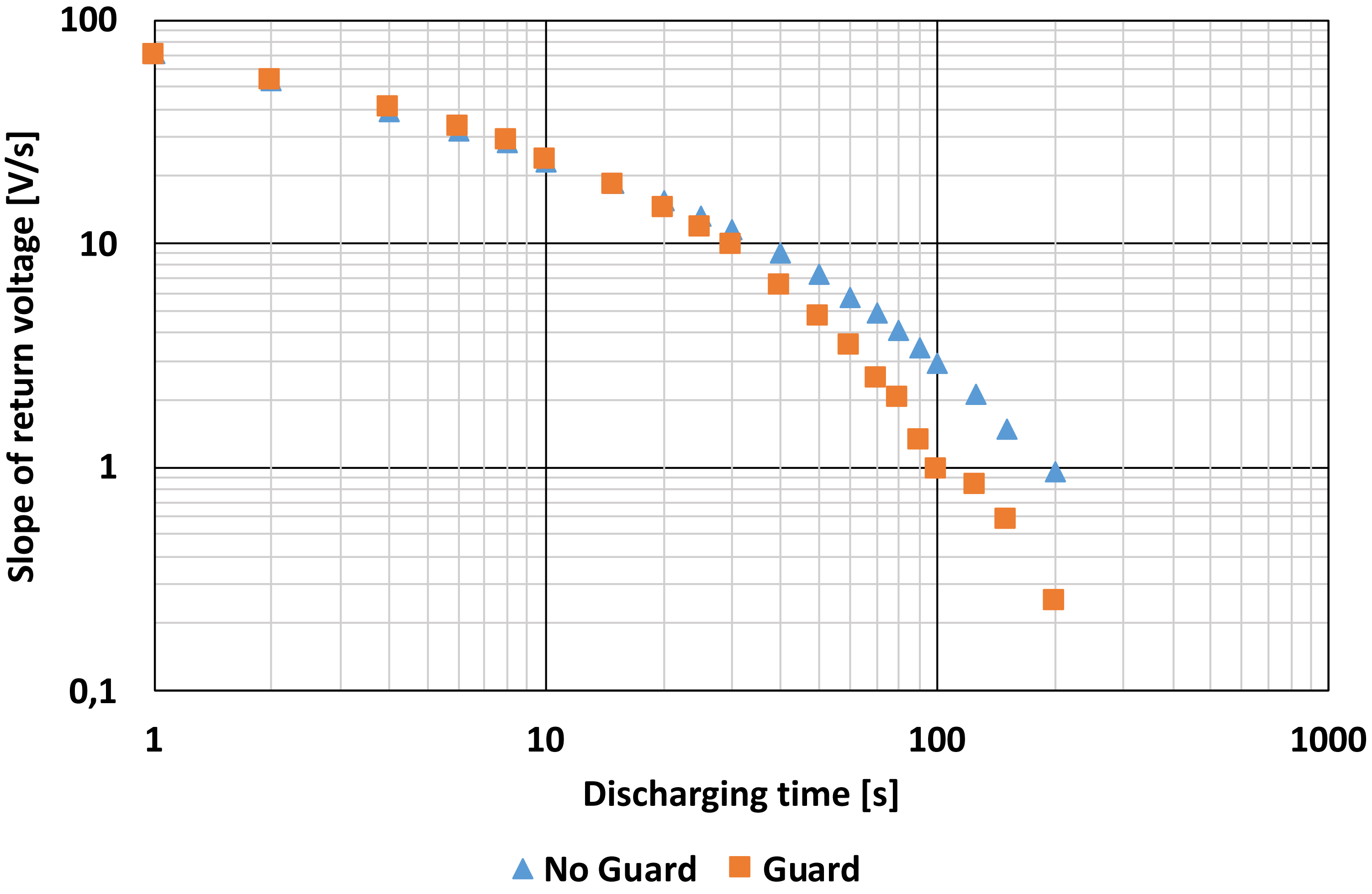
- Impedance of commercial switches around $10^{15\text{-}16}$ **Ω**
- This result in high leakage current for material test.
- The voltage follower is used for bootstrapping



	SW1	SW2	SW3
Charging	ON	OFF	ON
Discharging	OFF	ON	ON
Measurement	OFF	OFF	OFF

Test measurements

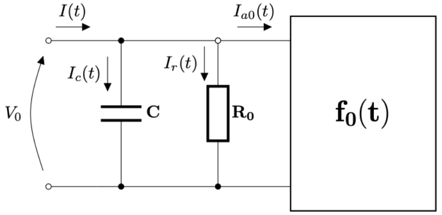
- Slope of decay voltages:
  - No Guard: -59.211 V/s
  - Guard: -31.803
- The slopes of return voltages are higher after longer discharging times
- Due to the polarization of polymeric insulation parts of the electrode arrangement



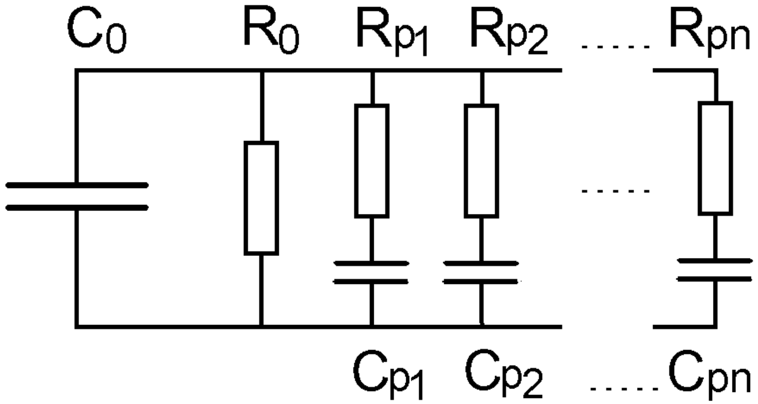
DIELECTRIC MODELING BASED ON EVR RESULTS

Determination of the equivalent circuit

- The slope of return voltage of *R-C* branches:



$$S_r = \sum_{i=1}^{n} \frac{V_{C_{pi}}}{\tau_{ri}} \qquad \tau_{ri} = R_{ri} C_0$$



- Slope of return voltage in case of *n R-C* branches and given charging and discharging times:

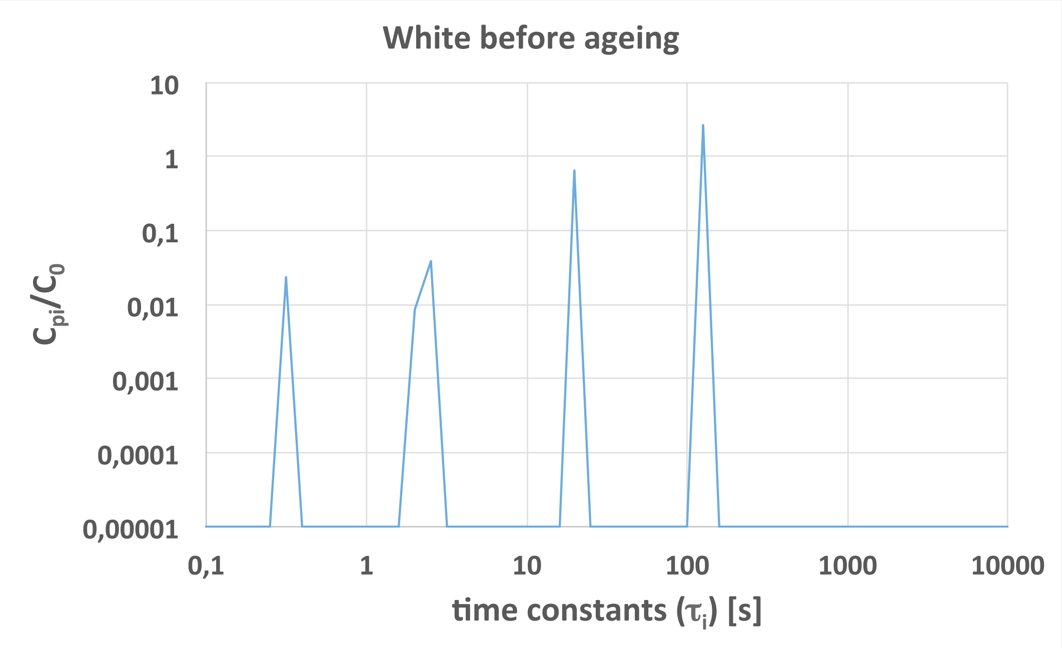
$$S_r(t_{ch}, t_{dchn}) = V_{ch} \sum_{i=1}^{n} \frac{\left(1 - e^{\frac{-t_{ch}}{\tau_{pi}}}\right) e^{\frac{-t_{dchn}}{\tau_{pi}}}}{\tau_{ri}}$$

Spectrum-like solution — I.

- Solutions finding in the 0,1…10000 s time constant range
- 10 polarisations in each decade
- Uniform distribution by lg(τ)
- Changing the intensity of every single processes, the $(S_r(t_{dch1})\ldots S_r(t_{dchn}))$ result vector of EVR measurement can be found.
- Least Square Method

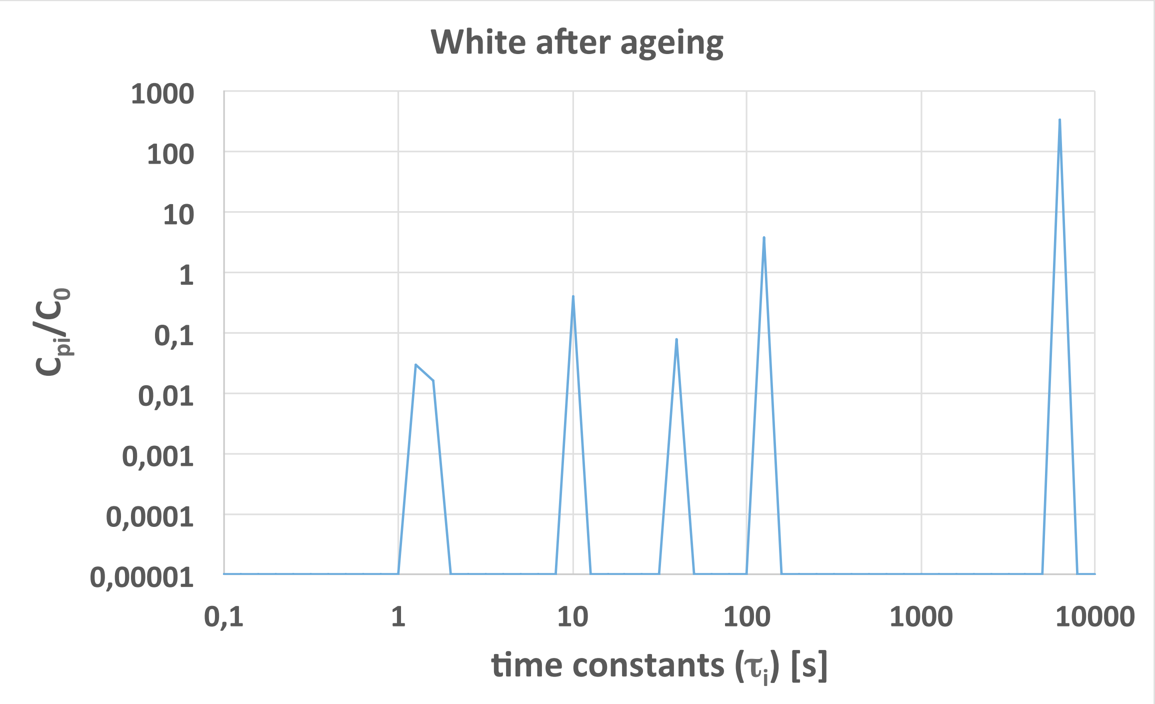
Spectrum-like solution— II.

- LV PVC insulated power cable



- Before ageing

- After accelerated thermal ageing (110°C, 900 h)



Nanodielectric samples — I.

- Samples:
  - Pure resin
  - 1 w% MgO nanoparticles (MgO)
  - 1 w% MgO nanoparticle, surfaceGLYMO (MgO+GLYMO)
- Main properties (ZCU measurments)*

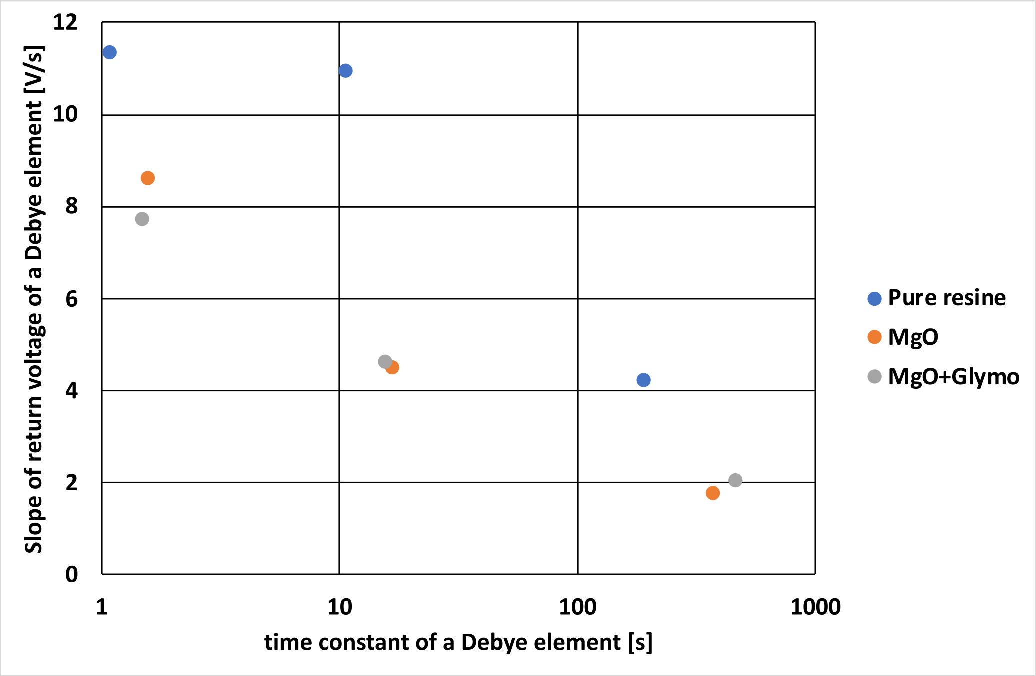
Sample	$\tan\delta$	ε_r	ρ	E_{bd}
Pure resin	0.0033	2.95	6.28×10^{12}	37 kV/mm
Resin + MgO	0.0041	3.43	5.01×10^{13}	42.3 kV/mm
Resin + MgO + GLYMO	0.0036	3.15	7.14×10^{14}	43.1 kV/mm

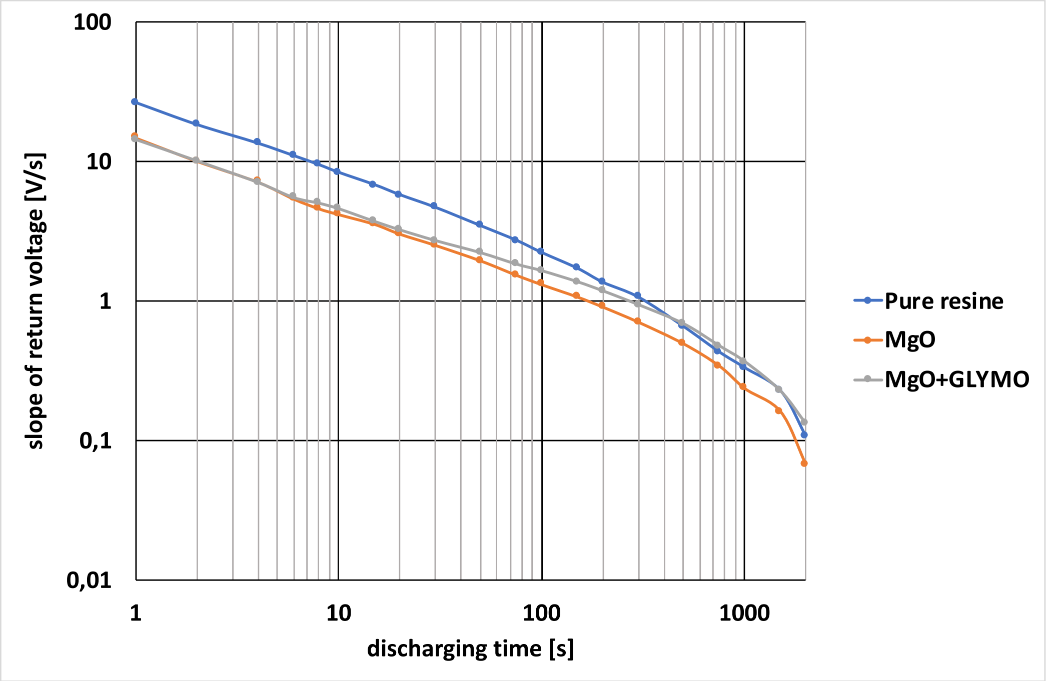
Sample	$S_d[V/s]$	$S_r[V/s]$
Pure resin	5.26	27.69
Resin + MgO	3.20	16.48
Resin + MgO + GLYMO	2.25	15.33

*Hornak,J.,Trnka,P.,Kadlec,P.,Michal,O.,Mentlík,V.,Sutta,P.,...Tamus,Z.A.,2018, Nanomaterials, 8(6).

Nanodielectric samples — II.

- EVR measurements
- Finding the minimal Debye elemets





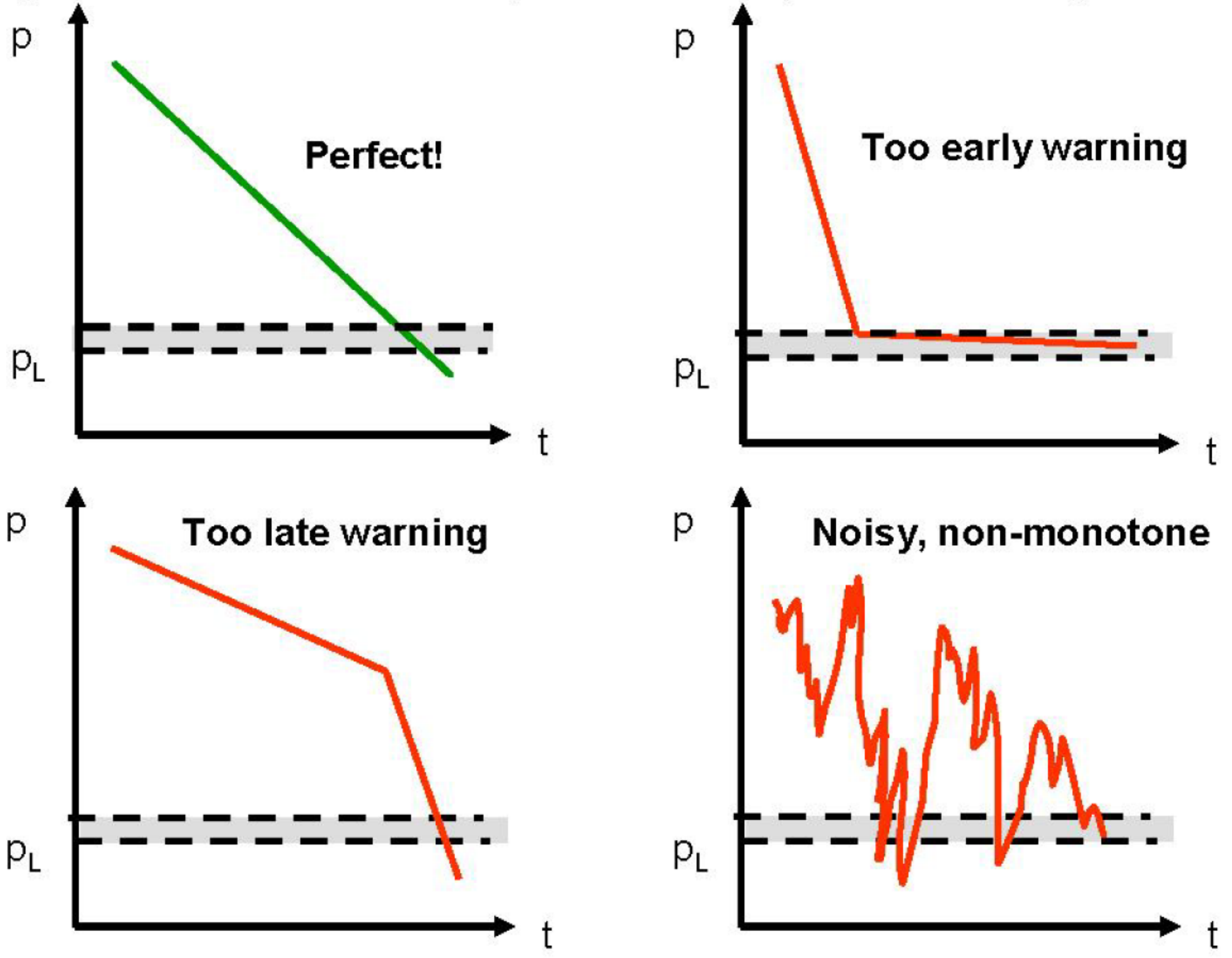
- Intesity of slow polarisation processes decreases
- The distributin shifths towards high time constants
- Decreasing mobility of charge carriers
  - Nanoparticles* **
  - Surface modification***

*Takada, T., Hayase, Y., Tanaka, Y., & Okamoto, T. 2008, IEEE TDEI, 15(1), 152–160.
**Tanaka, T., & Imai, T. (Eds.), 2017, Advanced nanodielectrics : Fundamentals and applications
***Chen, G., Li, S., & Zhong, L., 2015, IEEE 11th Int. Conf. on the Prop. and App. of Diel. Materials (ICPADM) 36–39

AN INTERPRETATION OF FREQUENCY-DOMAIN MEASUREMENT

Finding diagnostic markers

- The best diagnostic marker has to follow the ageing of the equipment linearly
- The searching of diagnostic markers are based on accelerated ageing tests
- But the data provided by these tests are not reliable in many cases



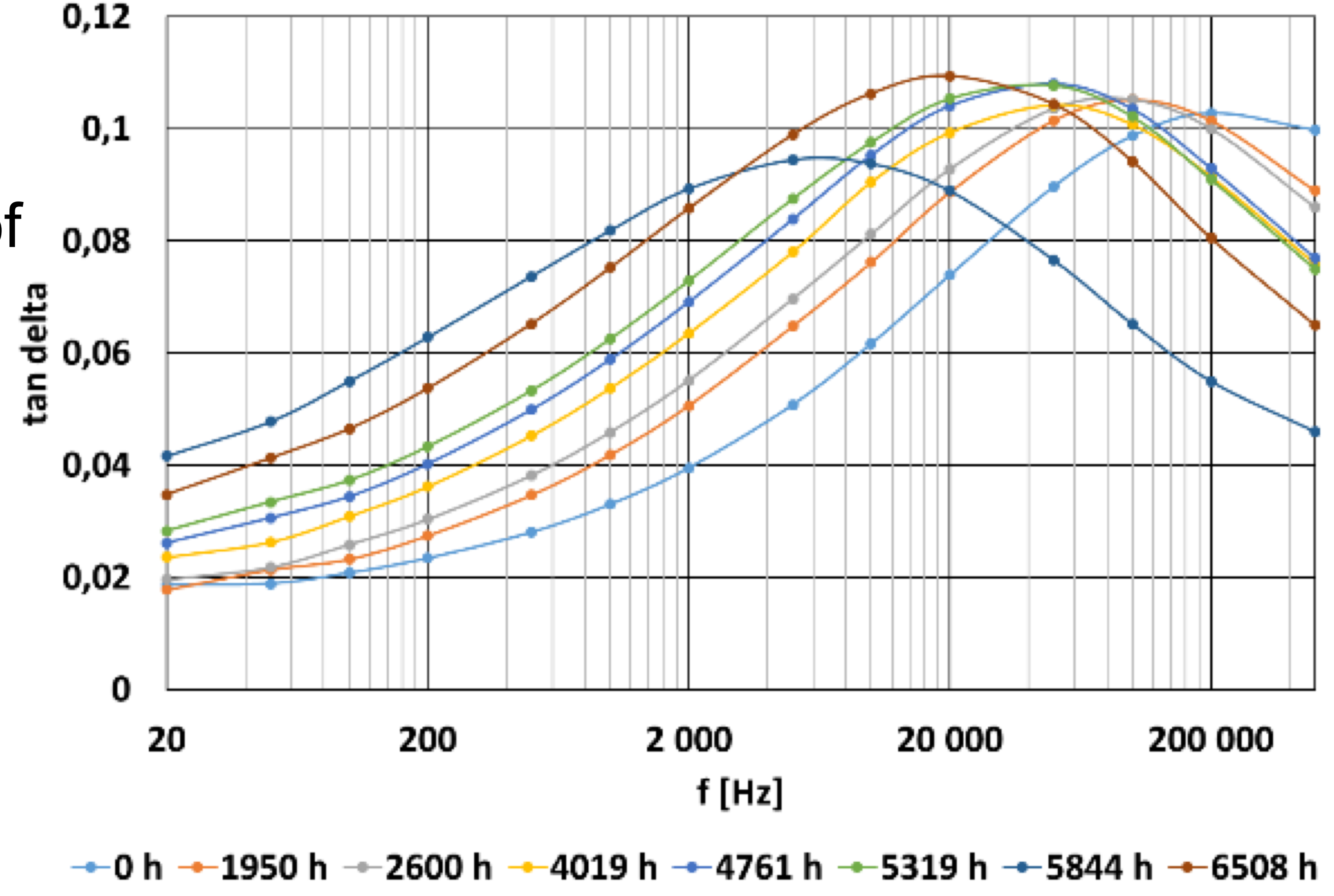
G.C. Montanari, IEEE ICPADM, Bali, Indonesia, 2006

Dissipation factor – Thermal aged EPR cable samples

- **Shifting of curves with ageing** can be observed
- “Shifting” cannot be applied for evaluation of ageing
- The centroids of the curves were calculated to characterize the “shifting”:

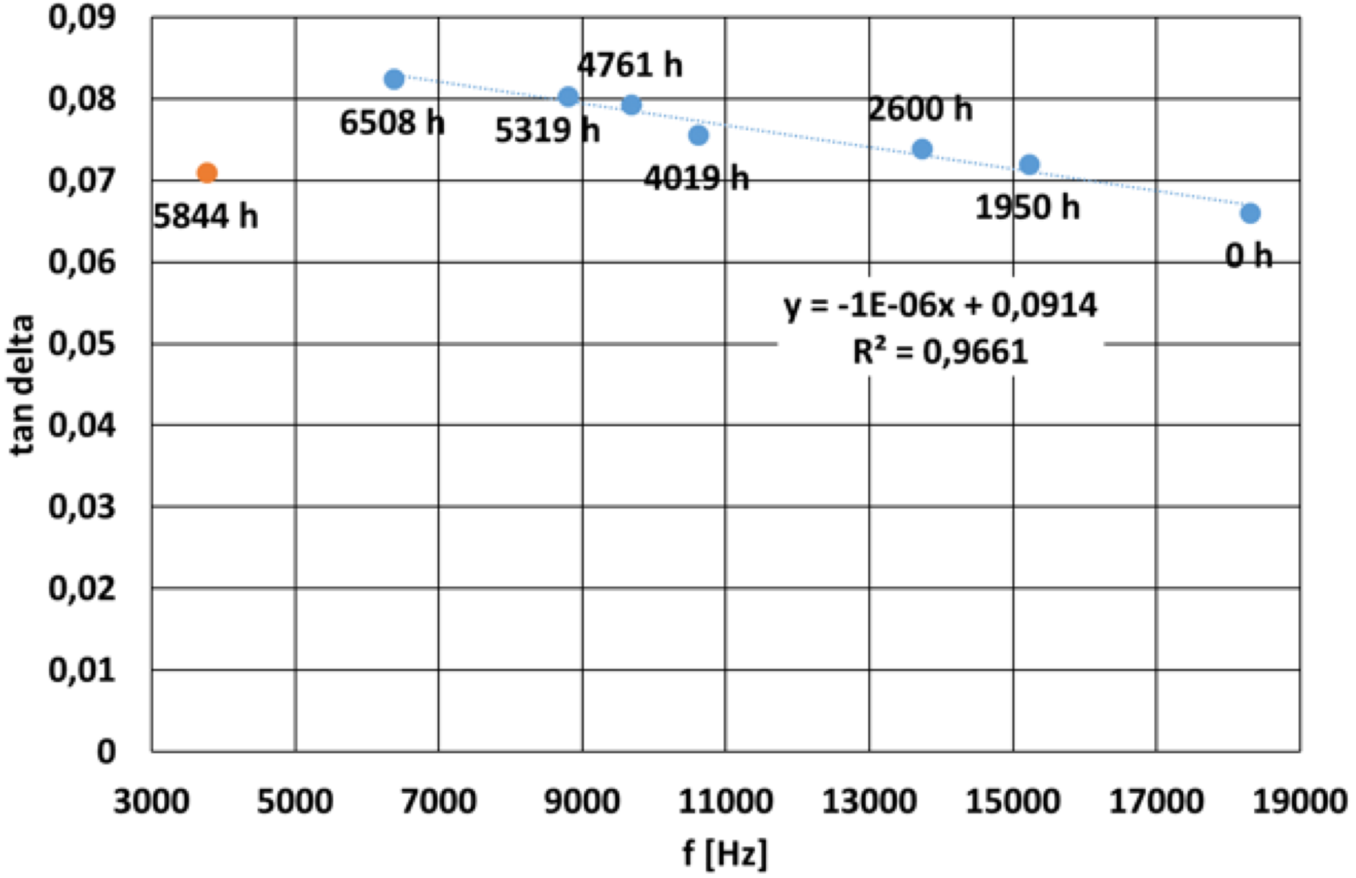
$$\lg f_C = \frac{\sum_{i=1}^{N} DF_i \lg(f_i)}{\sum_{i=1}^{N} DF_i}$$

$$DF_C = \frac{\sum_{i=1}^{N} DF_i \lg(f_i)}{\sum_{i=1}^{N} \lg(f_i)}$$



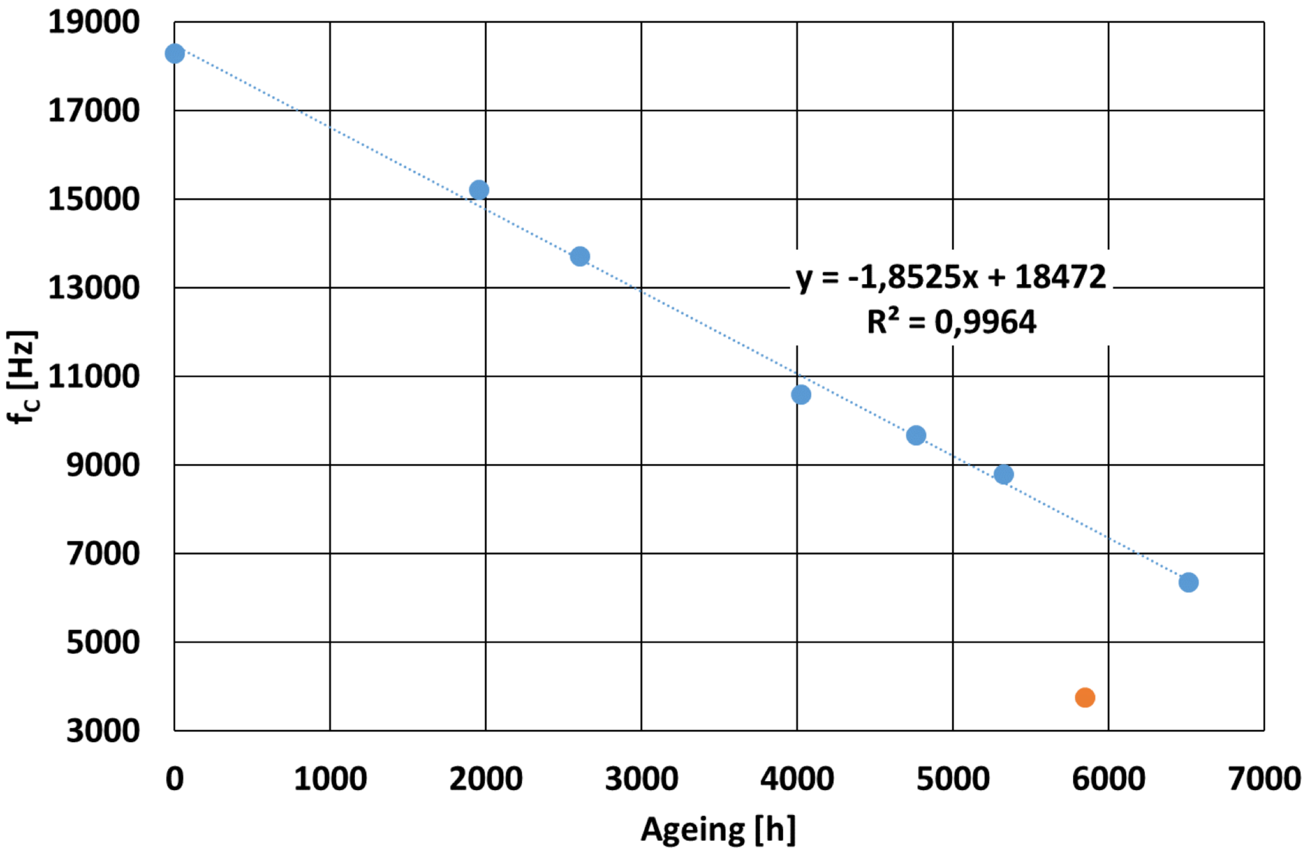
The position of centroids

- The **centroids fit on a straight line** (R^2=0.9661)
- Therefore both f_C and DF_C values can be used to track ageing
- The point of 5844 h aging time is an outlier data, it is not involved to the analysis



The central frequency (f_c) as a function of ageing time

- **Good correlation with ageing** (R^2=0.9964)
- This parameter is a **good marker for ageing**
- More ageing markers have been developed*



*Csányi, G.M.; Bal, S.; Tamus, Z.Á. Dielectric Measurement Based Deducted Quantities to Track Repetitive, Short-Term Thermal Aging of Polyvinyl Chloride (PVC) Cable Insulation. *Polymers* **2020**, *12*, 2809. https://doi.org/10.3390/polym12122809

CONCLUSIONS

Conclusions

- The dielectric response can be measured time- and frequency-domain by the current measurement
- The return voltage technique has been improved
  - Using several discharging and measurements the dielectric response function can be measured
  - The results can be used for dielectric modeling
  - Using electrostatic voltmeter the material samples can be investigated
- Frequency-domain measurements provide a spectrum of a dielectric parameter
- It is difficult to interpret them for condition monitoring
- Deducted quantities can help for easier analysis

Thank you for your attention!

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