Technical challenges linked to HVDC cable's development

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Content

- No introduction → read the article!

- Fundamentals of extruded cables
- Accessories and field control
- Fundamentals of MI cable
- Conclusions

FUNDAMENTALS OF EXTRUDED CABLES

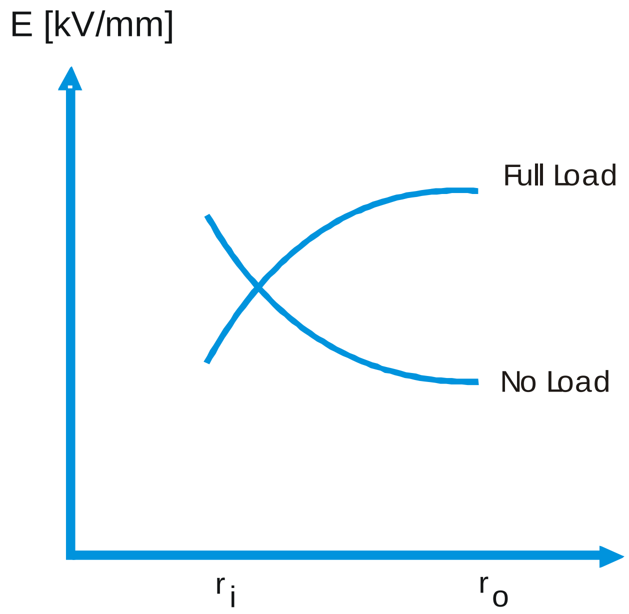
Different types of cables

- MI (Mass Impregnated) first AC but also for DC
- LPOF (Low Pressure Oil Filled) for both AC and DC
- HPGF (High Pressure Gas Filled) for AC
- HPFF (High Pressure Fluid Filled) for AC
- EPR for AC
- PE for AC (DC ?)
- XLPE for AC and DC (HVDC-Light)
- Filled polymers for DC (Nanocomposites)
- GIL (Gas Insulated Lines-SF6) for AC
- Superconducting Cables

Challenges with extruded HVDC cables

Characteristics of an ideal HVDC insulation material

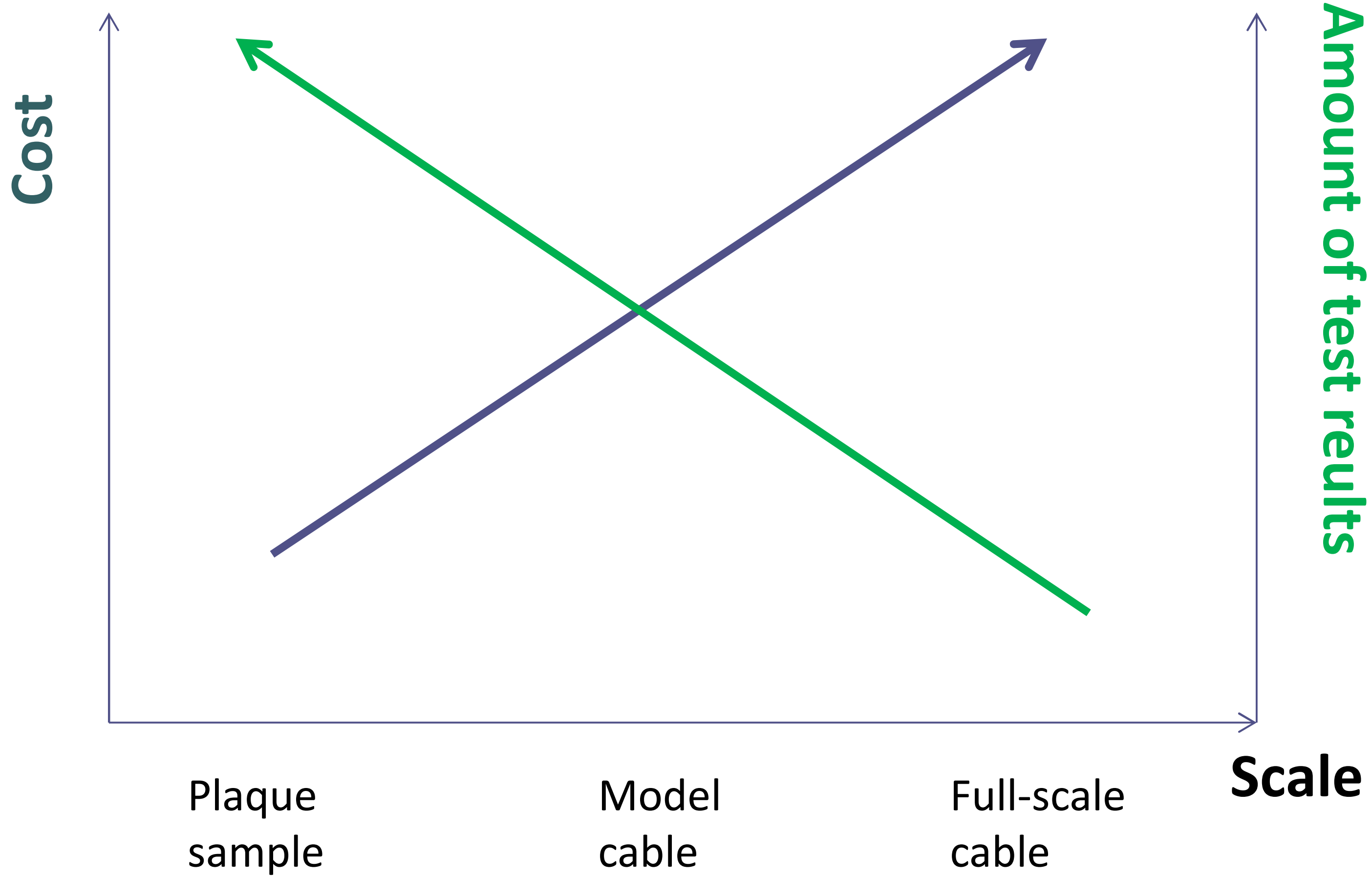
- Electrical properties:
  - High electrical withstand
  - Low DC conductivity -> Low thermal losses
  - Low space charge accumulation -> Electric field
  - Electrical aging



- Other properties (less discussed):
  - Thermal/mechanical aging
  - Processability
  - Quality control: material and cable
  - Chemically stable
  - Good mechanical properties
  - Not harmful to environment
  - Cost of material and production
  - ....

Challenges with extruded HVDC cables

Characteristics of an ideal HVDC insulation material



Challenges with extruded HVDC cables

Material characterization: Plaque samples vs. cables

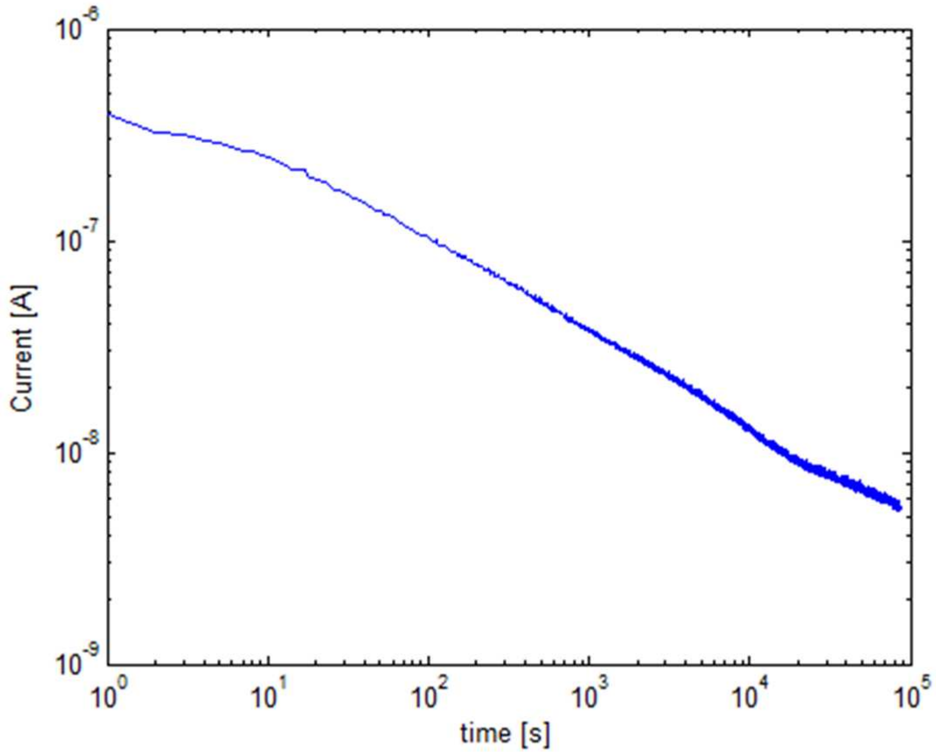
- Major differences between plaque samples and cables:
  - Different process condition
  - Cylindrical geometry of cables
  - Insulation thickness
  - Electrode material
  - Temperature gradient

  …
- Plaque sample results can be dominated by interface physics at the electrodes.
- One needs to be careful when making strong conclusions based on plaque sample results.

Challenges with extruded HVDC cables

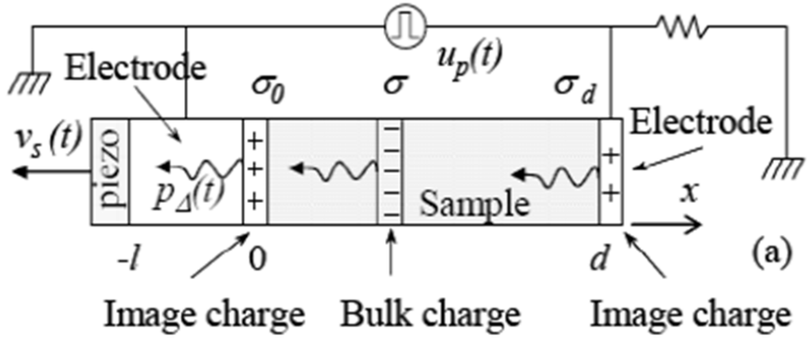
Material characterization: Low DC conductivity

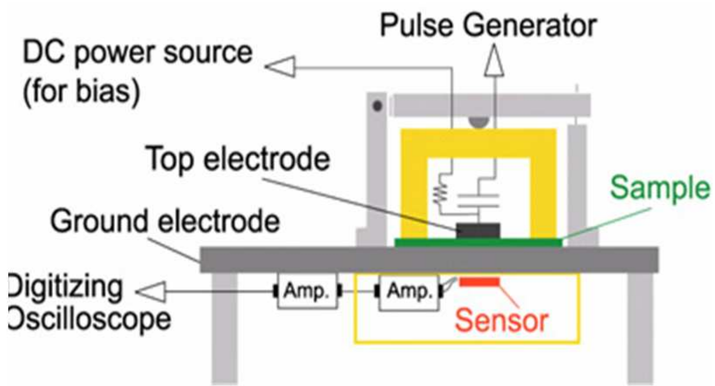
- Plaque sample sensitive to:
  - Sample thickness
  - Process condition
  - Heat treatment
  - Electrode material
  - Interface contact
  - Humidity
  - …
- The current does not reach steady state.
- Valuable but not easy to interpret.
- Same is valid for space charge mesaurements.



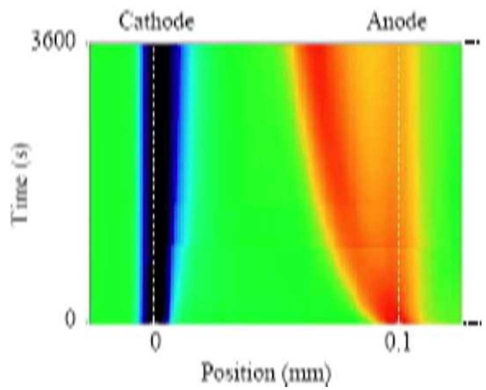
Challenges with extruded HVDC cables

Material characterization: Space charge (PEA)





- Pulsed Electro-Acoustic (PEA) measurement:
  - Mainly on plaque samples
- PEA on thick cables:
  - Cylindtrical geometry -> Distortion
  - Thick insulation -> Damping
  - Acoustic signal speed changes by temperature; temperature gradient distorts the signal strongly.
  - Reflection from multiple layers.



from: www.5lab.co.jp
and: Tanaka et. all."Material challenge of MgO/LDPE nanocomposites for high field electrical insulation", Cigre 2008

Challenges with extruded HVDC cables

Modelling and design

- Generic:

for each charge carrier:

$$\frac{\partial n_k}{\partial t} + \frac{\partial j_k}{\partial x} = R_k(n_l)$$

$$j_k = n_k \upsilon_k - D_k \frac{\partial n_k}{\partial x}$$

$$\upsilon_k = \mu_k E$$

$$j = \sum_k q_k j_k + \frac{\partial D}{\partial t}$$

Boundary conditions: A function of field and tempertature for each carrier.

- Complicated.

- Large number of parameters required.
- Sensitive to the parameters.

- Pragmatic:

Conductivity as a function:

$$\sigma = f_R(\vec{r}) f_T(T) f_E(E) \qquad j = \sigma E$$

$$\rho_e = \nabla \cdot (\varepsilon_0 \varepsilon_r E) \qquad \nabla \cdot j = -\frac{\partial \rho_e}{\partial t}$$

$$\rho_e = -\frac{\varepsilon_0 \varepsilon_r}{\sigma} \frac{\partial \rho_e}{\partial t} + j \cdot \nabla \left(\frac{\varepsilon_0 \varepsilon_r}{\sigma} \right)$$

$$\rho_m c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + S_{heat}$$

- Simple, fast and convergent
- Few parameters required
- Reasonable results
- Does not simulate all reality but a very useful model

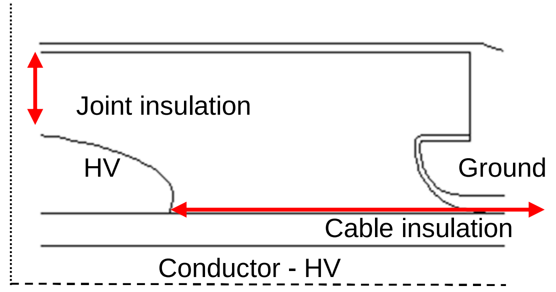
Which to choose?

ACCESSORIES AND FIELD CONTROL

DC-Field control

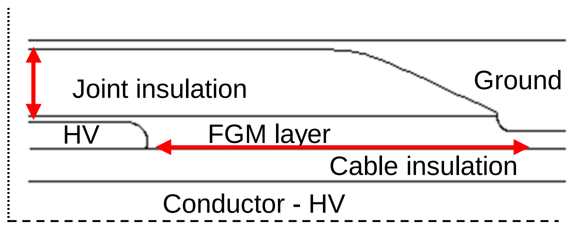
Geometry example

Geometric



- Geometry of conducting parts according to impulse stress and allowed interface fields

Non-linear resistive

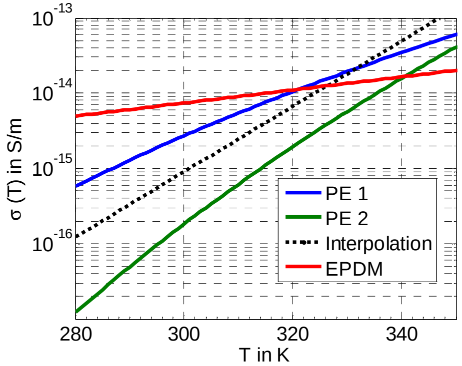


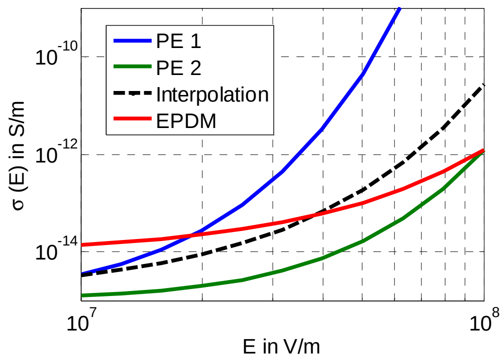
- Field control layer connects HV to ground
- Material properties to be chosen according to DC and impulse stress.

Electrothermal stresses in HVDC cable systems
Wave shapes, material properties and simulation models

Conductivity is strongly Influenced by temperature and electric field

– PE[1] and EPDM[2] ([1]Boggs et al, 2001, [2]relative to PE[1])





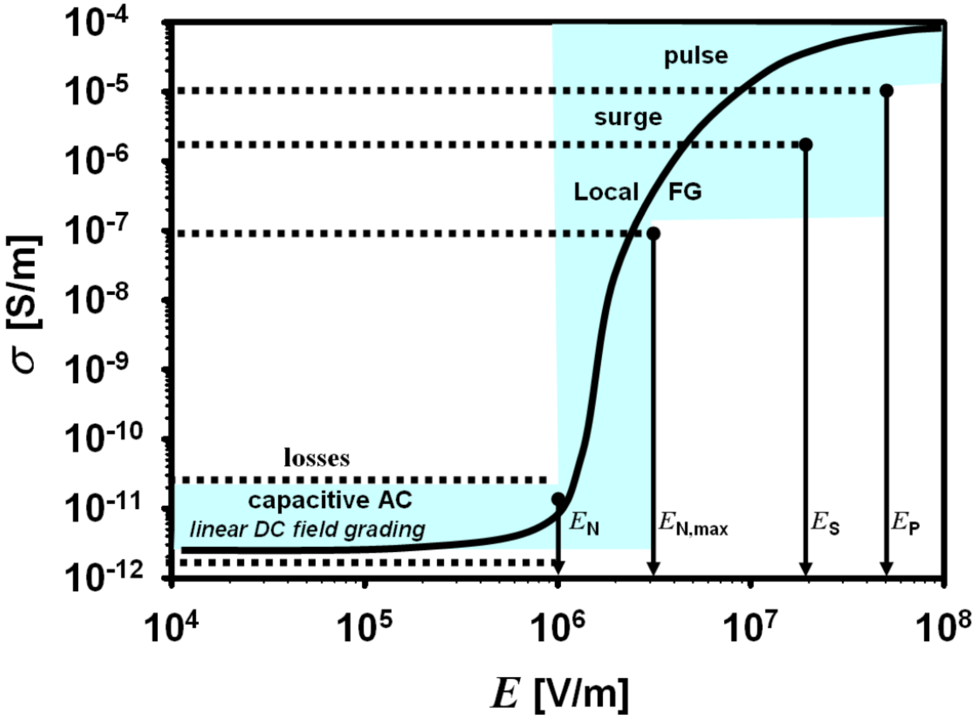
- Heat conduction in the solid
  - Current in the conductor
  - Resistive losses in the insulation

- Electro thermal coupling is essential for DC field simulations!

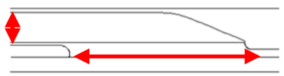
$$\nabla \cdot (\sigma(E,T)\nabla V) - \nabla \cdot \frac{\partial \varepsilon_0 \varepsilon_r \nabla V}{\partial t} = 0 \qquad \rho_M c_p \frac{\partial T}{\partial t} + \nabla(-\lambda \nabla T) = Q(E, I_0)$$

DC-Field control
Material properties

- Field grading material
  - Non-linearity according to DC and impulse stress.



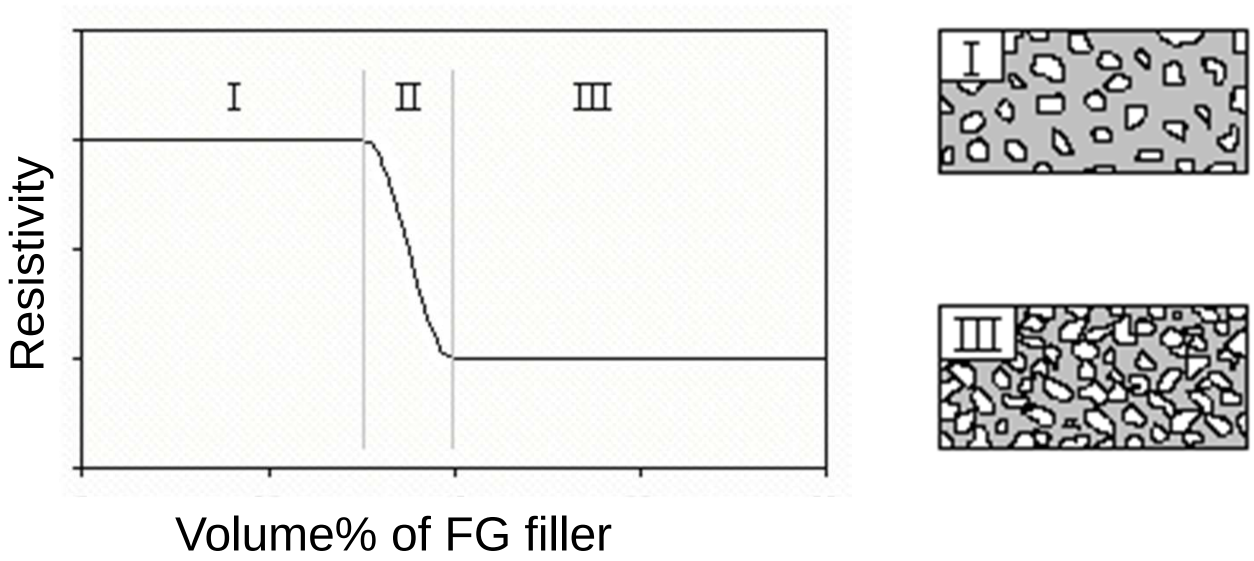
Non-linear resistive



Field control

Non-linear resistivity / conductivity

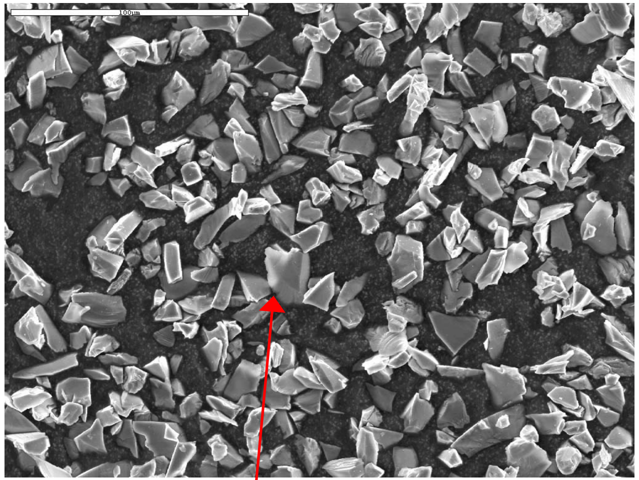
- FGM consist of filler particles which form a network of contacts.
- 20-40 v% of particles



- In region 3 the electrical properties are determined by the particle material and the contacts between the particles.

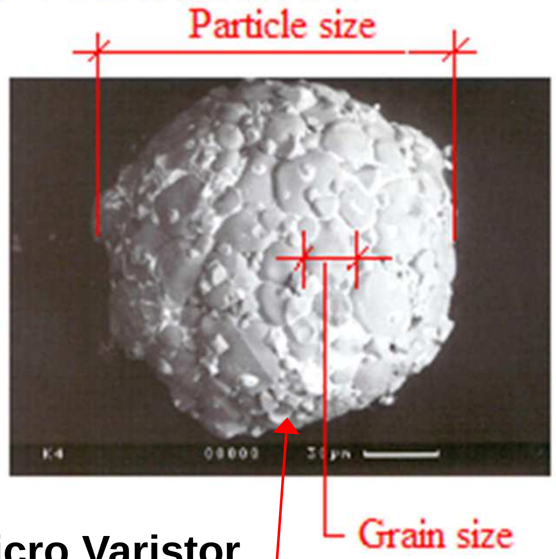
Field control

Non-linear resistivity / conductivity



SiC

Particle-Particle contact is non-linear



ZnO Micro Varistor

Non-linearity comes from grain boundaries mainly

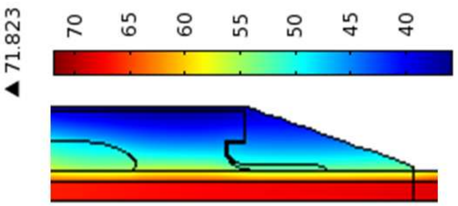
- In both cases the non-linearity is related to Schottky barriers
- Carbon black is also often used as a second filler, connecting the FG particles
- Other material concepts to arise

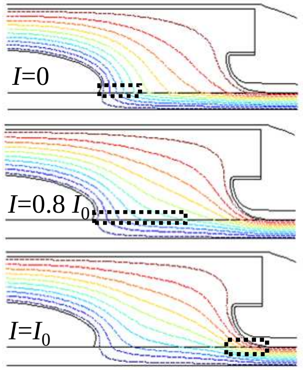
DC-Field control

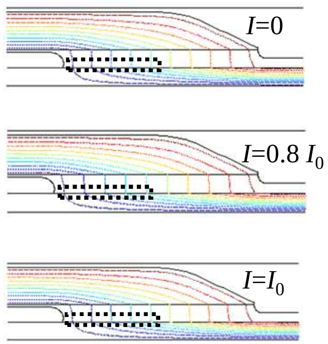
Electric field distribution - comparison

- Comparison of different load scenarios under DC voltage

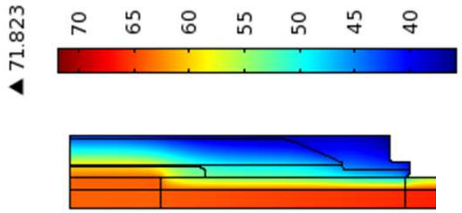
Geometric

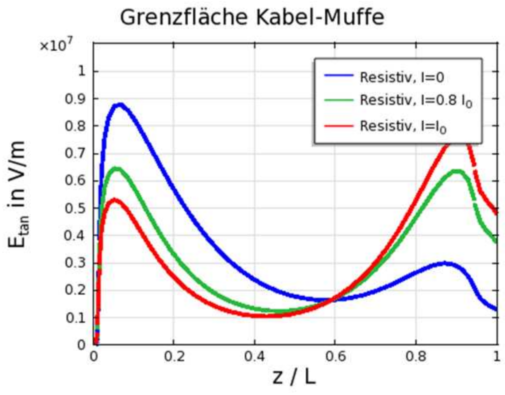


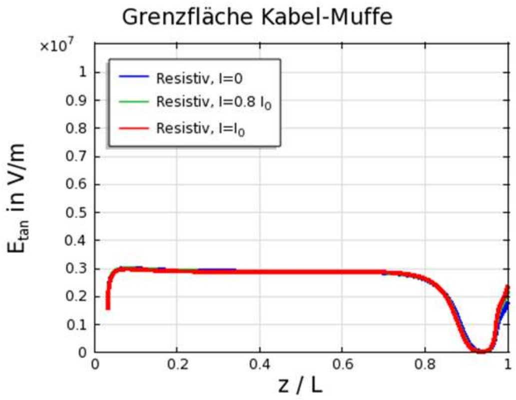




Non-linear resistive





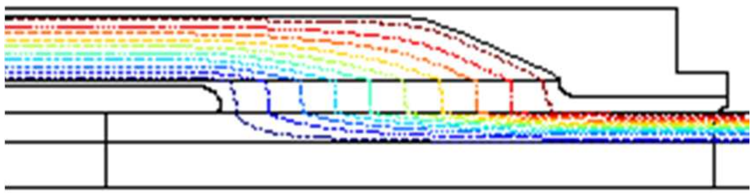


- Non-linear resistive layer dominates the field distribution
- Robust against variations in load and/or material properties, due to „adaptive resistive" control

DC-Field control
Electric field distribution - comparison

- Coupling of electrical and thermal material properties is essential to capture the dynamics/behaviour of HVDC accessories

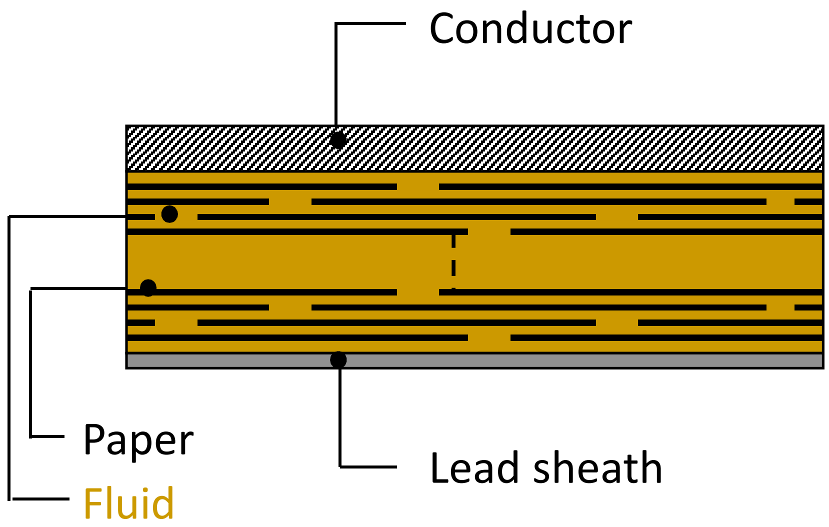
- A layer of non-linear resistive field grading material leads to robust behaviour under DC stress.
- A layer of non-linear resistive field grading material gives a more even field distribution under DC stress.



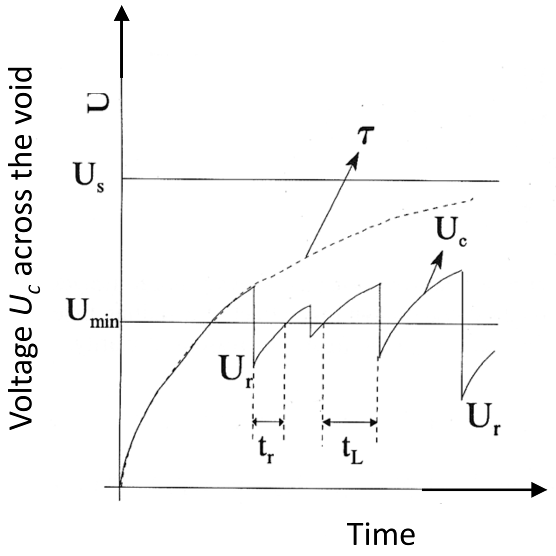
FUNDAMENTALS OF MI CABLE

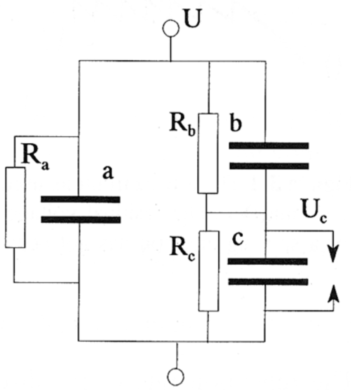
MI Cable

HVDC **M**ass **I**mpregnated cable



Partial Discharges at DC





Void

One can calculate the discharge

- Repetition rate
- Magnitude

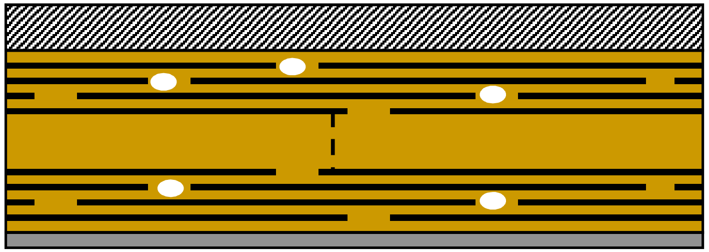
… of 1 void

Model the hydrodynamic behaviour of the cable and one can calculate the discharge

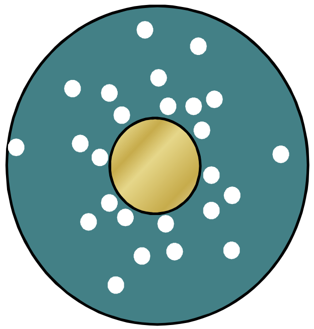
- Repetition rate
- Magntiude

of the whole cable.

Partial Discharges at DC - many voids



Voids can appear in in
- butt-gaps
- between paper layers
- inside paper

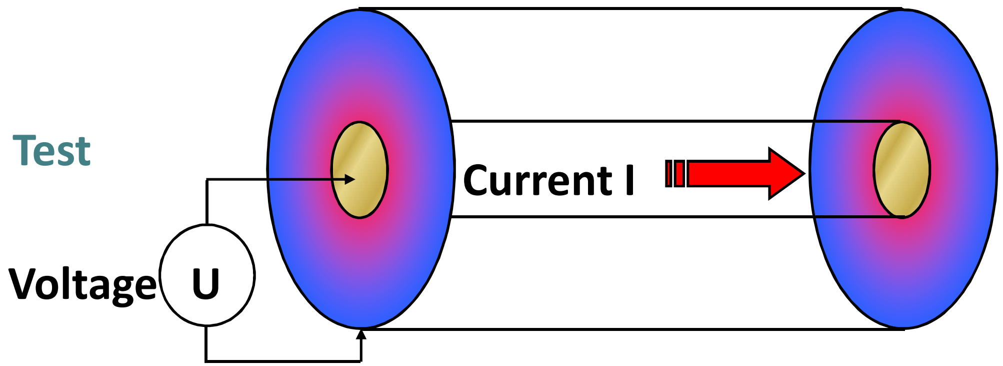


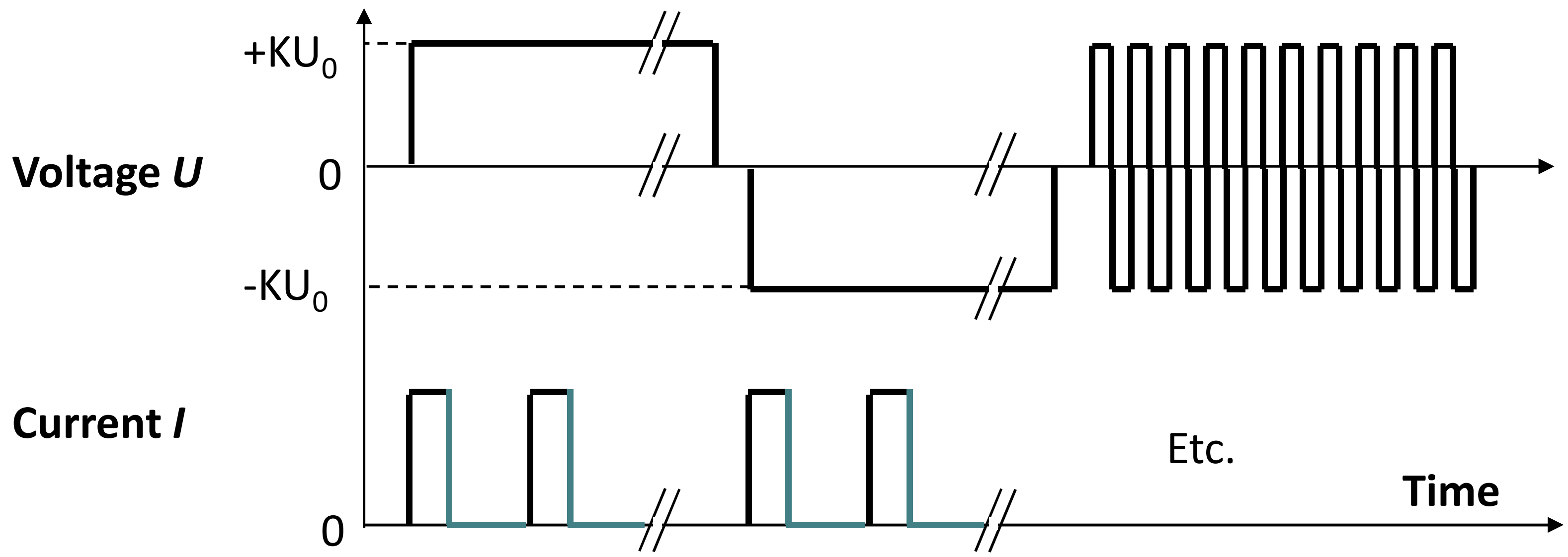
Void distribution

Type Testing the HVDC - MI cable

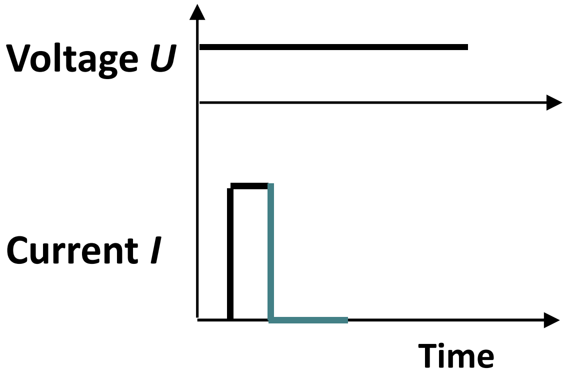
Backbone of a Type Test:

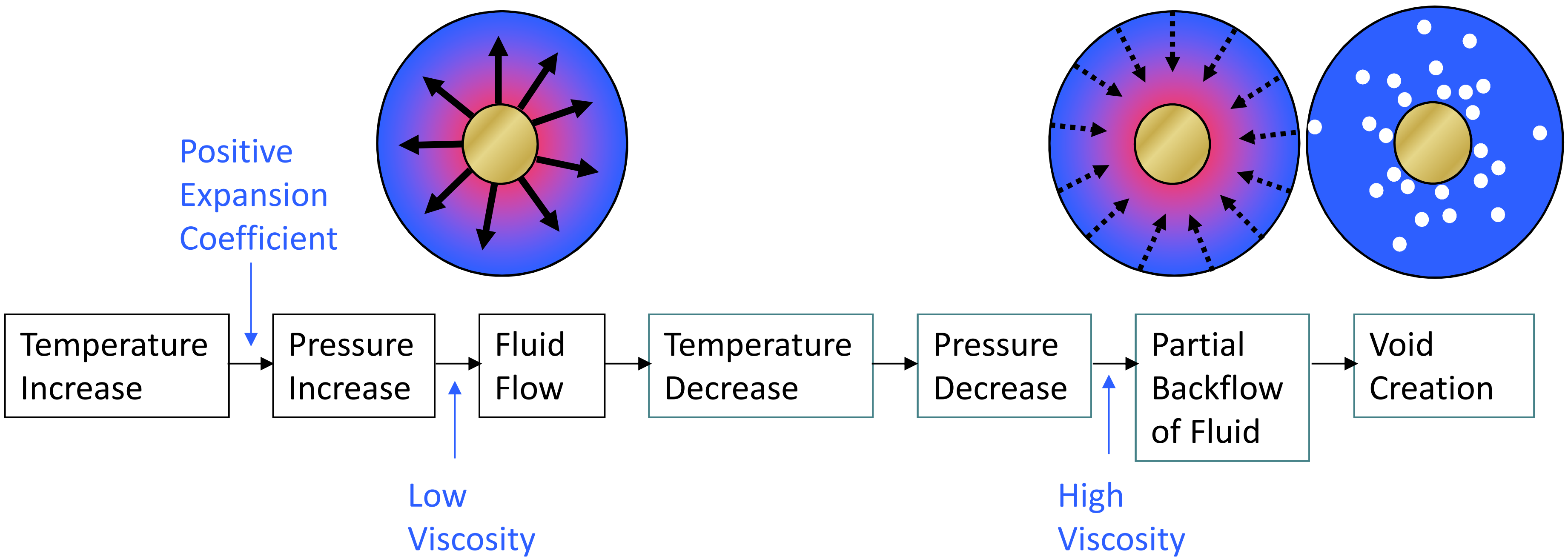
- Bending Test
- **Load Cycle Test and Polarity Reversal Test**
- Switching Surge Withstand test
- Lightning Impulse Withstand Test
- External Water Pressure Withstand Test
- Visual Inspection



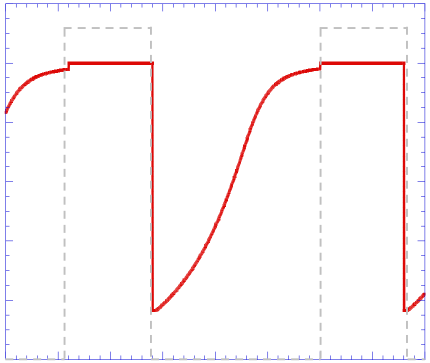


The Fundamentals

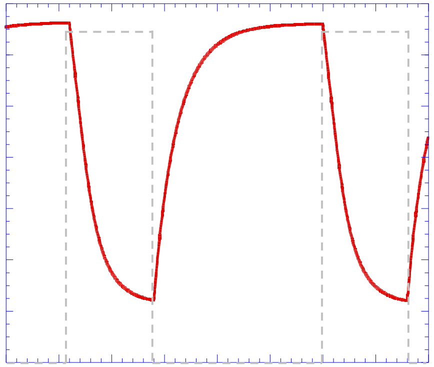




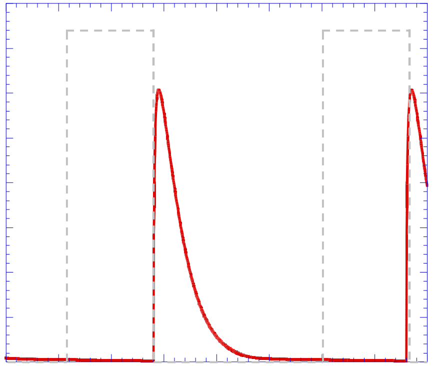
Model Predicts…



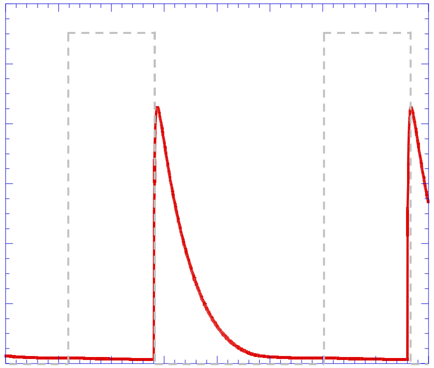
Average Void Diameter



Void Volume

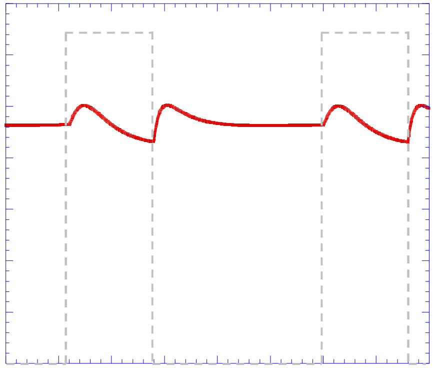


Void Density



PD repetition rate n

Conductor Current



n times q:

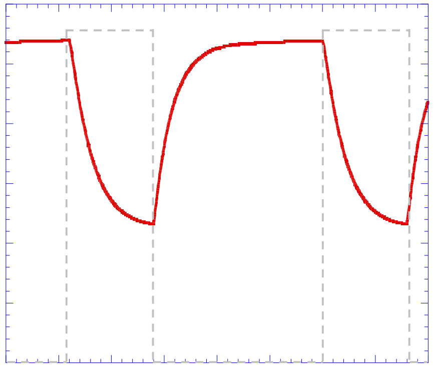
PD repetition rate x
PD magnitude

nq: repetition rate times magnitude

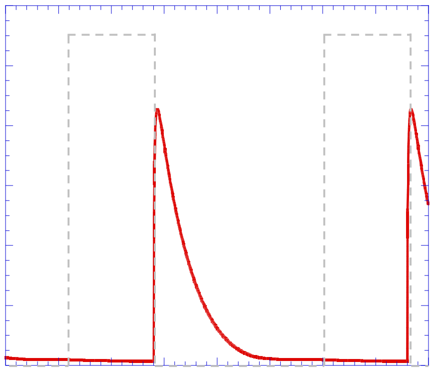
Does a physical meaning exist
behind the measure nq?

$$\frac{nq}{I_{leakage}} \cong void\ \ volume$$

Turning the Cable 'Inside-Out'



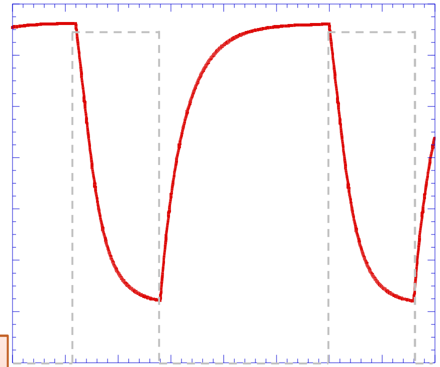
$$\frac{nq}{I_{leakage}}$$



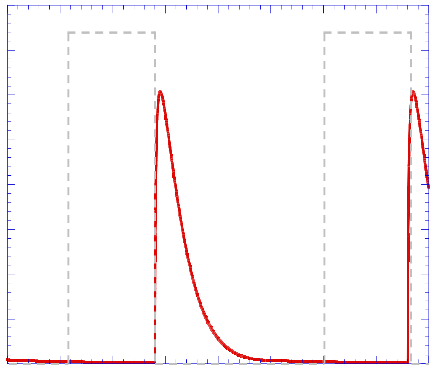
PD repetition rate

Measuring electric quantities **outside**

Learning about hydrodynamic quantities **inside**



Void Volume



Void Density

CONCLUSIONS

Conclusions

- The future faces increased voltages and powers
- Challenges:
  - Understanding the physics
  - Proper measurement principles
  - Upscaling
  - Quality Assurance and Quality Control