Tailoring of new Field Grading Materials for HVDC Systems

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Structure

- Motivation
- Challenges of DC-Insulation-Systems
- Introduction of a characteristic nonlinear $\kappa$-$E$-curve
- Design of a FGM for HVDC Cable Joints
- Conclusions
Motivation
Requirements towards the future grid

- Integration of de-centralized, renewable energy sources
- Transportation of electrical energy over long distances

Approach: HVDC

(one) prerequisite:
Robust DC-Insulation systems
Challenges of DC-Insulation-Systems
“DC does not occur” – F.H. Kreuger

The insulation system undergoes two states:

- **Capacitive graded** (after switching on the system, polarity reversals, transient overvoltages)
- **Resistively graded** (steady state)
- …and everything in between

The **conductivities** of the system

- govern the steady state (as well as the accumulation of charge carriers)
- Are not always well known (long measurement times, complex mechanisms)
- Can vary widely with temperature, humidity, age, etc.
(Nonlinear) Field grading as a simplification

Introducing a well-known field grading material (FGM)…

- helps defining the field distribution (conductivity higher compared with surrounding materials)
- enables field grading even in the event of transient overvoltages (when using a nonlinear FGM)

Today not often used in HV-components

Possible obstacles:
- Riskier when not properly designed/chosen
- Lack of standards
- Lack of (commonly agreed) terminology
Introduction of a model characteristic curve
... and some new parameters

- Simple description via $\kappa$-$E$-curve (S. Blatt [Bla2016])
  - Fits nonlinear materials, like MO-Varistors, Microvaristors, etc.
  - Enables simulations over the full range of conditions
  - Makes use of a small set of comparably intuitive parameters

$$\kappa(E) = \kappa_0 \cdot \frac{N_1}{N_2} \frac{E - E_1}{E - E_2}$$

Basic requirements can be described, using only:

- Base conductivity: $\kappa_0$
- Switching point: $E_1$
- Slope of nonlinearity: $m$
- (Nonlinearity modeling Parameter: $X$)
- Saturation field strength: $E_2$
Design of a FGM for HVDC Cable Joints

1) Conductor (HV)
2) Cable insulation
3) Connector (HV)
4) Connector-Shielding (HV)
5) Outer semicon (GND)
6) Joint insulation body
7) Joint screening (GND)
8) FGM – Layer

From ABB
Design of a FGM for HVDC Cable Joints
Stationary electrical simulation

- Goal: Finding allowed range for conductivity in stationary operation
- 1st step: Optimize conductivity according to tangential field stress

![Diagram showing conductivity optimization in HVDC cable joints]
Design of a FGM for HVDC Cable Joints

Lower Limit for Base Conductivity

Measured Values:

- Silicone Rubber: $\kappa_{\text{Silicone}} \approx 10^{-15} \ldots 10^{-14} \text{ S/m}$
- XLPE: $\kappa_{\text{XLPE}} \approx 10^{-16} \ldots 10^{-15} \text{ S/m}$

$k_0 \geq 100 \cdot \max\{\kappa_{\text{Silicone}}, \kappa_{\text{XLPE}}\}$
Design of a FGM for HVDC Cable Joints

Stationary thermal simulation

- Goal: Finding allowed range for conductivity in stationary operation
- 1st step: Optimize conductivity according to tangential field stress
- 2nd step: Maximum allowed conductivity according to temperature
Goal: Finding allowed range for conductivity in transient operation *

1st step: Calculate desired conductivities for standard switching and lightning impulse according to $\kappa = \frac{\varepsilon_0 \varepsilon_r}{\tau}$

2nd step: Apply safety margin to previously calculated values

* Process according to [Chr2010]
Goal: Finding allowed range for conductivity in transient operation *

1\(^{\text{st}}\) step: Calculate desired conductivities for standard switching and lightning impulse according to \( \kappa = \frac{\varepsilon_0 \varepsilon_r}{\tau} \)

2\(^{\text{nd}}\) step: Apply safety margin to previously calculated values

* Process according to [Chr2010]
Design of a FGM for HVDC Cable Joints
Comparison Linear vs Nonlinear FGM

- Goal: Finding allowed range for conductivity in transient operation
- 1st step: Calculate desired conductivities for standard switching and lightning impulse according to $\kappa = \frac{\varepsilon_0 \varepsilon_r}{\tau}$
- 2nd step: Apply safety margin to previously calculated values

![Graph showing conductivity vs. electric field]
Comparison of Results
Linear vs. Nonlinear – time dependent
Conclusions

- HVDC-Insulation systems still provide challenges
  - Conductivities (or more general charge transport effects) are influenced by many factors
  - Therefore the buildup of space and surface charges is hard to predict

- Introducing (nonlinear) field grading materials makes the systems easier predictable
  - …and can help creating more reliable devices

- A wider range of nonlinear FGMs that can be tailored to address the specific needs of a device would be very useful

- A prerequisite for this are commonly understood models and termini for describing this class of materials
Thank you for your attention!

References:


Summary

- **Determined Parameters** for specific nonlinear curve:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base conductivity</td>
<td>$\kappa_0 \in [10^{-12}, 5 \cdot 10^{-9}] , \text{S/m}$</td>
</tr>
<tr>
<td>Switching field strength</td>
<td>$E_1 = 0.7 , \text{kV/mm}$</td>
</tr>
<tr>
<td>Slope of nonlinearity</td>
<td>$m = 4.7 , \text{mm/kV}$</td>
</tr>
<tr>
<td>Saturation field strength</td>
<td>$E_2 = 1.1 \cdot E_{LI} = 2.3 , \text{kV/mm}$</td>
</tr>
</tbody>
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- **Achieved Improvements**:
  - Desired dependency on electrical field strength over the full range
  - Approx. 10 times lower field stress at triple point
Application Example
Cable Joint

Why significant?
- **High number of joints** per system necessary (land cable: one joint every 1…2 km)
- **Most critical point** of the cable system

Why interesting?
Shows most of the beformentioned challenges:
- **Triple points of different materials**
- **Temperature gradients**
- **Space charge accumulation**