TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Electrical and Computer Engineering Institute of Electrical Power Systems and High Voltage Engineering

Charge Carrier based Conductivity and Breakdown Model for Oil Paper Insulation under High DC Voltage

IEEH

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Berlin, 4^{th} May 2014

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

Presentation Outline

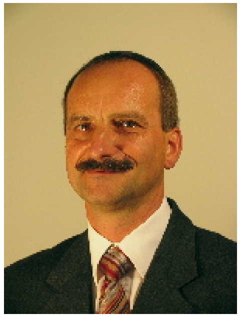
1 Institute of Electrical Power Systems and **High Voltage Technology**

Prof. Dr.-Ing. Peter Schegner

Professorship of Electrical Power Systems

Prof. Dr.-Ing. Steffen Großmann

Professorship of High-Voltage and High-Current Engineering



17 Research assistants

Funding: 1.3 M€

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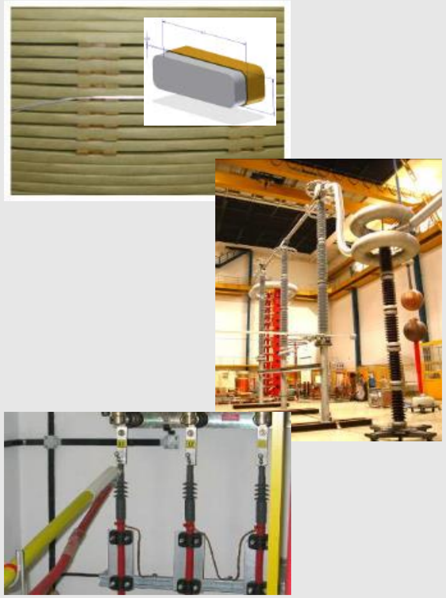
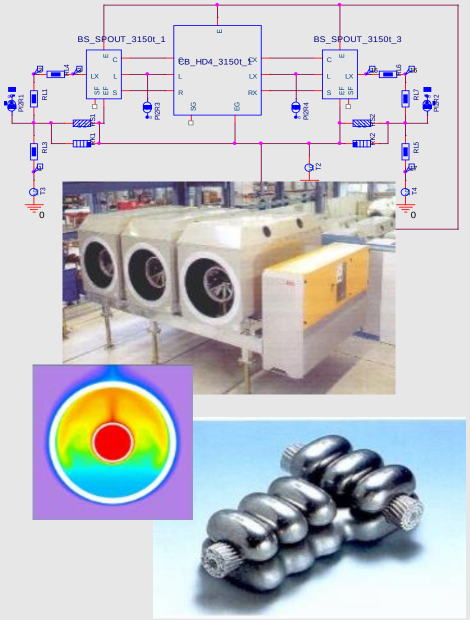
Research in High-Voltage and High-Current Technology

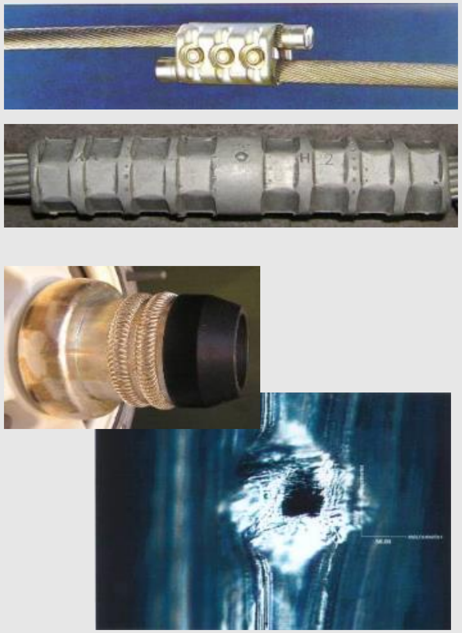
electrical insulation



ampacity and heating



electrical contacts and joints



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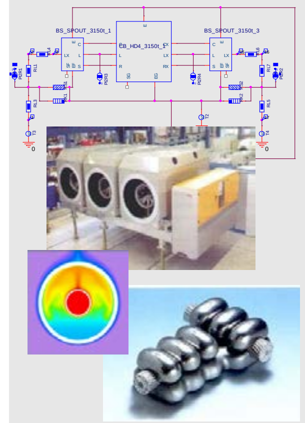
Research in High-Voltage and High-Current Technology

Electrical contacts and joints

- Aging of **static electrical joints** used in power engineering
- Characterization of the properties of intermetallic phases in **bimetal-joints** and evaluation of the influence on the joint resistance stability



Ampacity and heating of electrical equipment

- Application of the **thermal network** and CFD method to power engineering equipment and validation with experimental results

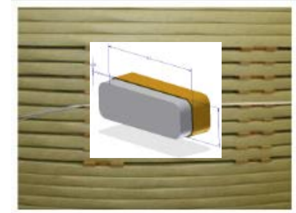
1 Institute of Electrical Power Systems and **High Voltage Technology**

Research in High-Voltage and High-Current Technology

High Voltage Engineering / Electrical Insulation

- Basic research on power engineering equipment under load at high AC-, DC-, Impulse and mixed-voltage
- Electrical stress investigations of oil paper insulation at high DC-voltage
- Electrical stress investigations of SF6 Epoxy insulation at high DC-voltage
- Evaluation of the insulation quality of low- and high voltage motors
- Electric pulse method application for drill heads of deep geothermal energy

Live-line working



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Research and Testing on solid insulation materials

- Dielectric Characterization
  - Conductivity measurements
  - Tanδ measurement by artificial sine source
  - PD measurement
- Climate Chamber and heating cabinets
- Lifetime investigation with AC and Impulse stress
- Mechanical Properties (Zwick)

→ multi physic tests to investigate system performance

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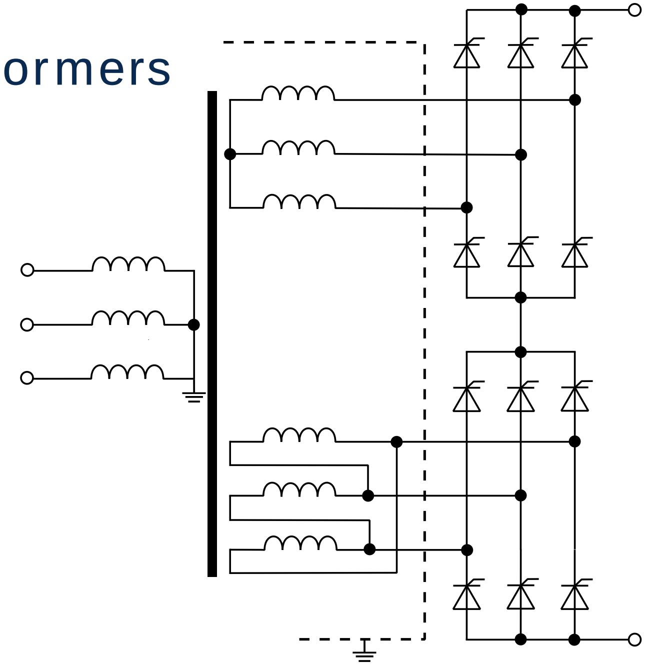
2 Motivation

HVDC Power Transformers

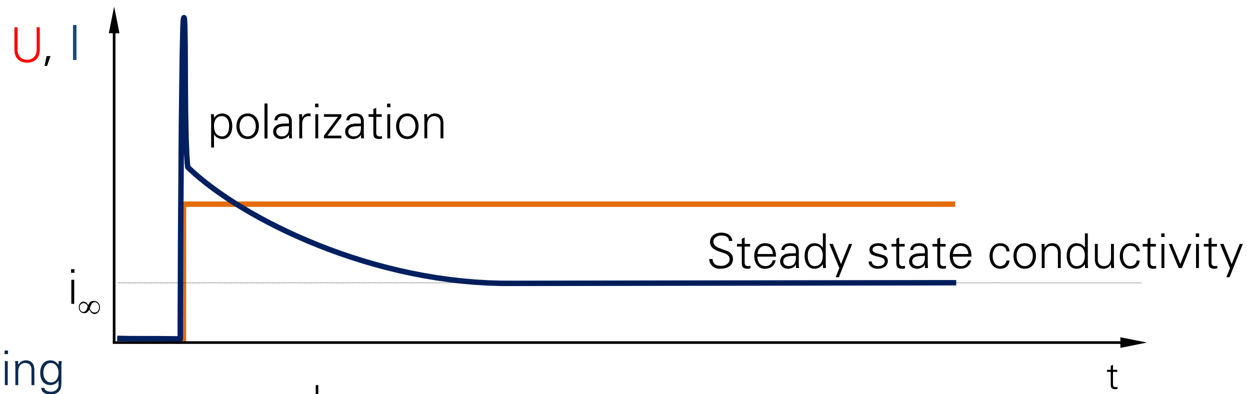


SIEMENS AG press photos

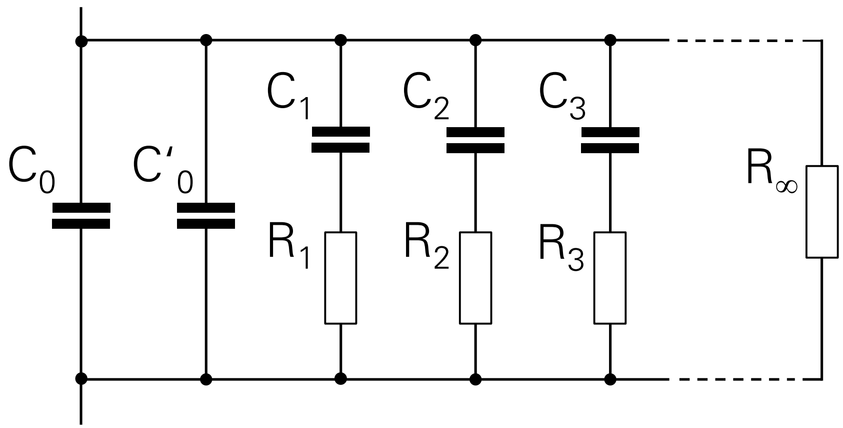
- What are breakdown strength values for different insulating materials?
- What is the breakdown voltage of technical application based models?
- Are there special DC dielectric mechanisms?

2 Resistive-Capacitive Conductivity Model

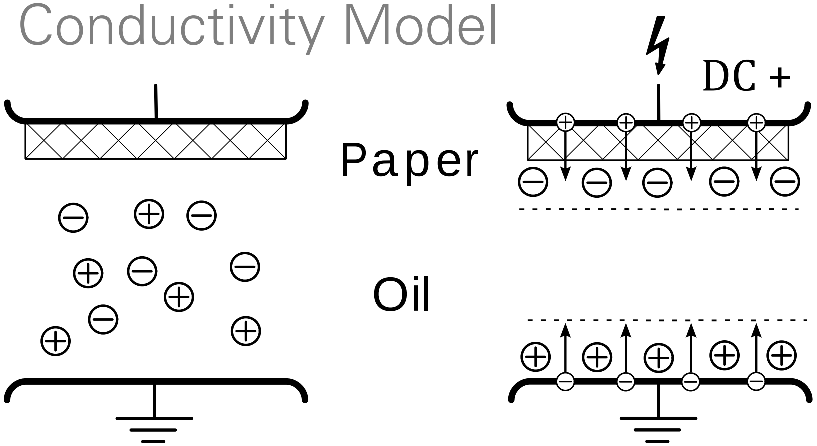
RC behavior of dielectric materials for single DC stress



- Linear modelling
- RC parameters are not physically based
- Only valid for one single test



3 Physical Conductivity Model



- Free moveable, intrinsic charge carriers in oil and paper
  → *hetero charges*
- Field strength dependent injection of additional charge carriers by electrodes → *homo charges*
- Formation of stable charge carrier layers in front of electrodes and barriers → *inner inhomogeneity*

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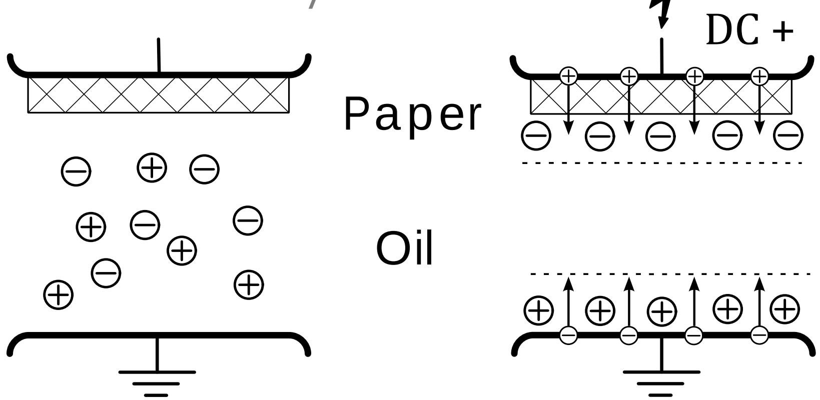
3 Physical Conductivity Model



- Differentiation in four charge carrier species
  - Intrinsic charge carriers: ⊖ anions ⊕ cations
  - Injected charge carriers: ⊖ electrons ⊕ holes
- Analogue assumptions for oil and paper

  → difference in mobility and diffusion behavior

4 Poisson-Nernst-Planck-Modelling

4.1 Notation

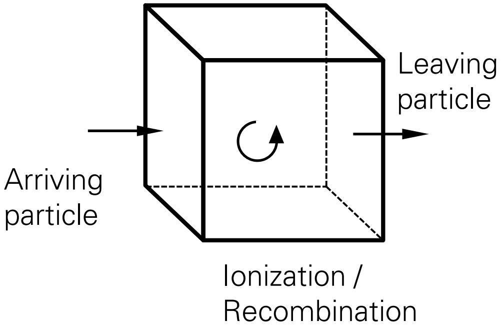
$$-\Delta\,\varphi = \frac{e}{\varepsilon_0 \varepsilon_r} \sum z_i n_i$$

$$\frac{\partial n_i}{\partial t} + \nabla\left(z_i\, \mu_i n_i \nabla\varphi - z_i D_i \nabla n_i\right) = \sum r_j$$

drift in electric field — diffusion — source terms for ionization and recombination

Volume

$dV = dx\ dy\ dz$



φ	Electric potential [V]
n_i	Charge carrier density of i^{th} species [1/m³]
$\varepsilon_0\varepsilon_r$	Permittivity of the material
e	Elementary charge
D_i	Diffusion coefficient of i^{th} species [m²/s]
μ_i	Mobility of i^{th} species [m²/Vs]
r_j	Source terms for ionization and recombination [1/s]
z_i	Valence number of i^{th} species [1]

4 Poisson-Nernst-Planck-Modelling

4.2 Boundary Conditions

- Electric Potential: $\varphi = 0$ $\varphi = u(t)$
- Injection: $\Gamma_{n,p} = 0$ $\Gamma_{e,h} = a_i \, E^b e^{-c/E}$
- Resorption: $\Gamma_{n,p} = 0$ $\Gamma_{e,h} = -\mu_i \, E \, n_i$

4.3 Start Conditions

- For every species: $n_i(x, y, z, t = 0) = n_{i,0}$

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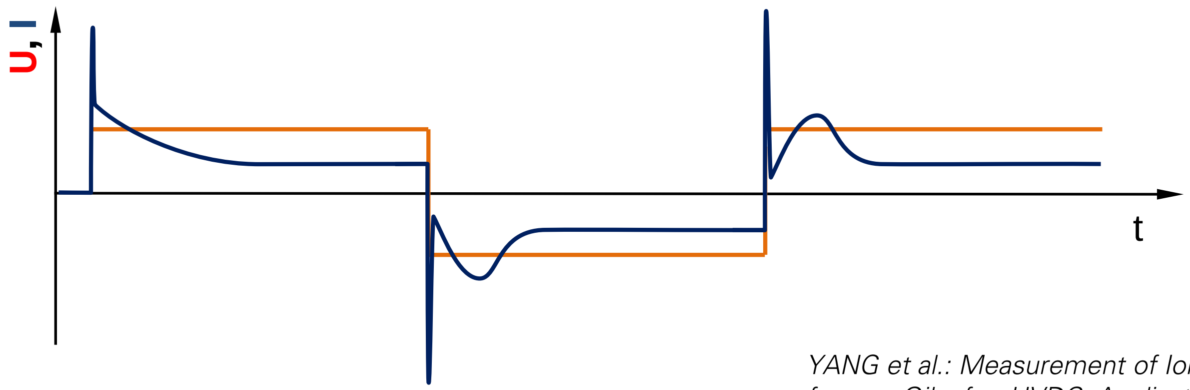
5 Bipolar DC Stress on Insulating Oil

- Current-time-behavior for insulation oil for polarity reversal test:

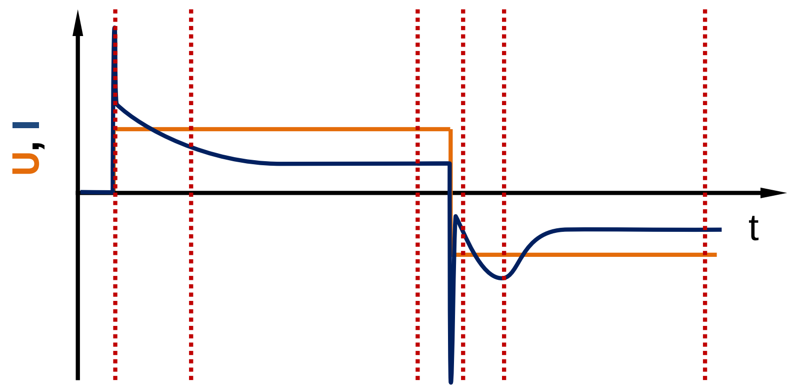


YANG et al.: Measurement of Ion Mobility in Transformer Oils for HVDC Applications, ICHVE 2012

- First DC stress: polarization of metal electrodes with hetero charges
- Next DC stresses: current-time-maximum and „*time of flight*“
- There is an Influence of the pause time between the reversals on the current behavior

5 Bipolar DC Stress on Insulating Oil

Result of the transient PNP calculation on a polarity reversal test



⊕ Cations

⊖ Anions

ground

test voltage

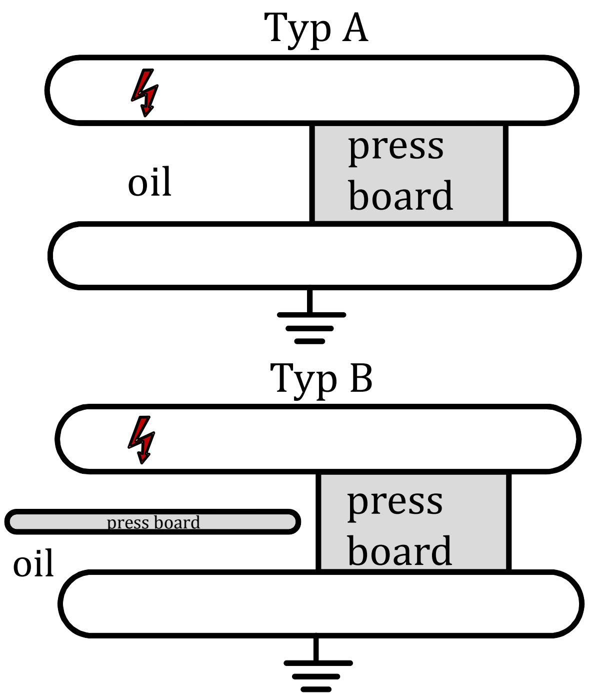
5 Bipolar DC Stress on Insulating Oil

- Measured and calculated current-time-behavior for polarity reversal test

5 Ion Movement, Field Strength & Breakdown

Breakdown test setup by Ebisawa et al.

Ebisawa et al.: DC Creepage Breakdown Characteristics of Oil-immersed Insulation, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 16, No. 6; 2009



Type	breakdown distance / mm	barrier thickness / mm	$\hat{U}_{d,m}$ / kV
A	10	-	73,3
	30	-	157
	60	-	240
B	30	2,5	287
	30	5	307
	30	15	360

Why is there an increase in breakdown strength ?

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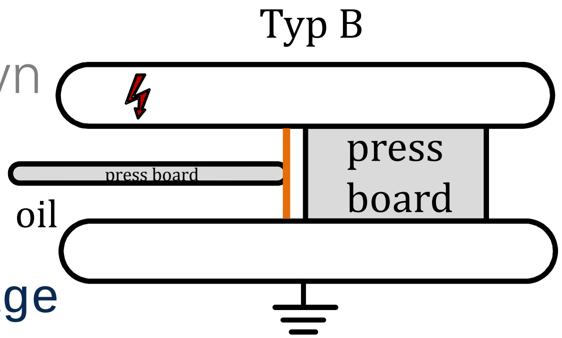
5 Ion Movement, Field Strength & Breakdown



Field strength evaluation

Field strength calculation at breakdown voltage

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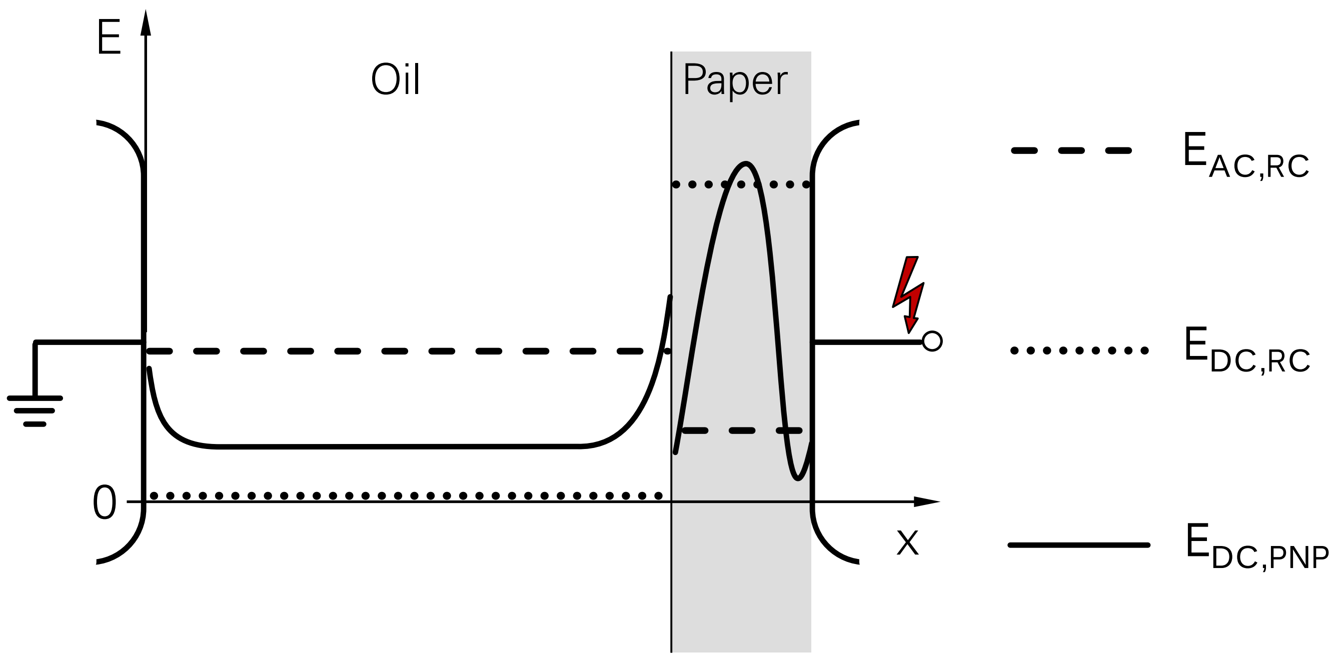
5 field strength distribution within an oil paper gap

Qualitative field strength distribution with an oil paper gap by RC and PNP-Method

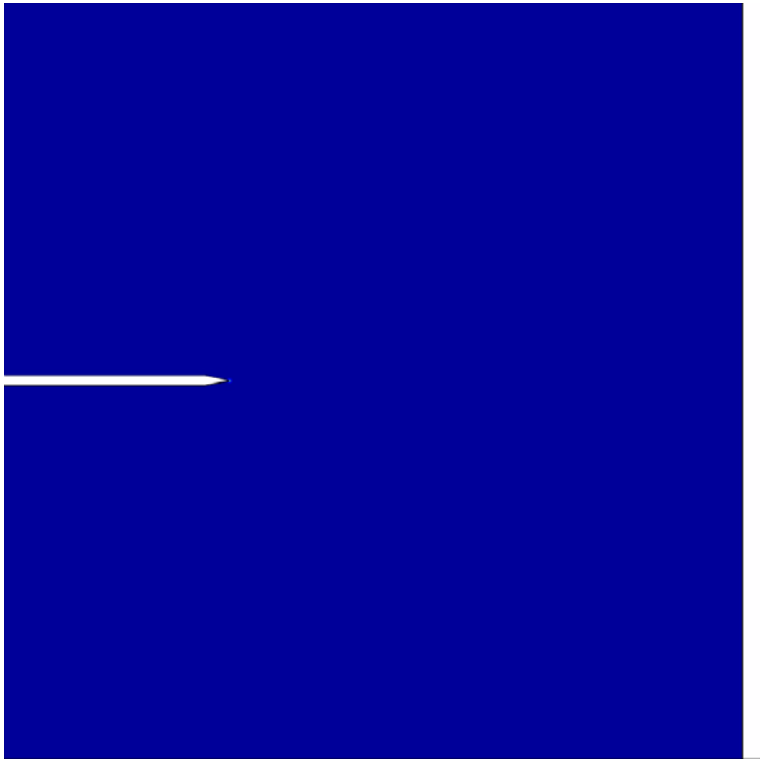


5 Needle-Plate-Arrangement with Barrier in Air

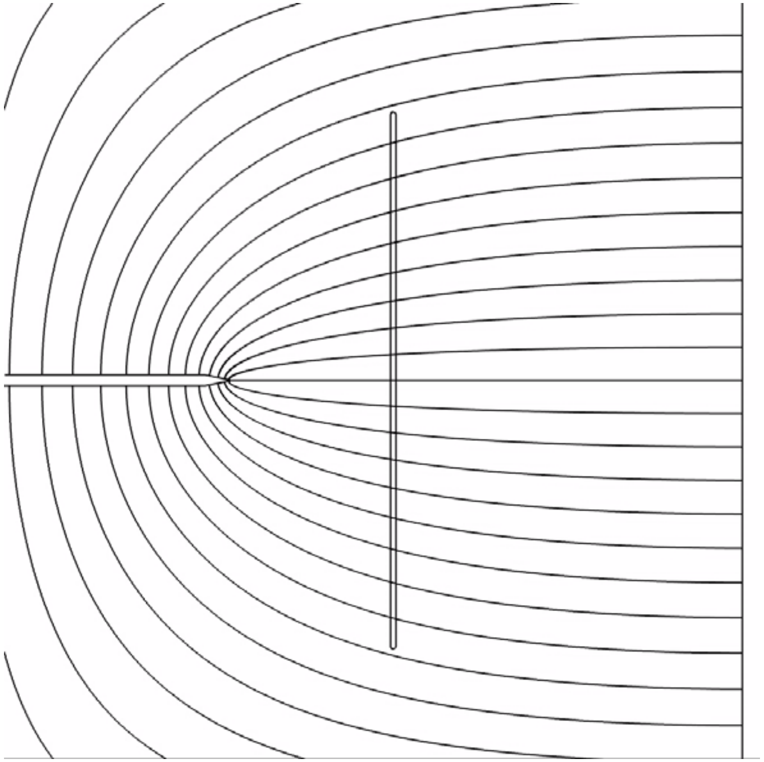
- Needle at high voltage potential (left)
- Grounded Plate (right)
- Barrier (middle)
- Left plot: concentration of electrons (variable scale)
- right: stream line plot

5 Needle-Plate-Arrangement with Barrier in Air

Concentration of Electrons



Stream Line Plot



6 Conclusion

The dielectric behavior of an insulation material or system is determined by the drift and diffusion of single charge carrier species and their different properties.

The dielectric conductivity is not an integral process, although only an integral current can be measured. Is might be resistive but not ohmic.

Provision	Transport	Recombination
Intrinsic charge carriers	Electrostatic, field-related movement	Recombination at the opposite electrode
Injected charge carriers	Diffusion related movement	Density dependent recombination

$$\kappa = f(?)$$

6 Conclusion

- Using the PNP method one is able to calculate conductivity processes and the field strength distribution within the insulation.
- The nonlinear characteristics of the oil paper insulation under DC stress are result and not condition to the Poisson-Nernst-Planck equation.
- The accumulation of charge carriers at electrodes and barriers leads to the formation of stable layers with high charge carrier density and field strength with in the oil.
- Low mobility (low conductivity) with in the dielectric material leads to high charge carrier concentration.

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»Wissen schafft Brücken.«