Herausforderungen und Lösungen für Isoliersysteme und Schaltelemente in leistungselektronikdominierten Netzen

Willem Leterme, Trier, 18.06.2026

IAEW at RTWH Aachen

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Transmission Grids and Energy Economics
Active Energy Distribution Grids
High Voltage Technology

Alumni and corporate networks

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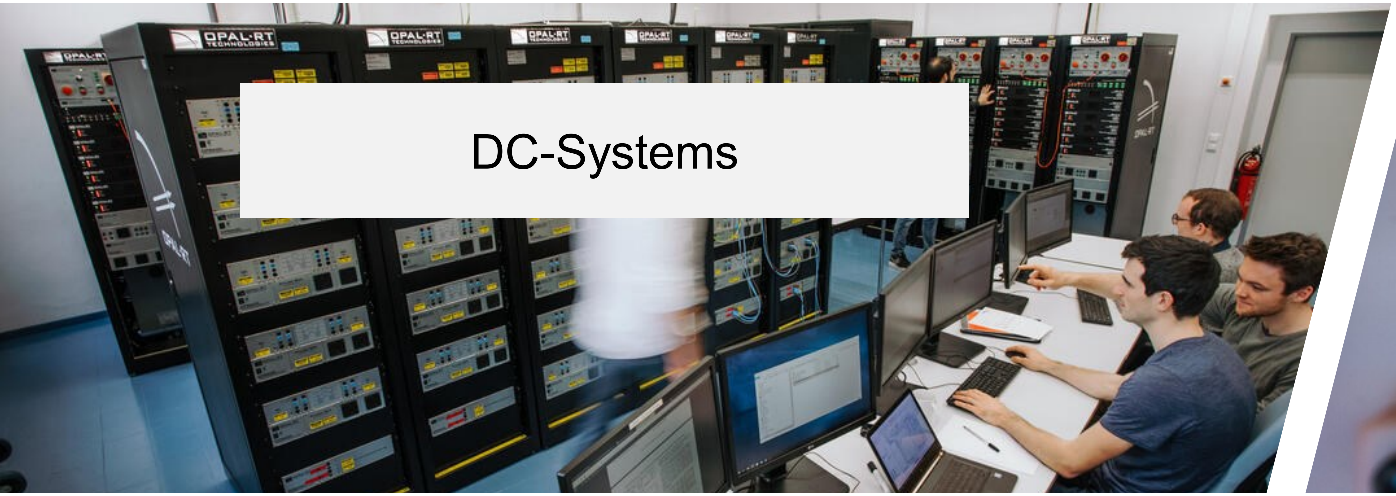
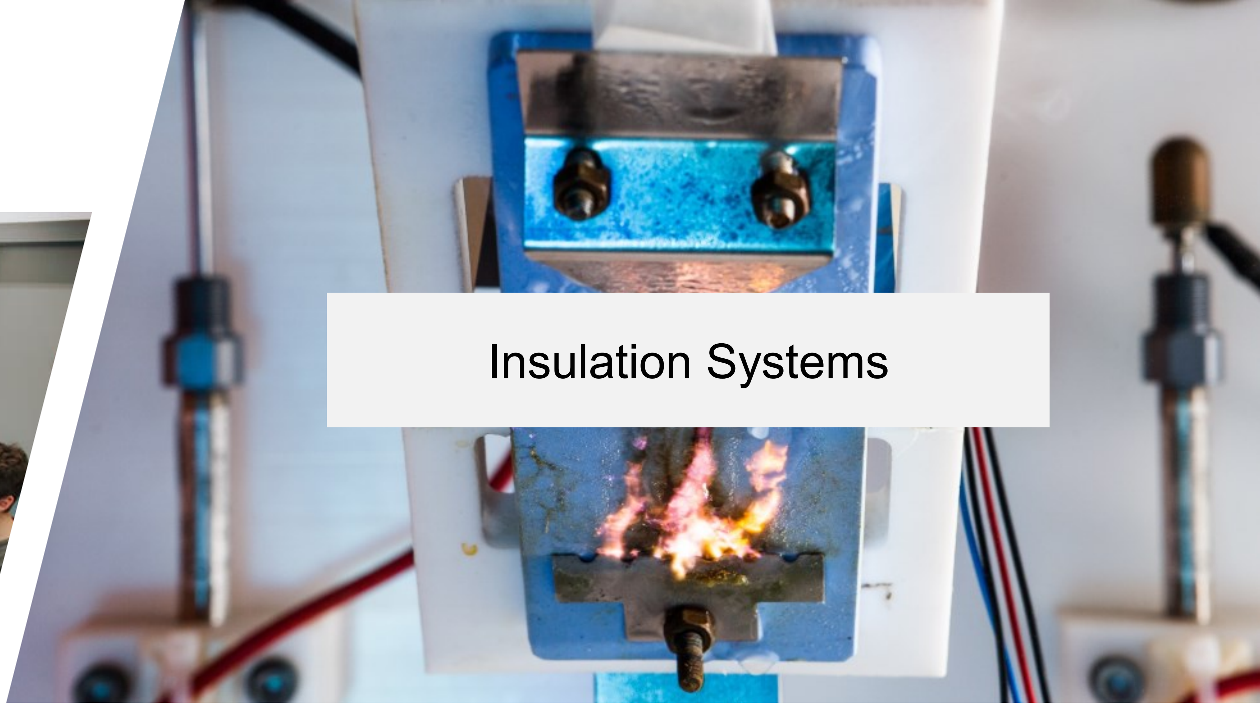
Chair of High Voltage Technology

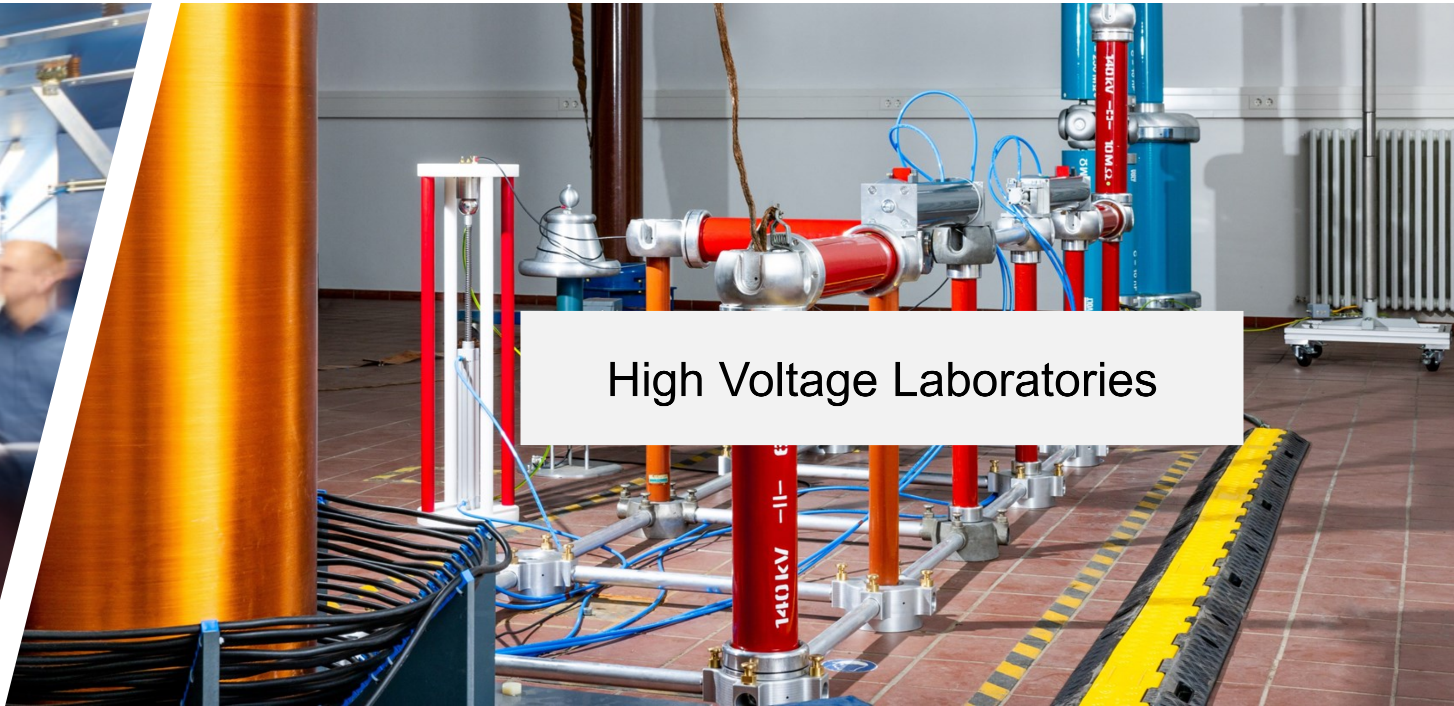


DC-Systems



Insulation Systems

Primary Technology and Diagnostics



High Voltage Laboratories

Power-electronics and legislations provides new impetus for research in high-voltage technology

- Characteristics of existing AC systems fundamentally change
  - Widespread use of power-electronic converters results in high-order harmonics challenging existing insulation systems
  - Intermediate AC stages in power-electronic converters result in waveforms widely different from 50 Hz

- New DC systems emerge at all voltage levels
  - Medium-voltage DC systems are considered to upgrade existing distribution grids
  - High-voltage DC systems emerge either in point-to-point connections or as multi-terminal grids

- In addition, bans on F-gases and PFAS-related substances requires rethinking existing mainstream solutions

- This presentation discusses challenges and solutions for insulation systems and switching elements in the modern power system

Primary Technology and Diagnostics

Switching and Switchgear Concepts
Environmentally friendly AC and DC circuit-breakers

Arcing Phenomena
Experimental investigation and magnetohydrodynamic modeling

Digital Twins
Physical and data-based modeling concepts

Digitalization Strategies for Asset Management
Risk-based through model-based damage prediction

References

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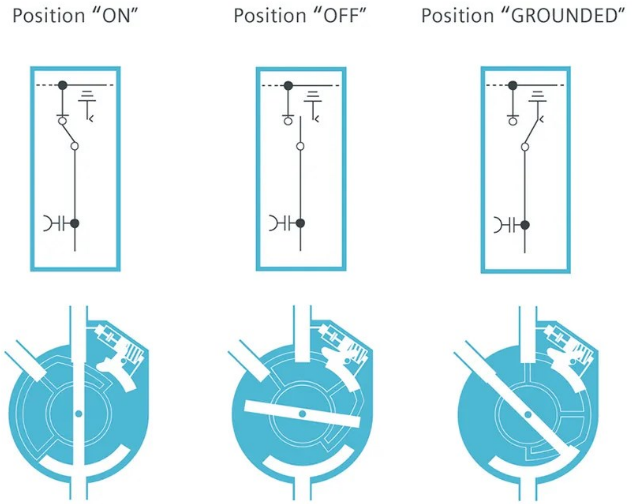
Interrupting AC currents without SF6 requires new approaches

- Load break switches are the main switchgear component in secondary distribution stations
  - Typically installed in ring main units (RMU)
  - Interruption of load current (up to 1.25 kA) and serve as disconnector switch
- Substitution of SF_6 entails challenges due to lower dielectric strength and interruption capability of alternative eco-friendly gases
  - Direct replacement by alternative gases is not possible
  - Load break switch design needs to be adapted
- New concept for medium-voltage load-break switches based on CO_2 and N_2 and so-called "Hartgaseffekt"
  - Polymer nozzle supports interruption process with ablation of material

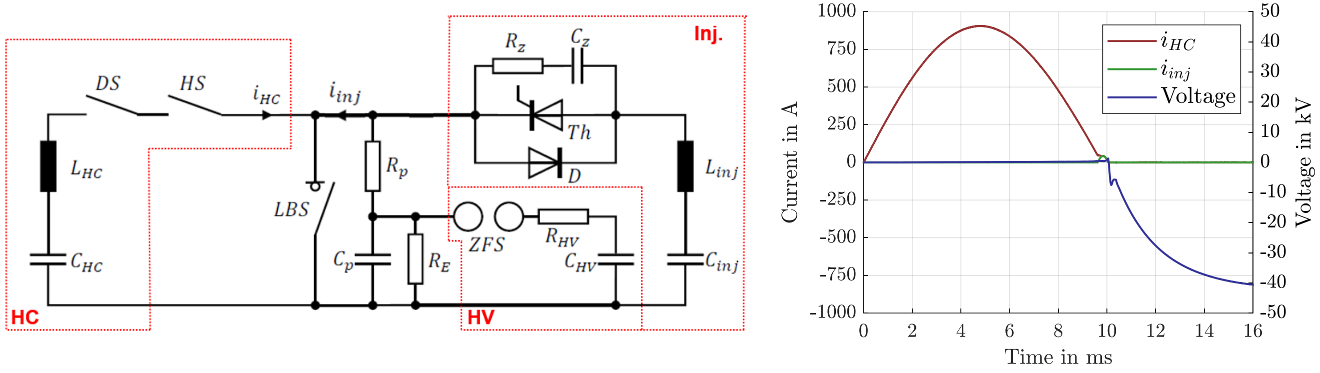
Source: ABB



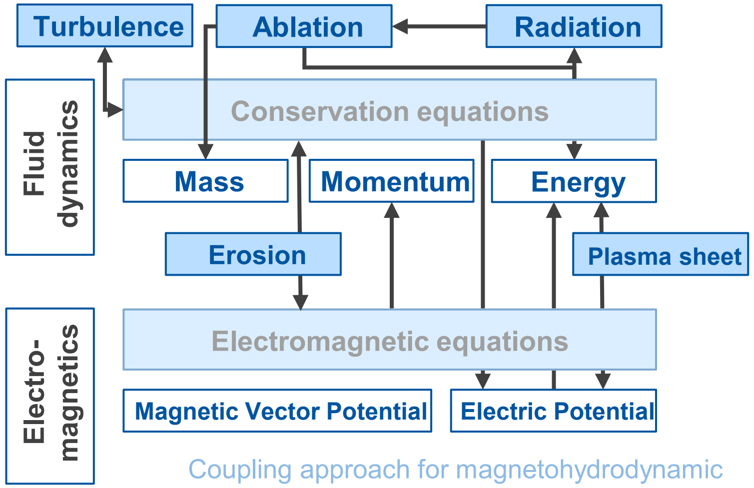
Load break switch with three switch positions
Source: Siemens

Switching and Switchgear Concepts

- Series of experimental research on this topology has been performed at RWTH
  - Selection of gases
  - Polymer materials for the nozzle
  - Interrupting and current making
  - Replacement of PTFE for nozzle materials
- Experimental research enabled by Weil-Dobke test circuit, yielding short circuit currents up to 36 kA and transient recovery voltages up to 140 kV
- Development of numerical simulation approach complementary to experimental research, e.g., to characterize
  - Core arc temperatures
  - Arc root dynamics
  - Gas plasma compositions



Weil-Dobke test circuit and test waveform



Coupling approach for magnetohydrodynamic simulations including necessary modeling approaches

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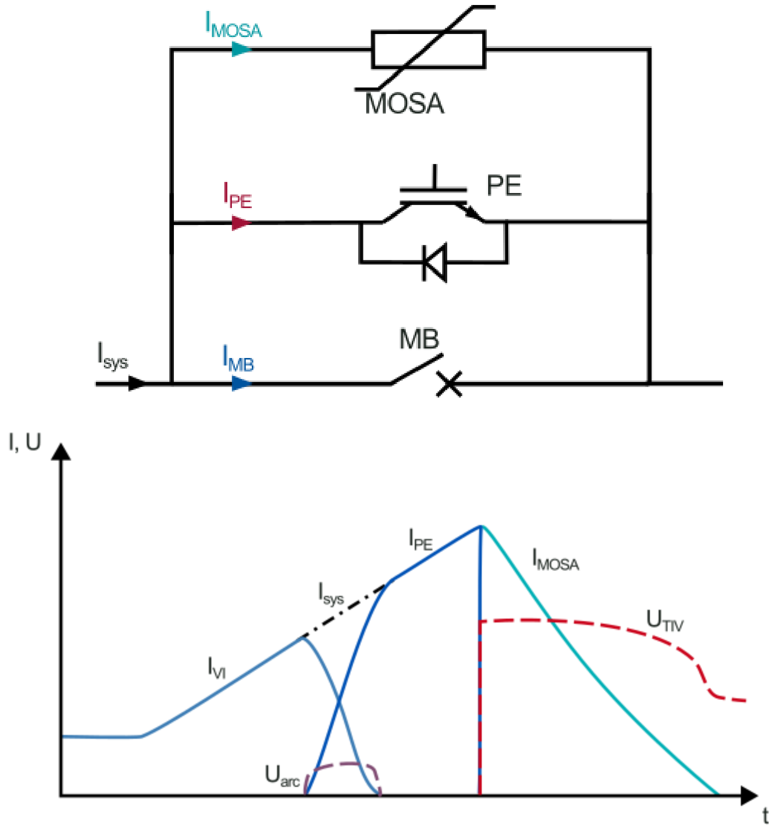
Interrupting DC currents requires fundamentally new approaches

- DC currents are characterized by absence of zero crossings, fast increase and high steady-state current
  - AC technology cannot be directly used given no zero crossings
  - DC breakers need to be 5-10 times faster, opening in milliseconds rather than tens of milliseconds
- DC circuit breakers are realized using several parallel branches
  - Low-loss main current path
  - Commutation path
  - Energy absorption path
- In MVDC, a relatively simple hybrid breaker can be used, using
  - Vacuum breaker in main current path
  - Semiconductor switch in commutation path
  - Surge arrester in energy absorption path

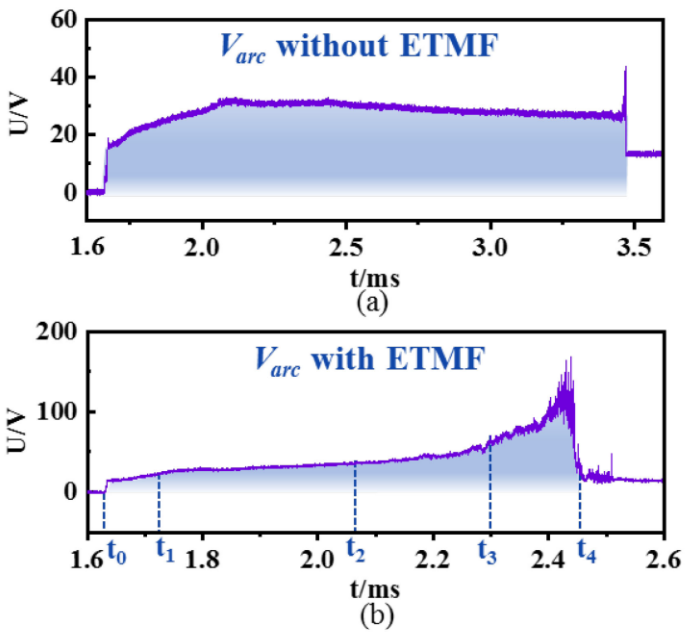


Hybrid DC Circuit breaker design and current interruption functionality

Interrupting DC currents requires fundamentally new approaches

- Ultra-fast Thomson Coil Actuator
  - Actuating the vacuum interrupter using a magnetic principle
  - Design optimization of the Thomson coil actuator to reduce costs
  - Multi-physics optimization of Thomson coil actuator

- Design of vacuum circuit breaker for enhanced interruption
  - AC contacts and vacuum circuit breaker designs are not optimized for DC application
  - Contact design (materials, geometry) of vacuum interrupter
  - Investigation of arc control mechanisms through magnetic fields (external transversal magnetic field, ETMF)



Arc voltage in vacuum interrupter (a) without ETMF and (b) with ETMF
Source: Wu et al., 2022, IEEE Transactions on Industrial Electronics

Model vacuum interrupter with Thomson coil actuator

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Insulation Systems

Test Procedure
Development of test methods for AC and DC components

Breakdown Phenomena
Medium-frequency and non-sinusoidal voltage stress

Aging Behavior
Ageing phenomena of insulation systems under thermo-electrical stress

Material Processing
Production, development and characterization of insulation materials

References

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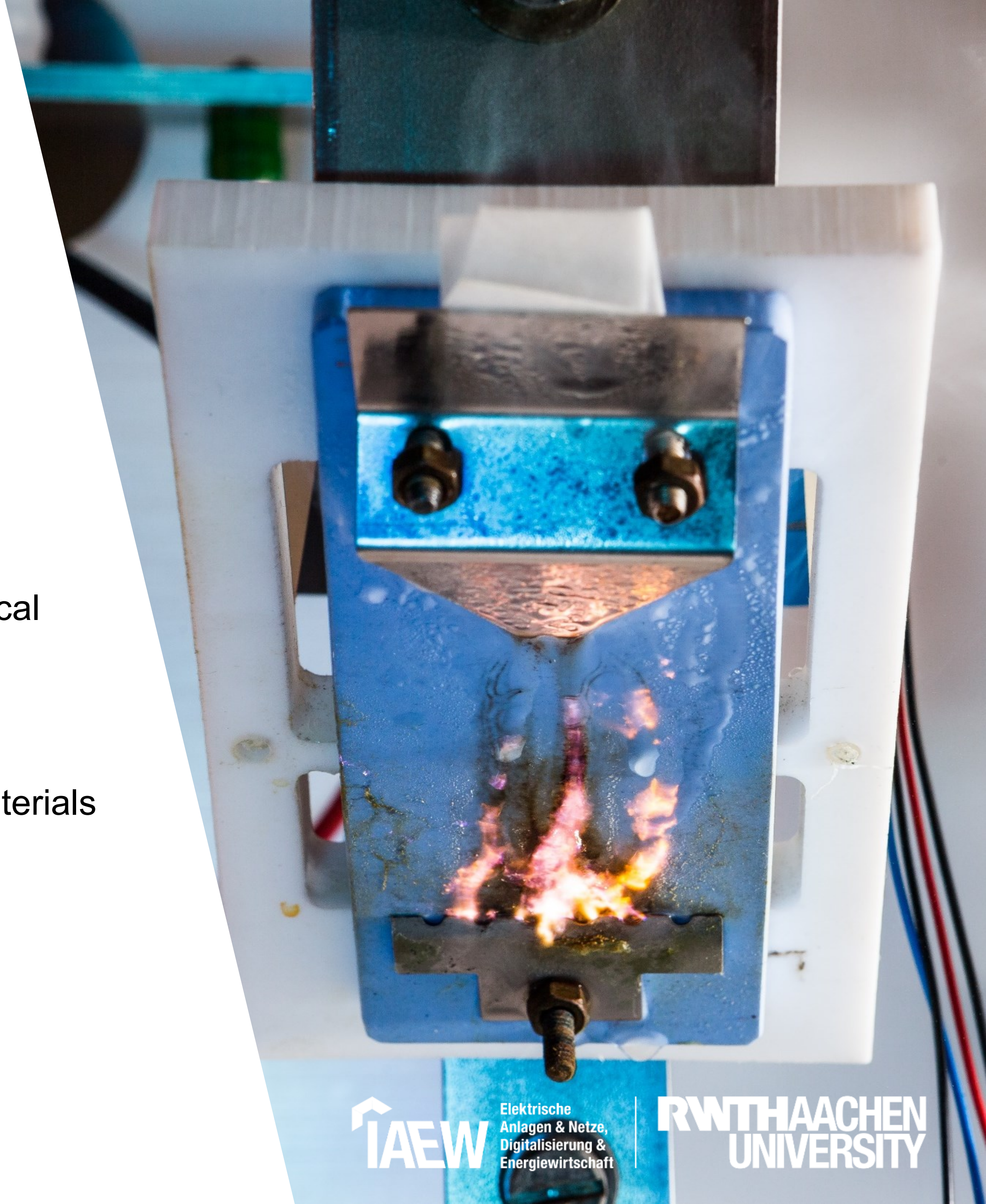


Impact of Medium Frequent Voltage Stress on Solid Insulating Materials

Background

Power Electronic Transformers in medium voltage grids

- Increased flexibility through power electronics
- Intermediate AC stage uses solid insulation preferred to oil-paper systems
- High switching frequencies enable a reduction of transformer size and costs

Challenges associated with the use of PET

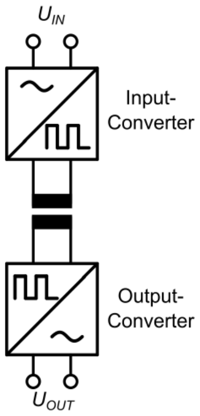
- How to design insulation systems for medium-voltage, medium-frequency rectangular waveforms?

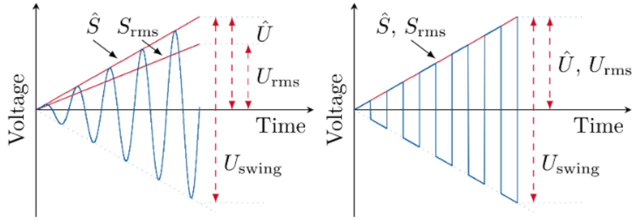
Key questions

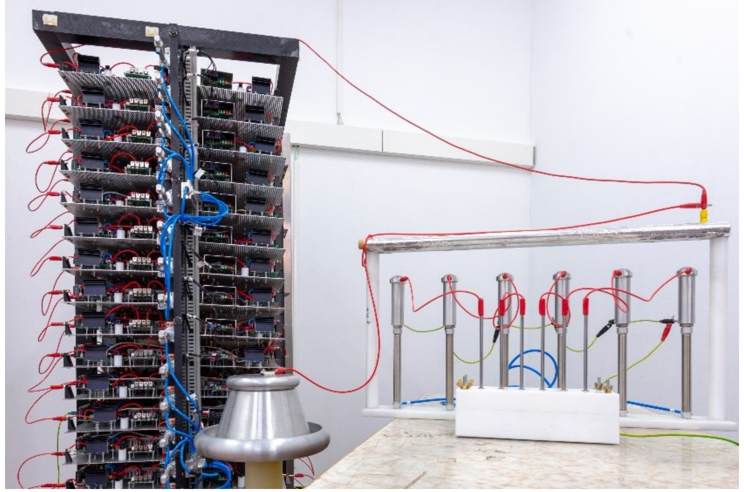
- How do breakdown strengths of solid insulation materials compare for different waveform shapes? What is the impact of frequency and DC offset?
- What is the role of partial discharges in these processes?

Approach

- Development of new testbench that can generate rectangular waveforms up to 10 kHz and 10 kV
- Development of partial discharge measurement system for rectangular waveforms
- Statistical study of breakdown and PD behavior using hardware experiments







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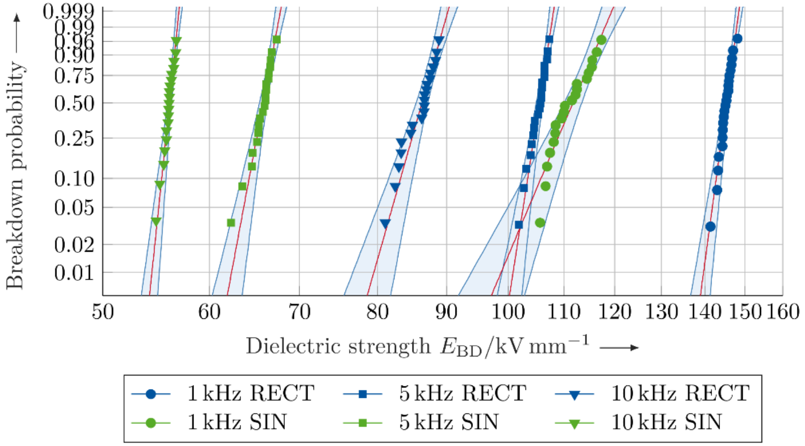
Impact of Medium Frequent Voltage Stress on Solid Insulating Materials

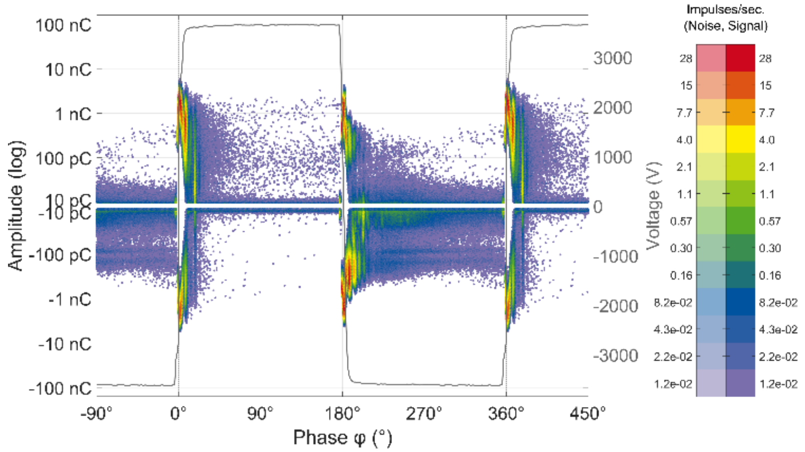
Key findings

Key conclusions

- Definition of waveform characteristics (rms-value, envelope, …) significantly impact conclusions on waveform effects, revealed especially considering a DC offset
- Different materials show similar conclusions, with difference only in terms of absolute magnitude
- Dielectric losses are implausible as main cause of failure, difference in partial discharge behavior cannot be ruled out

- Follow-up research focuses on partial discharges under different types of stresses and the effect of PD-resistant materials on breakdown voltages





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Effect of Composite HF Voltage Stresses on Performance of Oil-Paper Insulation

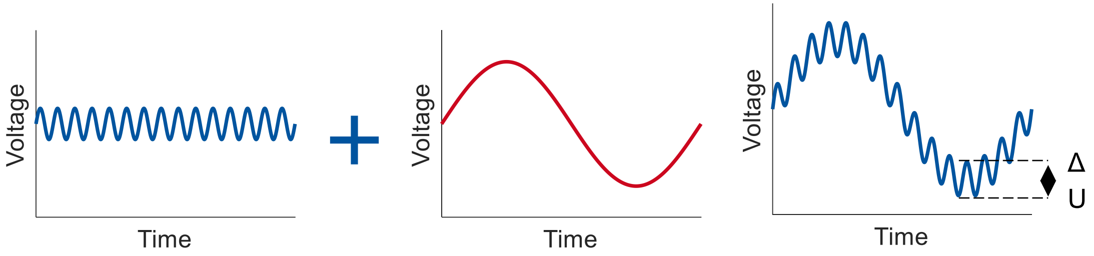
OIP insulation under converter-driven harmonic and supraharmonic stresses

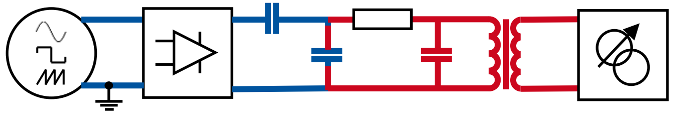
- Power-electronic converters and nonlinear loads increasingly distort grid voltages with harmonics and supraharmonics (2.5 - 30 kHz), whereas standards only cover up to 2.5 kHz
- Transformer oil-impregnated paper (OIP) insulation can be exposed to mixed, non-sinusoidal stresses (fundamental + multiple harmonics, sometimes with DC components), especially on converter/valve sides
- **Distortion is commonly stratified by frequency band** into low-order harmonics (<2.5 kHz), lower supraharmonics (2–9 kHz), and mid-/higher supraharmonics (>~9 kHz up to ~150 kHz), reflecting different emission sources and stress mechanisms.

➢ Distorted voltages can introduce **additional electrical and electro-thermal stress**, potentially accelerating aging and increasing failure risk

Impact of harmonics and DC bias on OIP insulation integrity

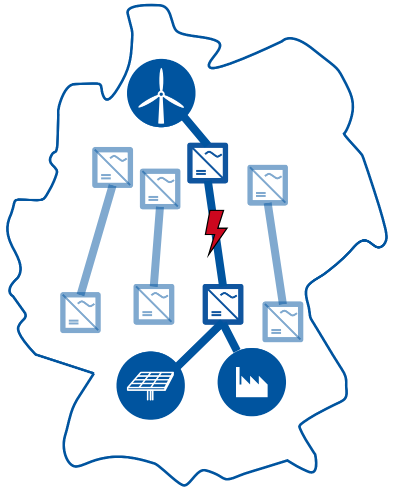
- PD behavior under mid-/higher-supraharmonic excitation (>~9 kHz) is largely unresolved for OIP
- Standardized long-term qualification/endurance protocols for converter-typical voltages are missing for OIP insulation systems

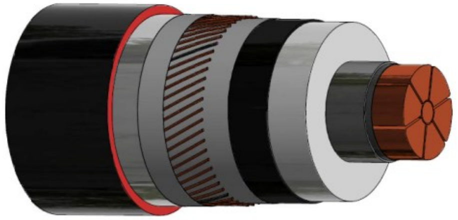


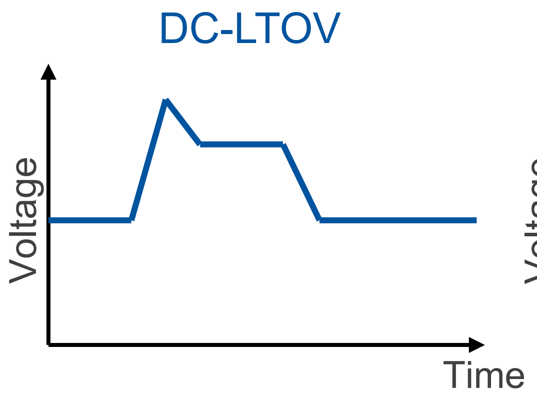


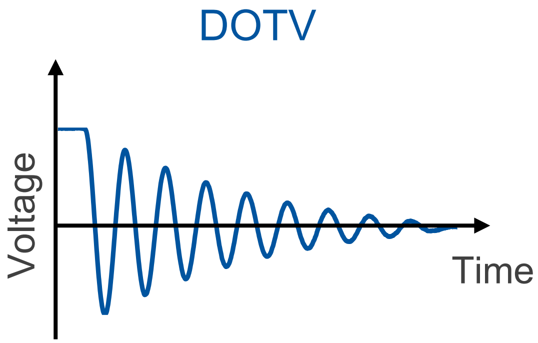
Breakdown in Polymeric Cable Insulation under DC Fault Voltage Stresses on Cable Insulation

- The German HVDC corridor projects consist of thousands of 525 kV **HVDC land cable systems** for the future energy system
- **DC fault voltage stresses** on the polymeric cable insulation differ considerably from lightning or switching impulses
  - Damped oscillating transient voltage **DOTV**
  - DC-superimposed long temporary overvoltage **DC-LTOV**
- **These stresses do not fall under existing** standards for the qualification of these cable systems and cannot be generated using existing test benches









- Development of suitable **test benches** & **investigation methods**
- ➢ Design & commissioning of the test benches
- ➢ Breakdown tests of MV cables under DOTV, DC-LTOV, and standardized voltage waveforms
- ➢ Assess criticality of DC fault voltage stresses

Electrical Treeing in Polymeric Cable Insulation under DC-LTOV

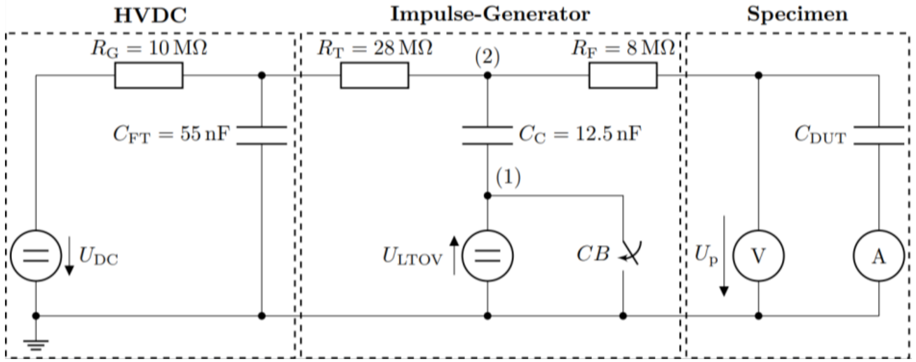
- **Various DC-LTOV waveforms** depending on system and fault parameters
- Test bench designs to generate DC-LTOVs
  - Inflexible design: 200kV DC-LTOVs, 10 ms rise time/150 ms time to 60% of peak (depending on used resistors) following double exponential
  - Flexible design: 30kV DC-LTOVs, envelope curve fully programmable
- The main cause of insulation failure is **electrical treeing**

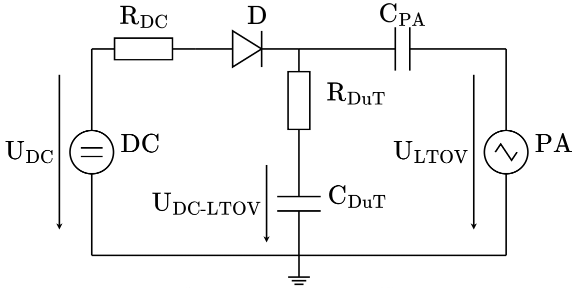
➢ Commissioning of test bench for treeing under various DC-LTOVs
  - ➢ Live optical and partial discharge monitoring during course of DC-LTOV waveform

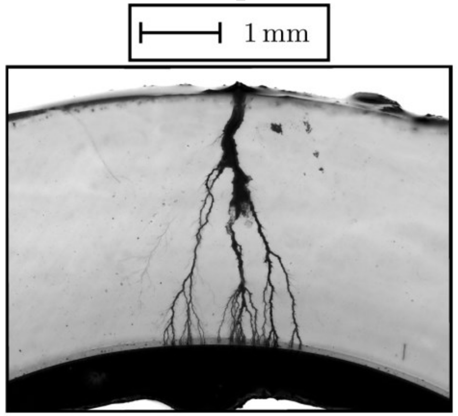
➢ Identify tree-promoting DC-LTOV parametrizations
  - DC-LTOV rising edge, overshoot, plateau and falling edge affect could influence inception and propagation of electrical trees

➢ Correlate certain parameter ranges with treeing dynamics

➢ Assessing DC-LTOV's criticality, building the foundation for discussions on updating cable testing standardization







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Vielen Dank
für Ihre Aufmerksamkeit

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