NTNU

Norwegian University of Science and Technology

Special Session

Insulation aspects of high frequency and pulsed voltage stresses

Kaveh Niayesh

Darmstadt, 04.09.2024

Energy Conversion Congress and Expo (ECCE) Europe 2024

Schedule of Special Session

Invited presentations (20 min. each including questions):

Dielectric breakdown mechanisms in high voltage high frequency insulation systems

Carsten Leu, Professor, Leipzig University of Applied Sciences

(Kaveh Niayesh, Professor, Norwegian University of Science and Technology)

High voltage power electronic converters - Dielectric performance, stresses and testing

Lars E. Lundgaard, Chief Scientist, SINTEF Energy Research

Inverter/Electrical machine insulation interactions: issues and possible mitigation actions

Andrea Cavallini, Professor, University of Bologna

Discussions (30 min.)

All contributors

HTWK Hochschule für Technik, Wirtschaft und Kultur Leipzig

Dielectric breakdown mechanisms in high voltage high frequency insulation systems

ECCE Europe 2024,Darmstadt, 04.09.2024

1 Dielectric stress of insulating materials

Challenges for the electrical insulation:

- New 3D power electronic topologies - new electrical insulation sections
- New materials with better mechanical and thermal stability as well as better thermal conductivity (ceramic, composite materials etc.)

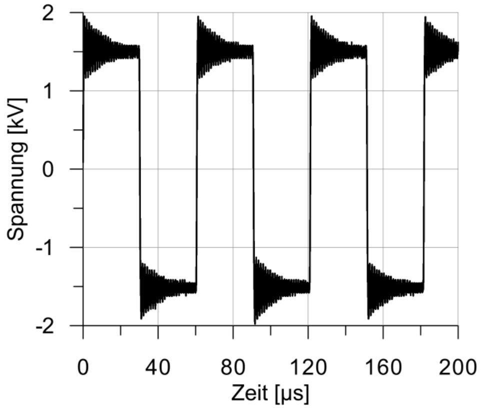
Electrical and dielectric stress, other discharge mechanisms, space charges

- Higher rate voltages, superposed voltages dielectric stress, discharges
- Higher switching frequency (switching with higher du/dt)
- New (composite) materials (non homogen structure, high gradient of permittivity, voids)
- Generated space charges influence electric field and random partial discharges

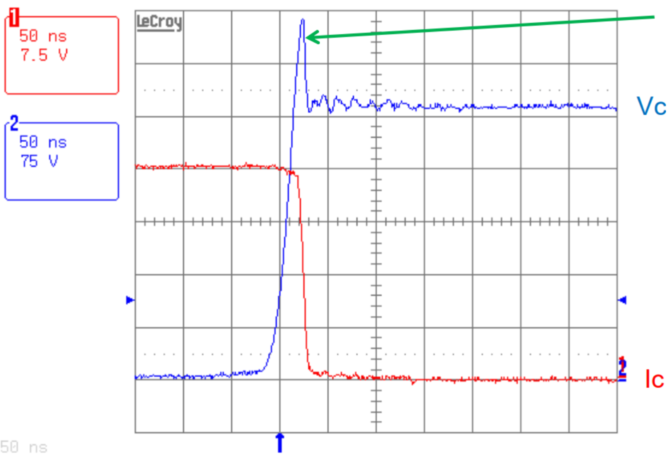
Content

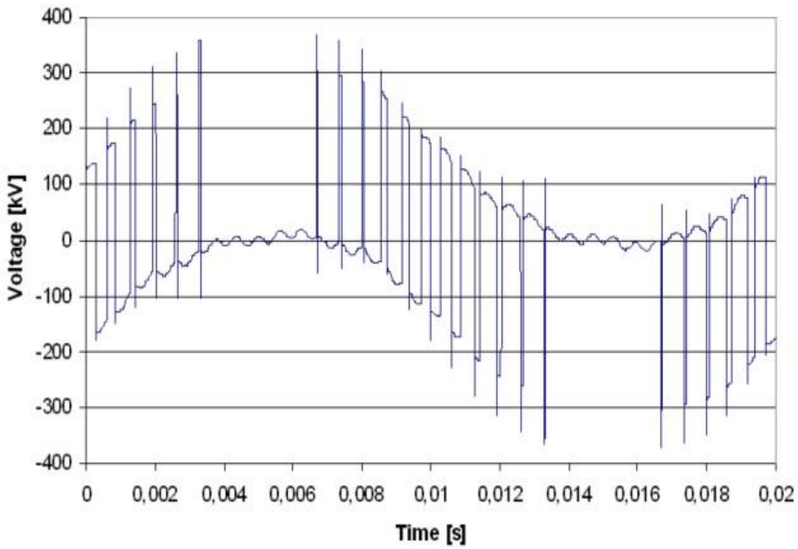
1. Dielectric stress of insulating materials
2. Influencing factors on dielectric breakdown
3. Change in dielectric parameters and heating breakdown
4. Summary

1 Dielectric stress of insulating materials in power electronic topologies: voltage waveforms

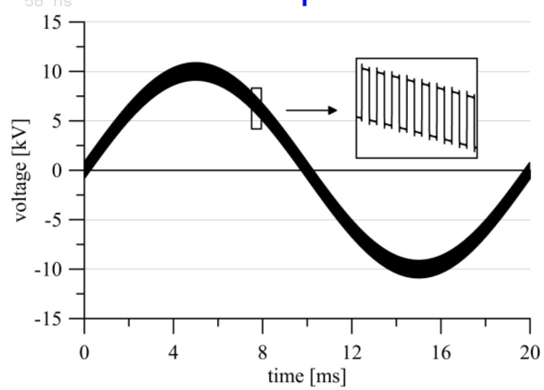


- switching frequency: 100 kHz and more
- higher amplitudes and steepness of switched voltages
- superimposed voltages (dc- or ac-voltage + high frequency voltage)
- Periodical transients





[Quelle: Cigré Brochure 447: Components testing of VSC system of HVDC applications, 2011]



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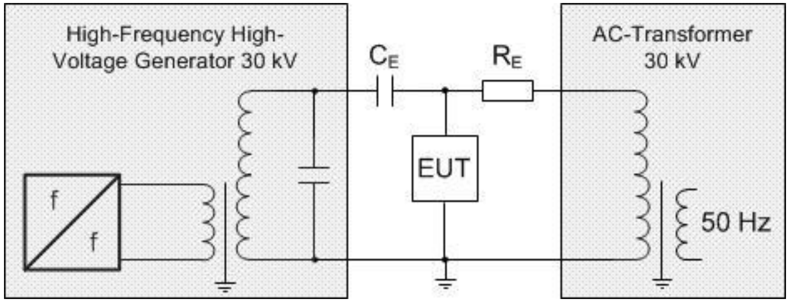
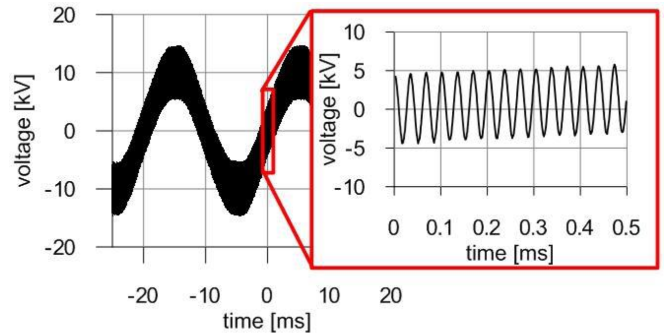
Experimental setup: reproducible voltage waveforms

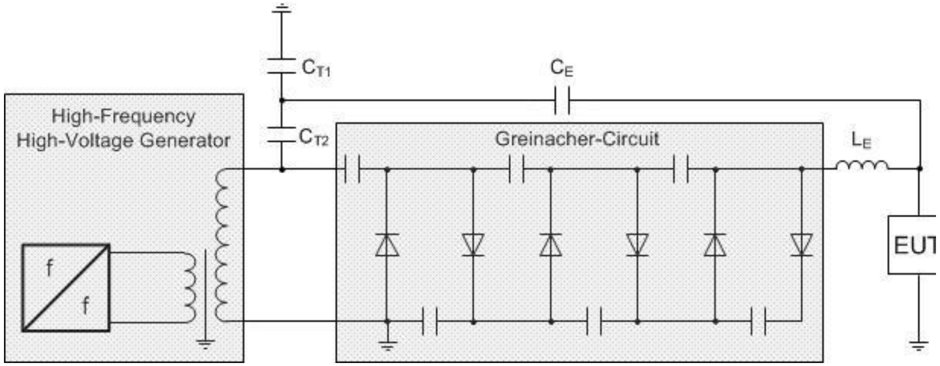
HV-kHz-Generator

- Principle of resonance
- Sinusoidal voltage
- Up to 70 kV, 50 kHz, PD free
- Voltage divide (gas as dielectric)
- Load: up to 1,7 nF, 10 mA (not only tesla-resonance-coils)
- Possibility to superpose voltages

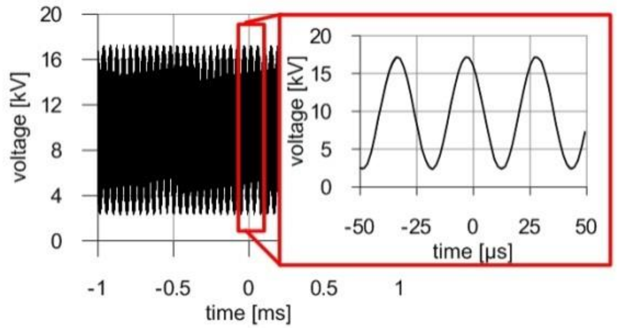


10 kV~ with 5 kV/37 kHz-HV



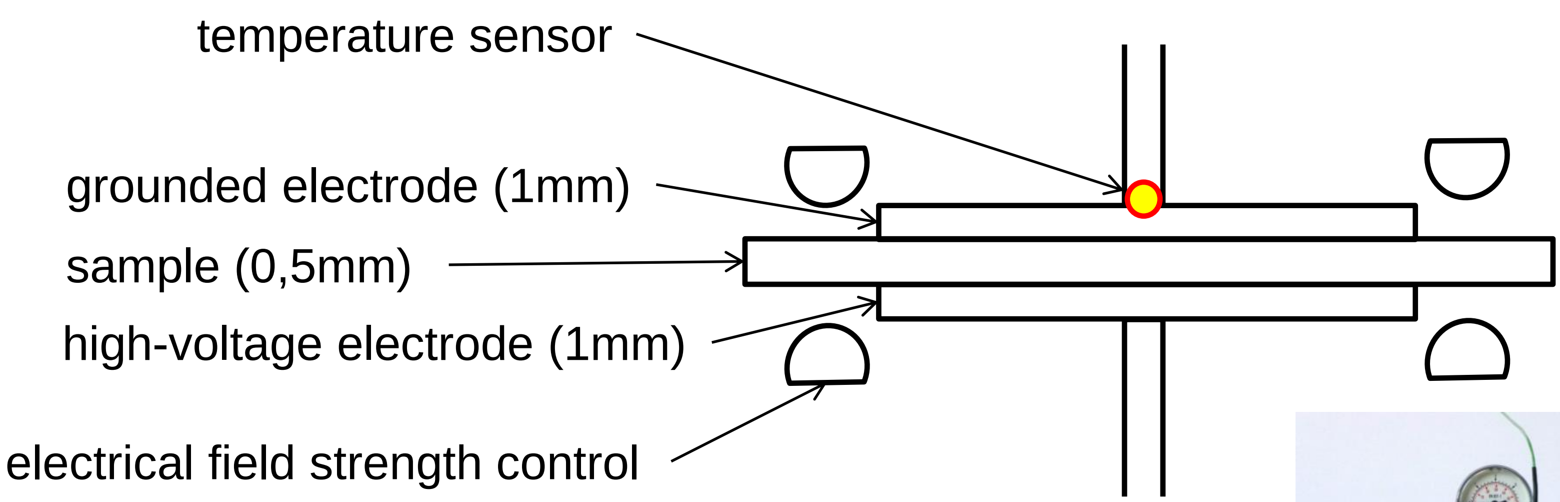


10 kV= with 7 kV/37 kHz-HV

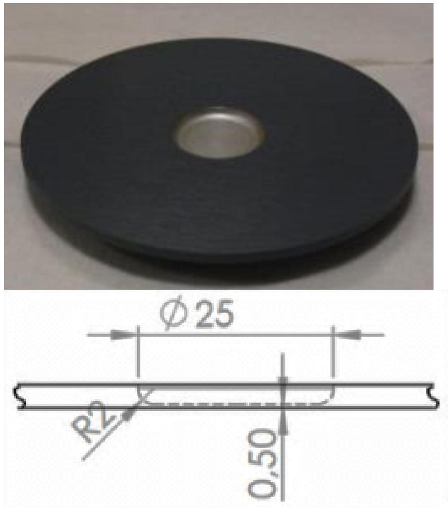


1 Experimental setup

Electrode configuration in SF_6



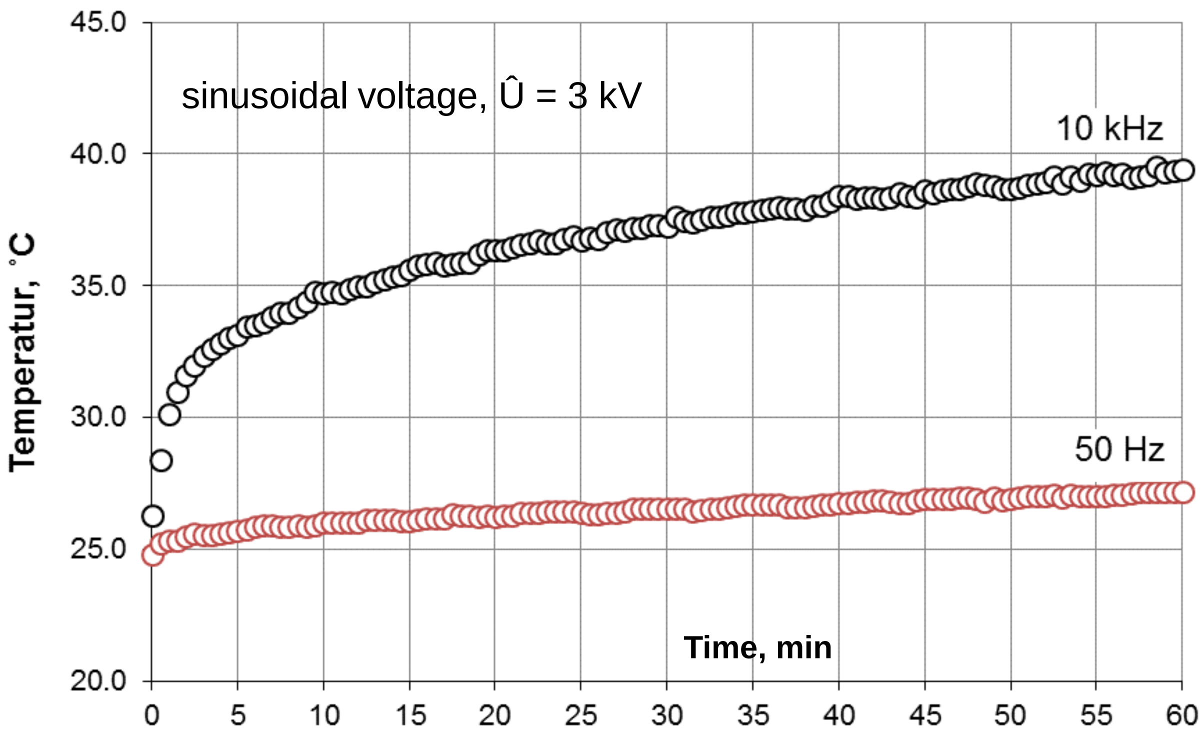
modification of probe with high electric strength for determination of breakdown voltage



2 Dielectric heating of composite material Sinusoidal kHz-voltage

transformer board ε_r = 1,7 (dried)
0.5 mm

➔ stronger dielectric heating at kHz-voltages!



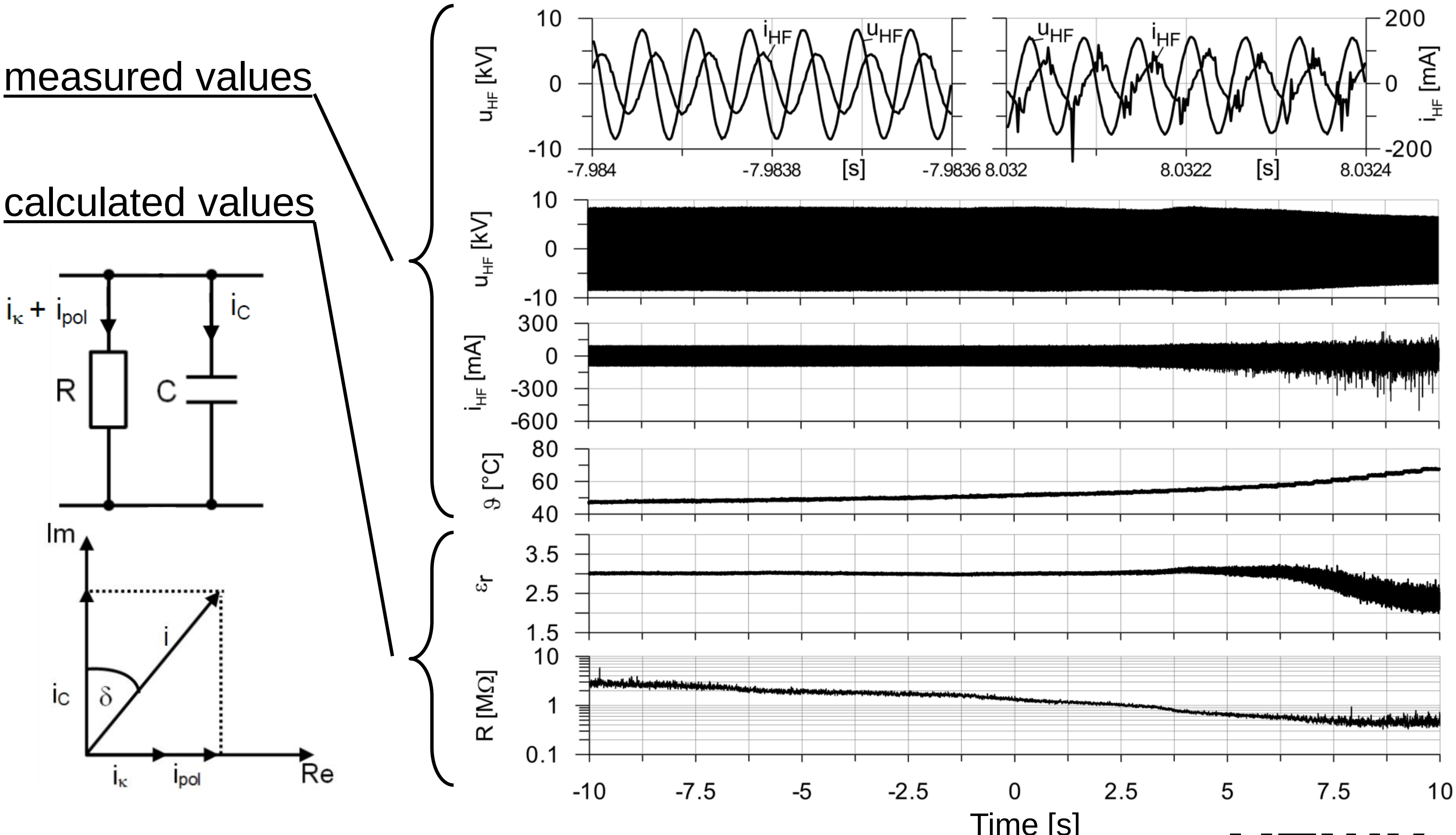
$$P_{diel} \sim f \cdot U^2$$

2 Dielectric heating process before losing dielectric strength at a kHz-sinusoidal voltage stress

Polyoxymethylen (POM) – *nonpolar Polymer*

measured values

calculated values



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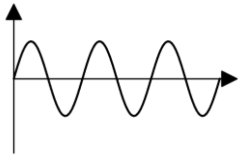
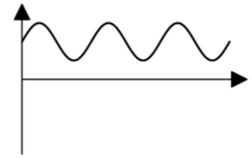
2 Dielectric heating process at voltages with and without superposed HVDC

Polyvinylchloride (PVC) – *polar Polymer*

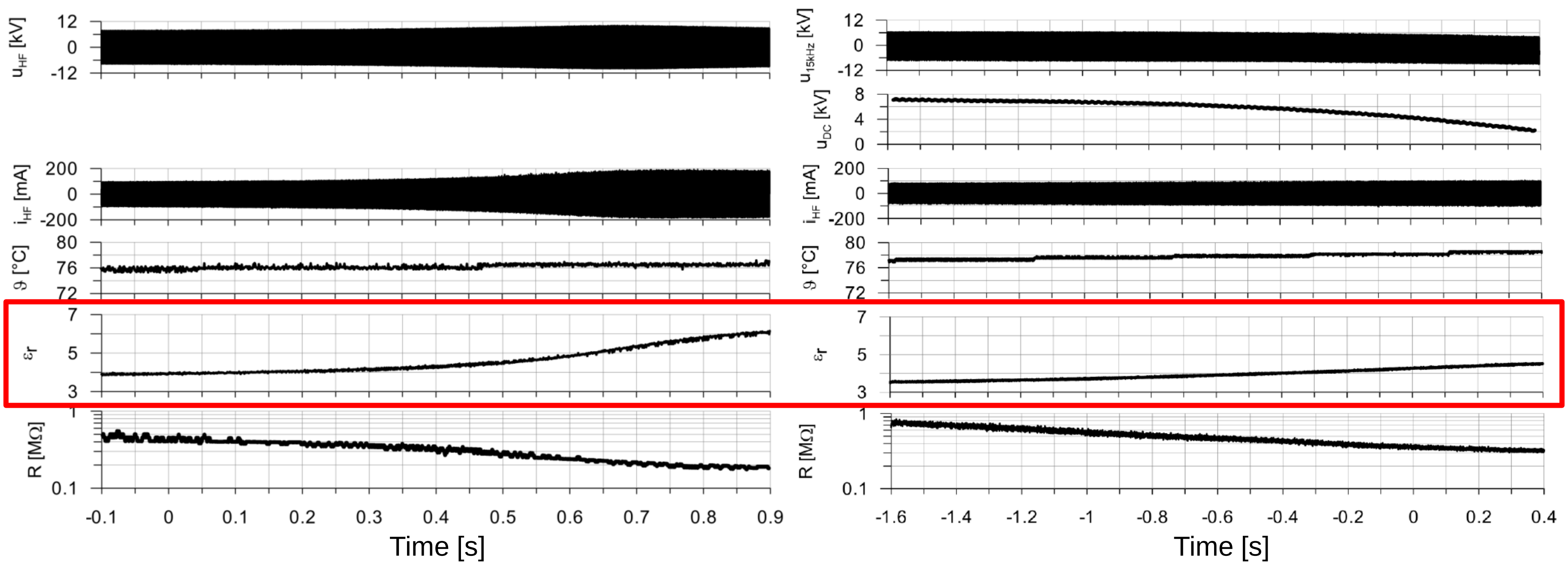
kHz- voltage



kHz+DC - voltage



Effect of HVDC to permittivity (sinusidoal voltage without change of polarity)



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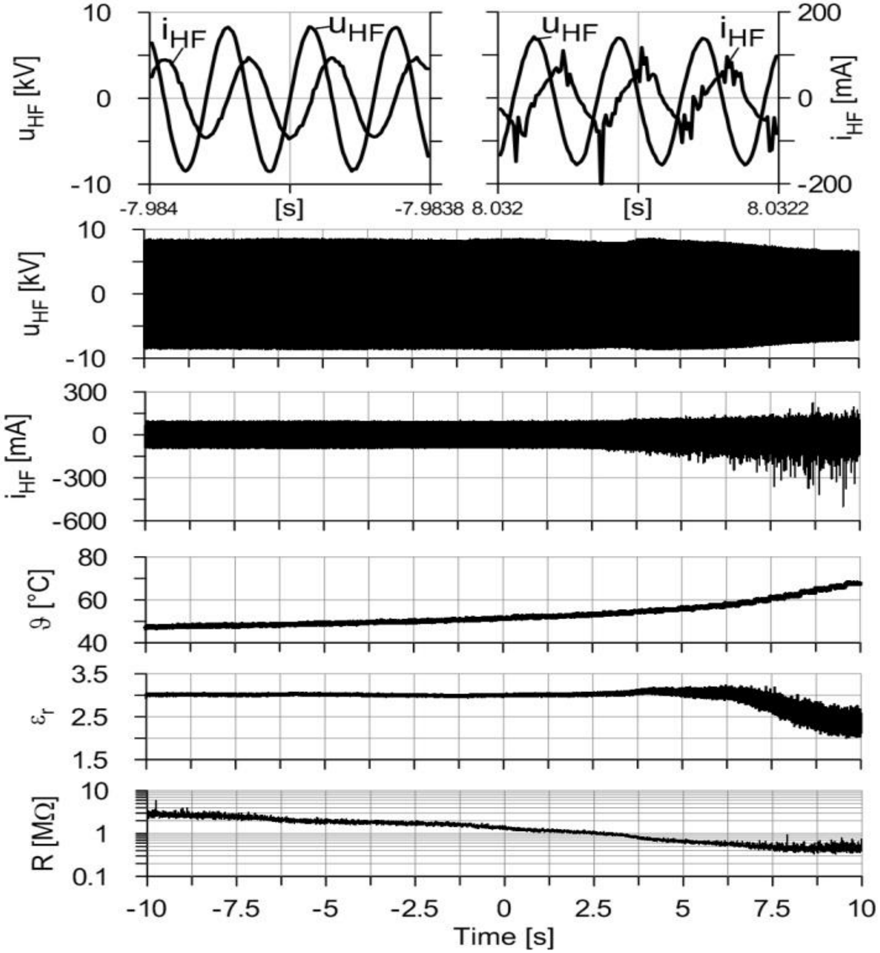
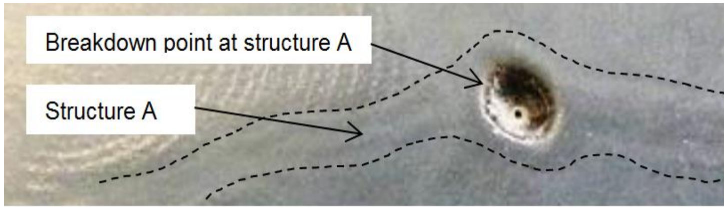
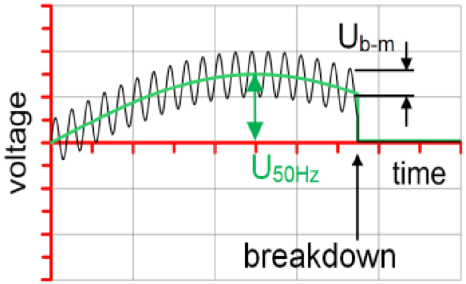
2 Dielectric heating process before loss of dielectric strength at kHz-sinusoidal voltage stress

Polyoxymethylen (POM) – *nonpolar Polymer*



Birle, Leu: Loss of dielectric strength of polymers due to high-frequency voltages in HVDC applications, JCable 2015





Heating Breakdown (not only in the maximum of voltage!)

Heat supply > Heat dissipation

As the temperature increases, the dielectric properties change until the material structure changes, resulting in a loss of the material's insulating function

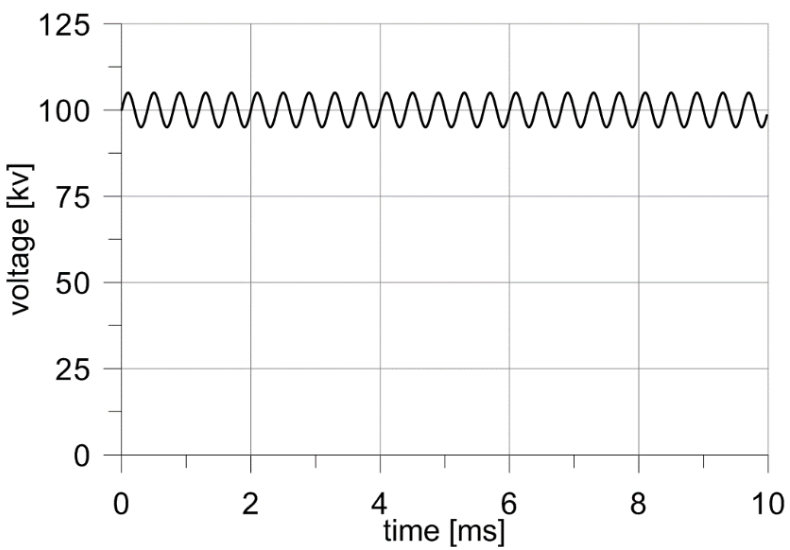
2 Process before loss of dielectric strength due to dielectric heating – sinusiodal voltage + HVDC

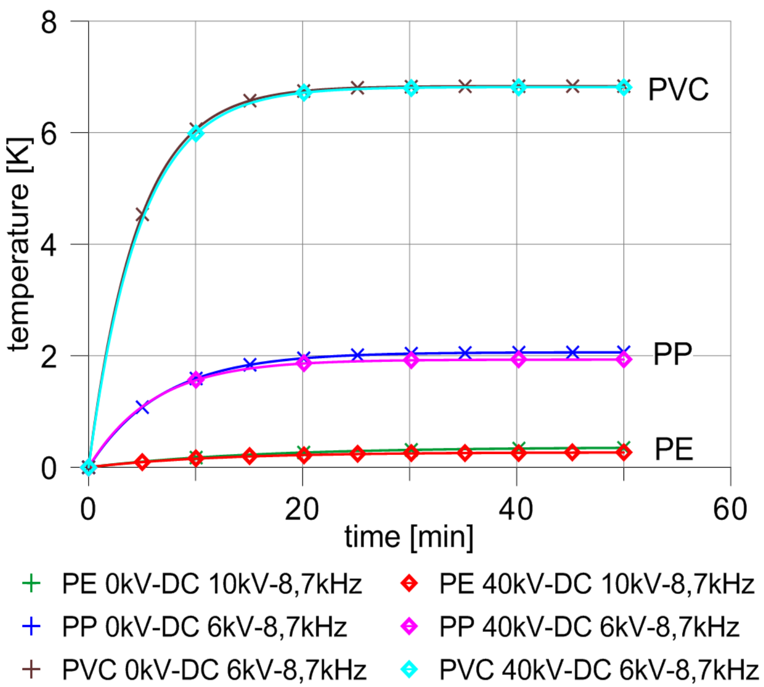
Nonpolar polymers in comparison

$$P_V = 2 \cdot \pi \cdot f \cdot C_0 \cdot \varepsilon_r \cdot tan\delta \cdot \left(\frac{U}{\sqrt{2}}\right)^2$$

$\varepsilon_{r\ PE} < \varepsilon_{r\ PP} < \varepsilon_{r\ PVC}$

Heating by superposed sinusoidial voltage (< 10%) non critically



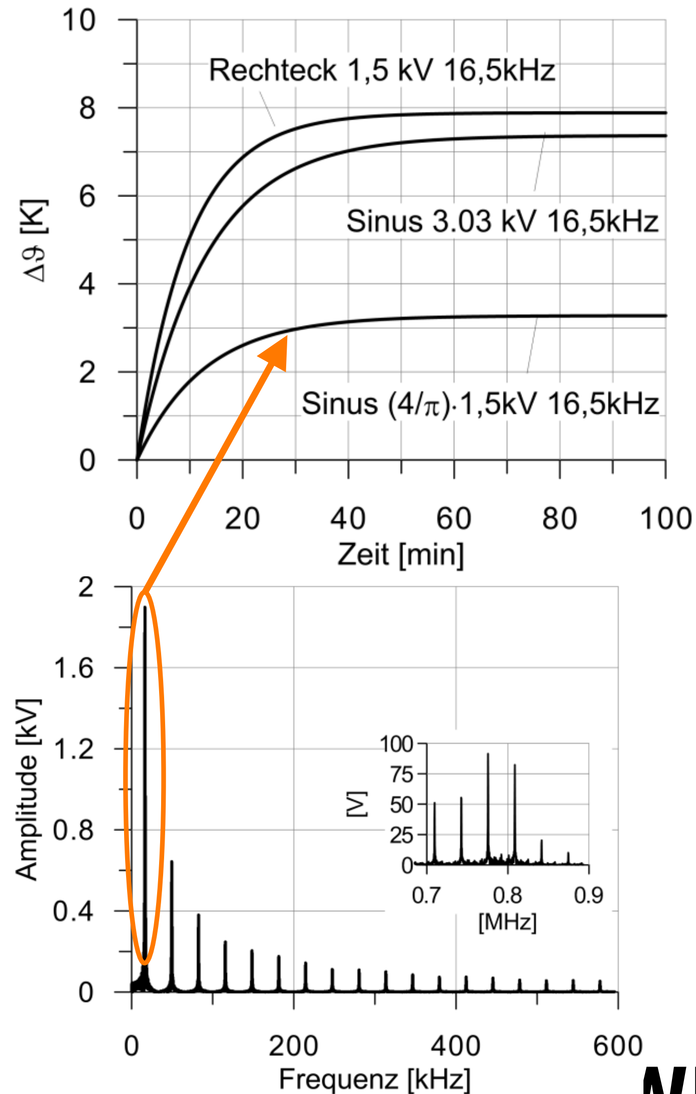


2 Dielectric heating of polymer material
Sinusoidal and rectangular 16,5-kHz-voltage

$$P_V = V \cdot 2 \cdot \pi \cdot \varepsilon_0 \cdot \sum_{i=1}^{n} \varepsilon''_{r,f_i} \cdot f_i \cdot E_{f_i}^2 \quad [W]$$

Voltage shape	Heat source density [W/cm³]
Rectangular, 1.5 kV	0.32
Sinus, 1.5 kV	0.079
Sinus, 4/π ·1.5 kV	0.1

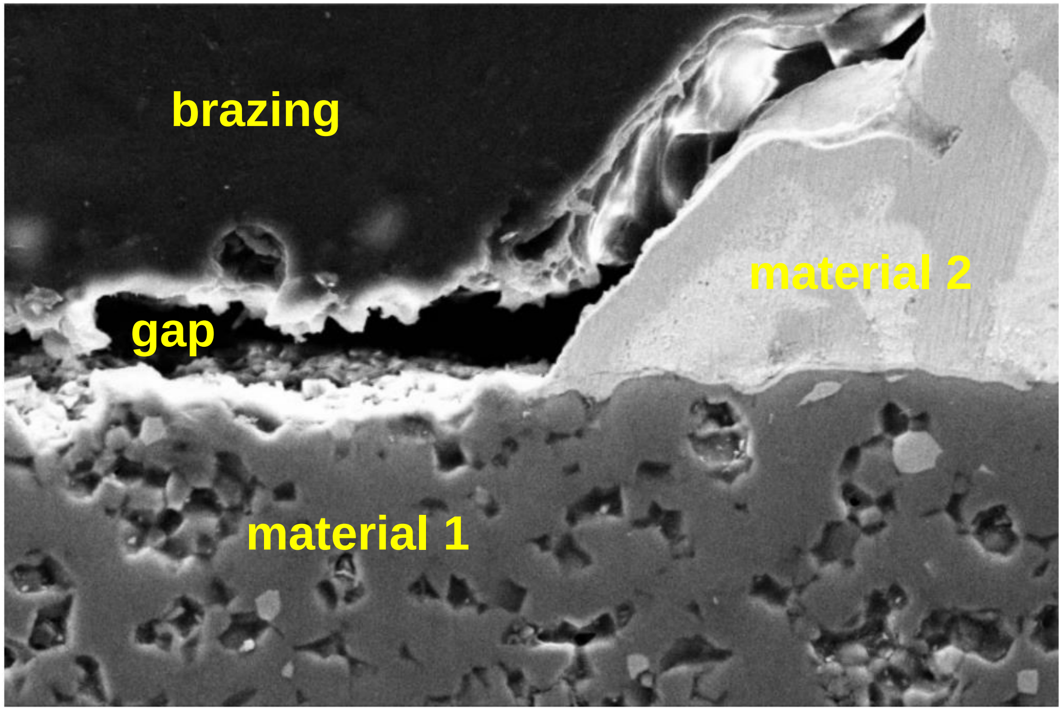
The heat source density in an insulating material is more then three times greater when subjected to a square-wave voltage than when subjected to a sinusoidal voltage with the same amplitude and frequency.

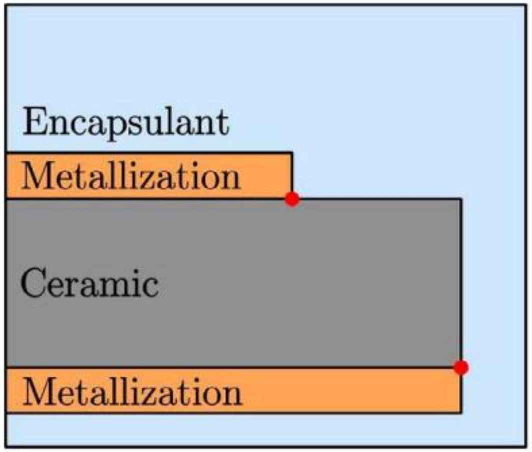


Quelle: M. Birle, Dissertation, TU Ilmenau

3 Intrinsic partial discharges

- Pores (voids) inside material 1 (ceramic) – low voltage strength
- Material 1 und material 2 with different permittivity - high gradient of electric field strength
- Gradient of permittivity and field strength as well at the transition gas (gap, pores) – material 1 or 2
- Sharp geometrie of brazing (electrode) in gas
- charge accumulation (surface of materials)





Electron micrograph of ceramic and metal brazing

Source: I. Semenov, NTNU

3 Intrinsic partial discharges

Partial discharges at HVDC with superposed kHz - voltage

the destructive power of periodic partial discharges is immense
(more discharges in a time unit and concentrated figure/power of discharge)

Long time erosion in a „strong“ insulation material block

Destroyed PMMA due to input of high energy plasma jet of partial discharge (no trees!)

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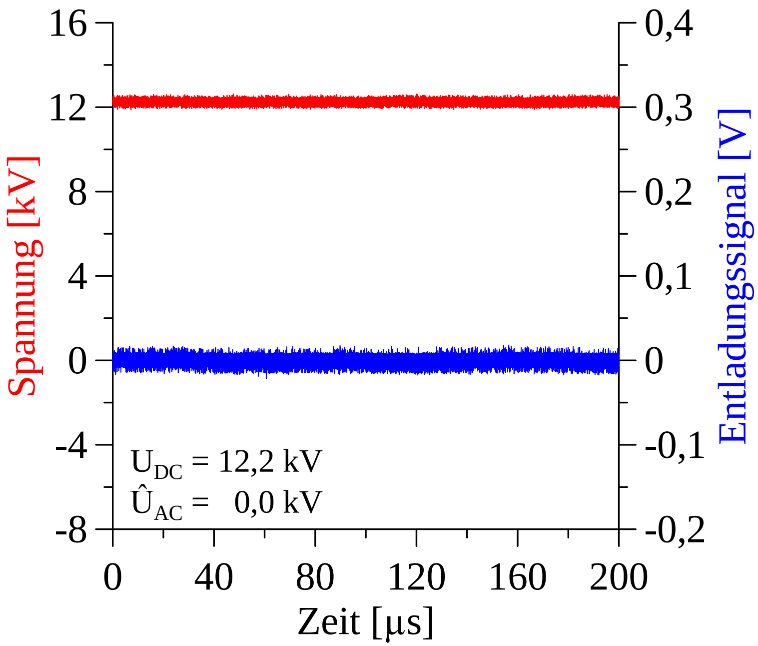
Partial discharges in gas (gaps, pores in the dielectric material)

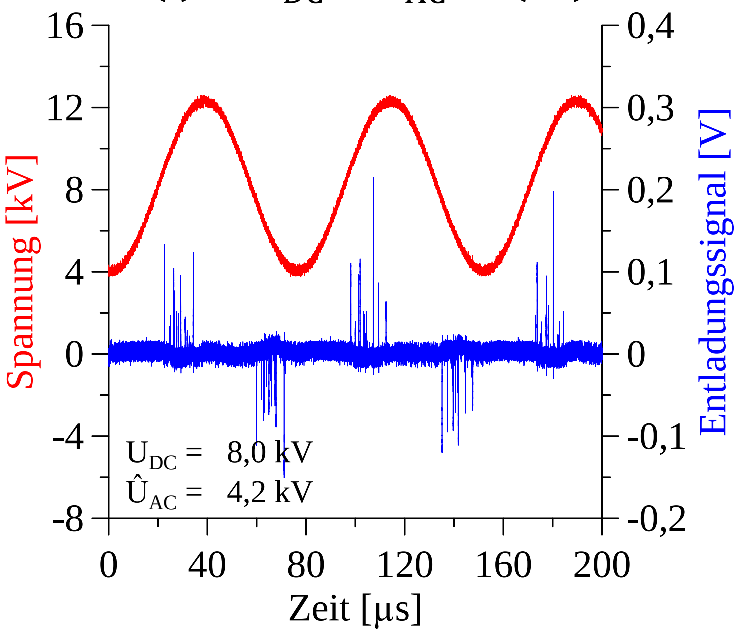
dc voltage

$$u(t) = U_{DC}$$



mixed voltage

$$u(t) = U_{DC} + \hat{U}_{AC} \sin(\omega t)$$



- du/dt means discharges at same amplitude of voltage (see diagrams: 12 kV)
- Time dependent charging and discharging processes are relevant
- Problem: accumulation of charges (difficult to quantify)

4 Summary

- Dielectric heating (higher permittivity, switching frequency, voltage amplitude, steepness of voltage) leads to a lower dielectric strength

- Transport of heat from the power electronic device to the heat sink through insulation layer is disturbed by its heating

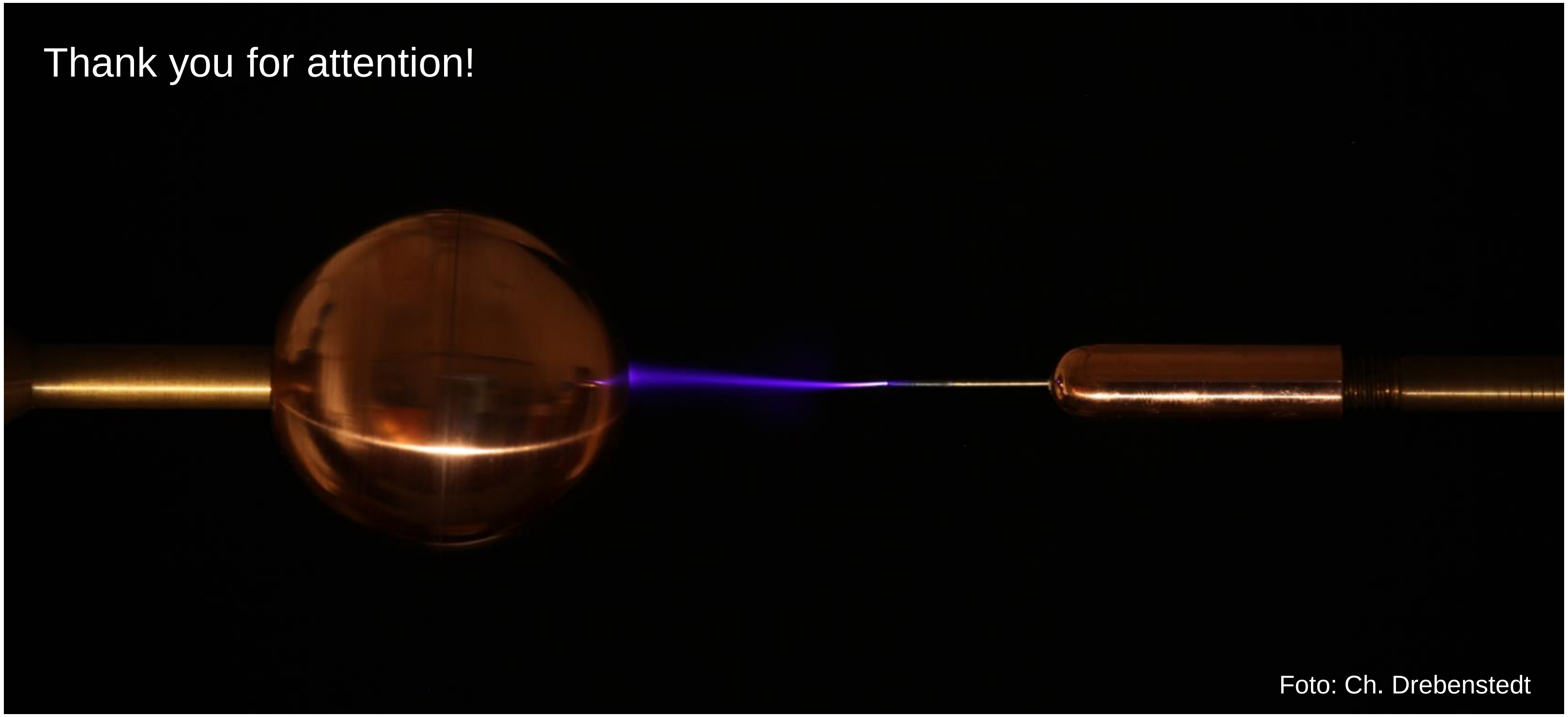
- higher du/dt: discharges due to delayed flow of charges following polarity of voltage

- Concentrated figure of discharge

Preventing partial discharges is essential!

- Aspects of an optimal design are: optimized heat balance and/or maximum cooling, mature potting technologies, consideration of parasitic elements (e.g. higher line losses, capacitive designs, wiring if necessary)

- Positive effects in layered insulation systems: uniform field distribution, maximum radii of curvature, homogeneity of materials, elastic and well-adhering material compounds, minimum gradients of dielectric parameters (permittivity, damping effects)


Thank you for attention!
Foto: Ch. Drebenstedt

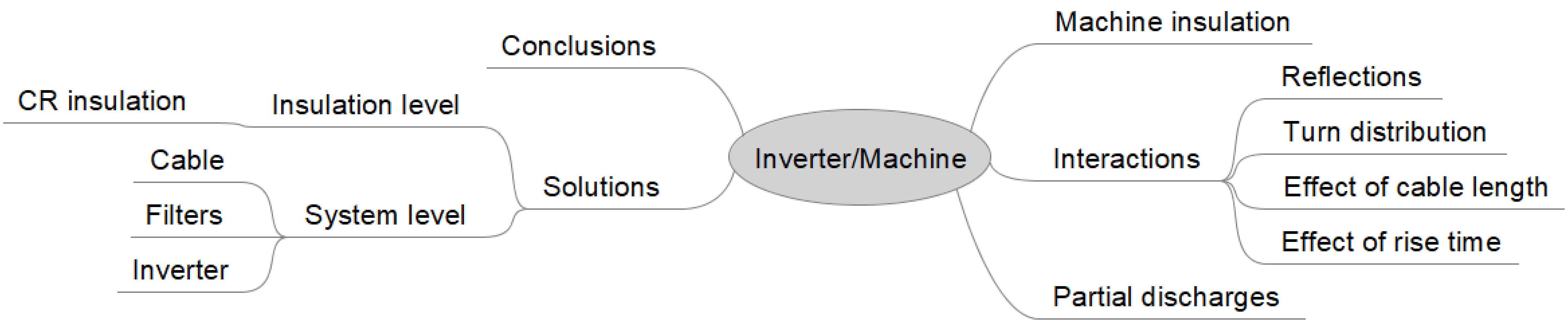
Inverter/Electrical machine insulation interactions: issues and possible mitigation actions

Andrea Cavallini

Wednesday, 04/Sept/2024: 11:00am - 12:30pm

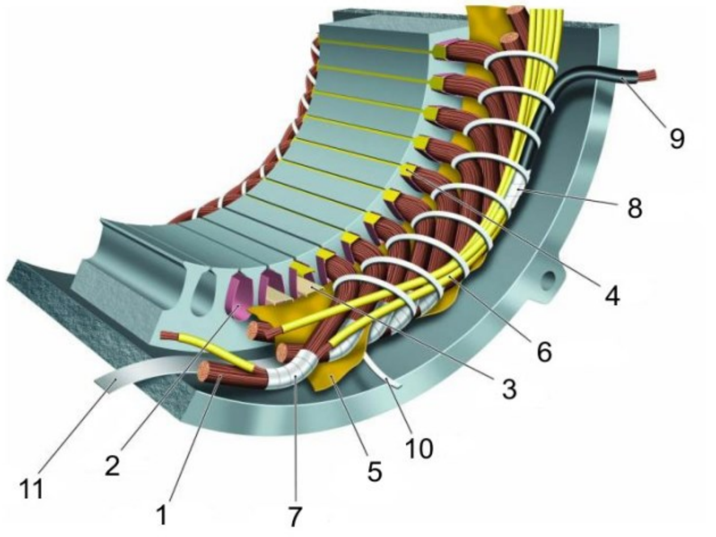
Location: 2.03 vanadium (2nd floor)

Outline

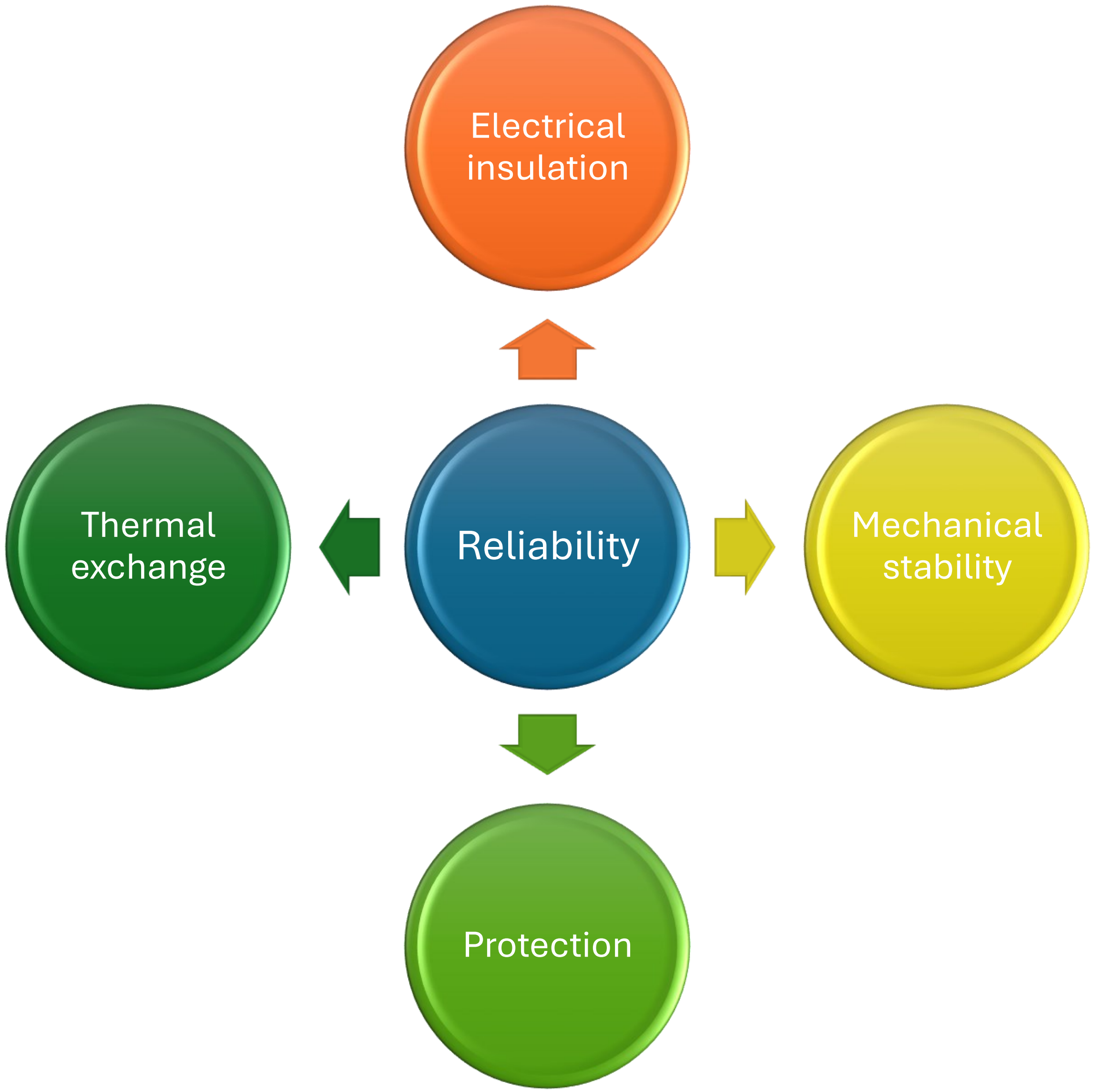


Conclusions
CR insulation
Insulation level
Cable
Solutions
Filters
System level
Inverter
Inverter/Machine
Machine insulation
Reflections
Turn distribution
Interactions
Effect of cable length
Effect of rise time
Partial discharges

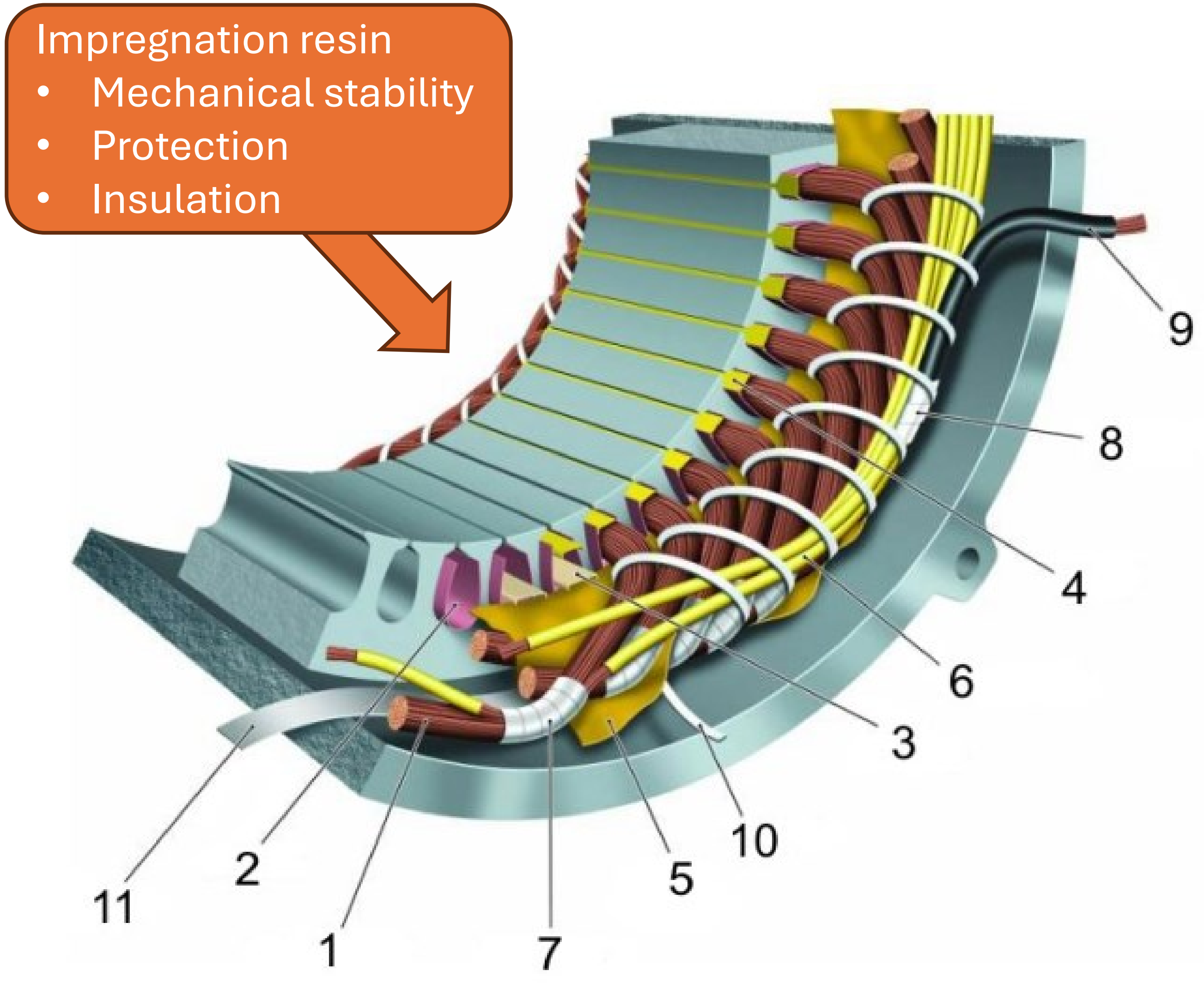
Machine insulation



Insulation system functions



Overview of insulation system components



1. Turn insulation
2. Slot liner
3. Slot separator
4. Wedge
5. Phase separator

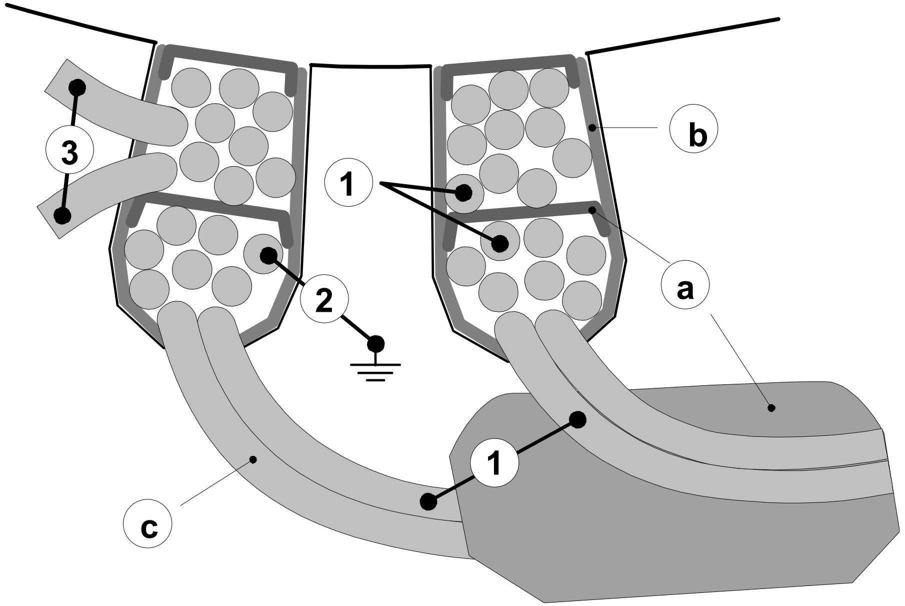
Electrical insulation

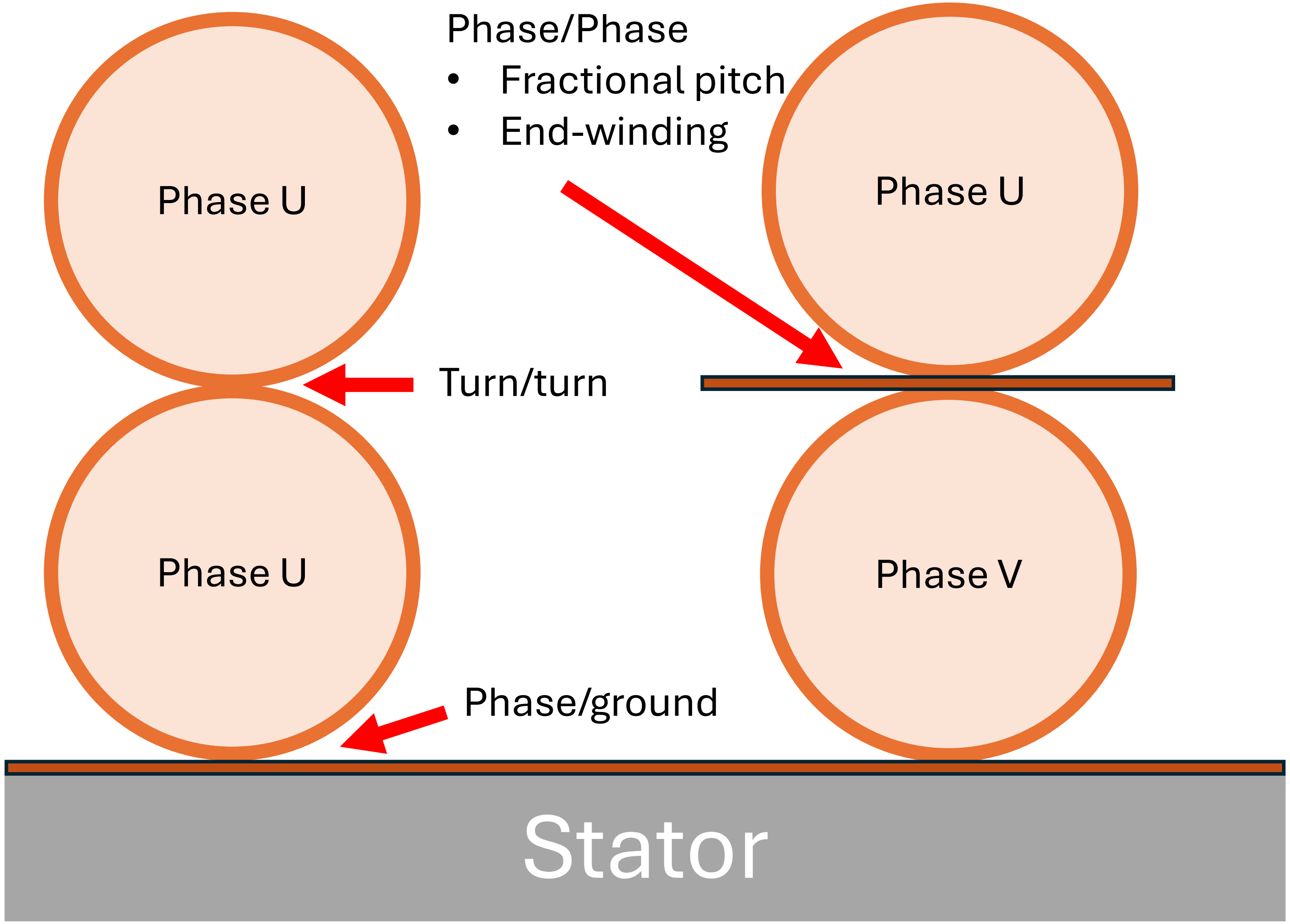
6. Lead sleeving
7. Coil-nose tape
8. Connection tape
9. Cable
10. Tie cord
11. Bracing

Mechanical stability
Protection

M. Chapman, N. Frost and R. Bruetsch, "Insulation Systems for Rotating Low-Voltage Machines," *Conference Record of the 2008 IEEE International Symposium on Electrical Insulation*, Vancouver, BC, 2008, pp. 257-260.

Insulation sub-systems (random wound)

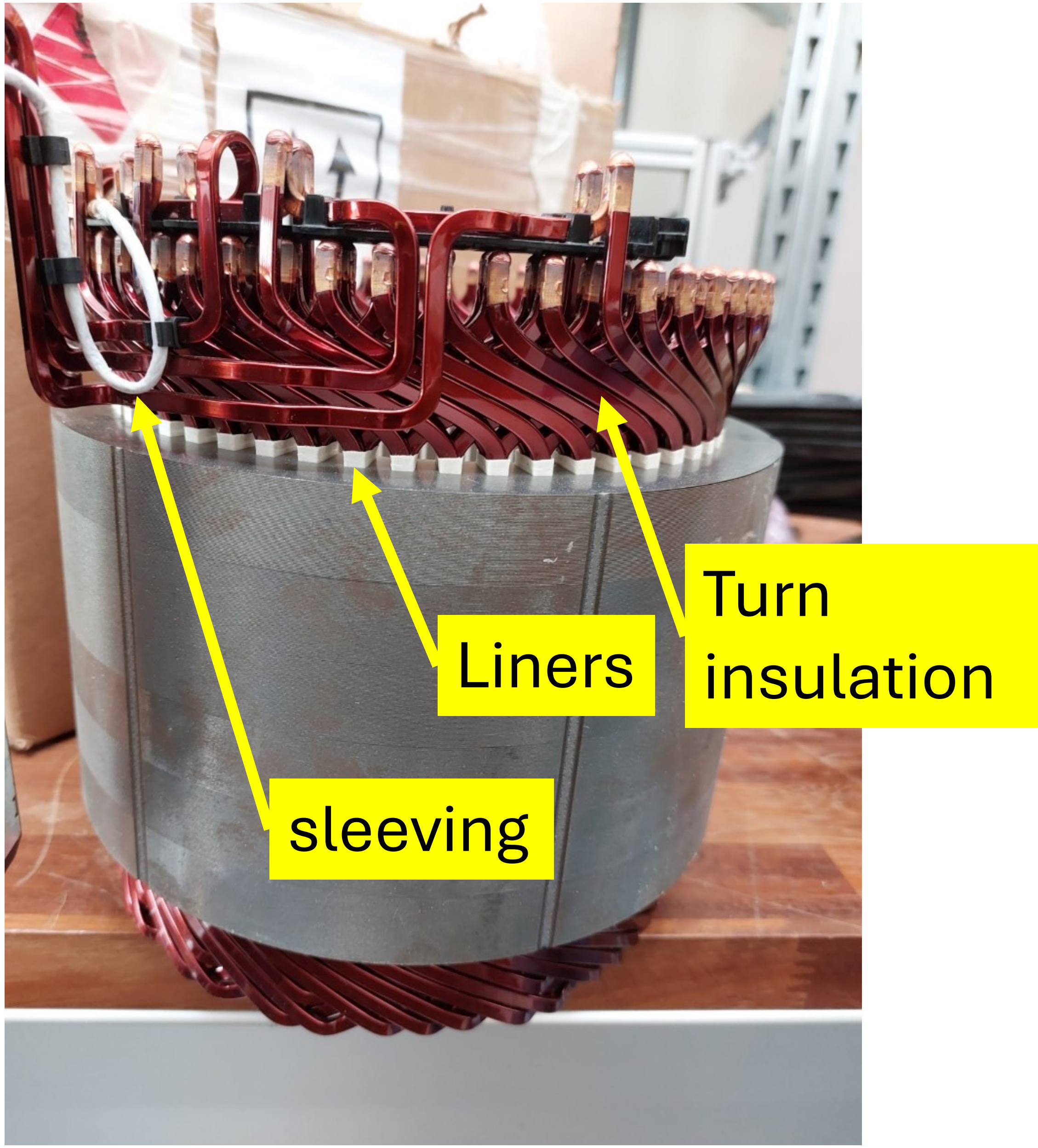




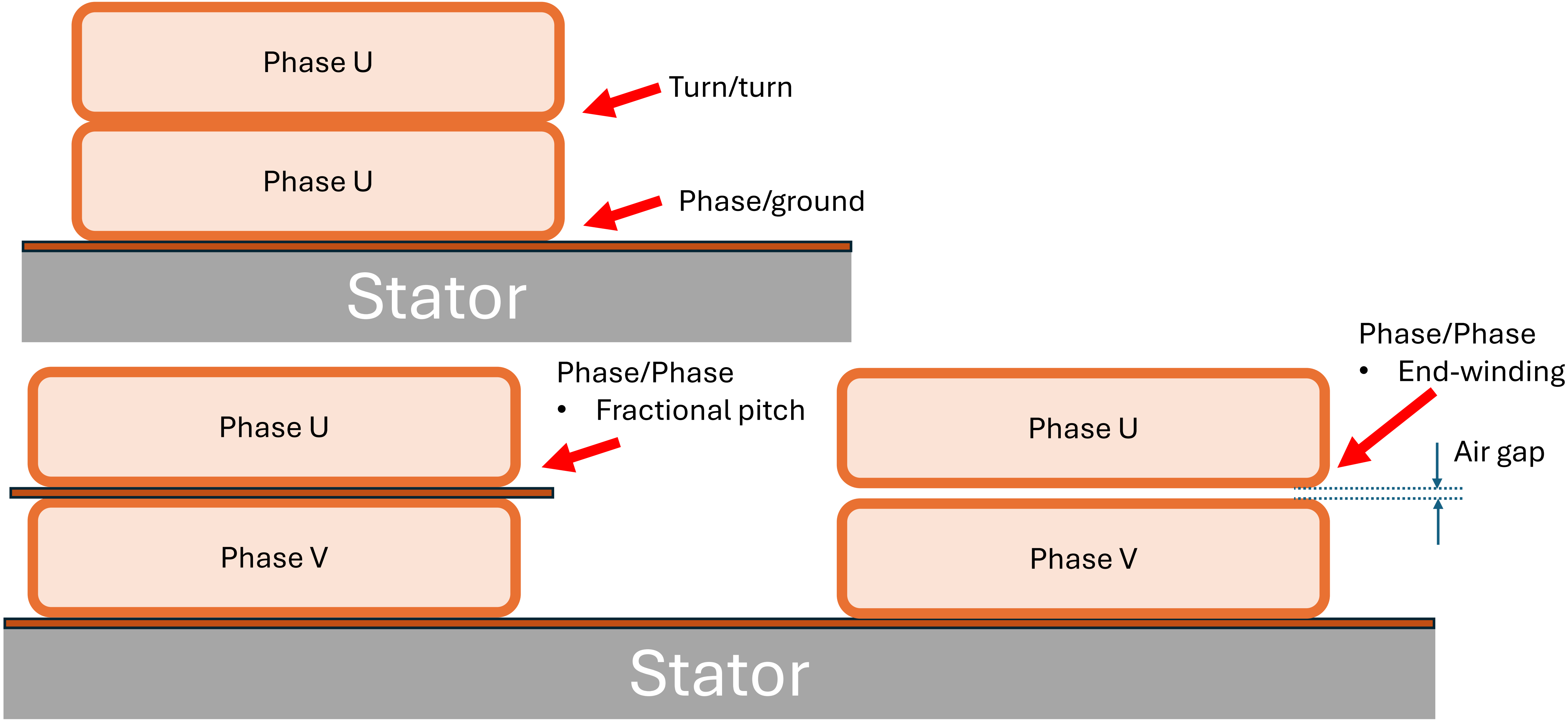
Insulation sub-systems (hairpin)

- Simpler, similar materials
- Note on enamels.
  - Industrial:
    - PAI
  - Electric vehicles:
    - PAI
    - PI
    - PEEK
    - PFA

Larger added value

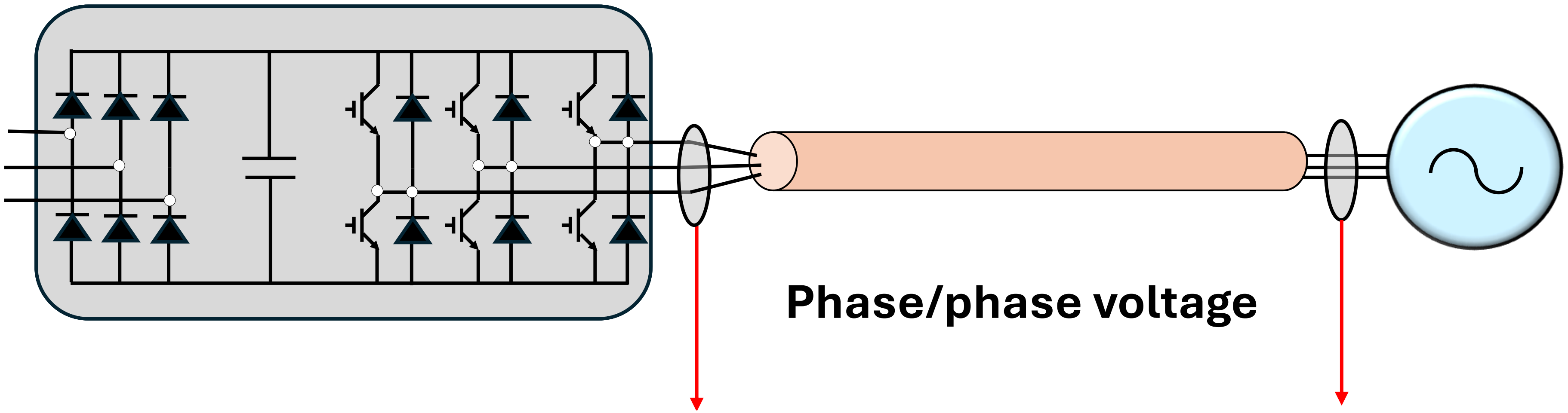


Insulation sub-systems (hairpin)

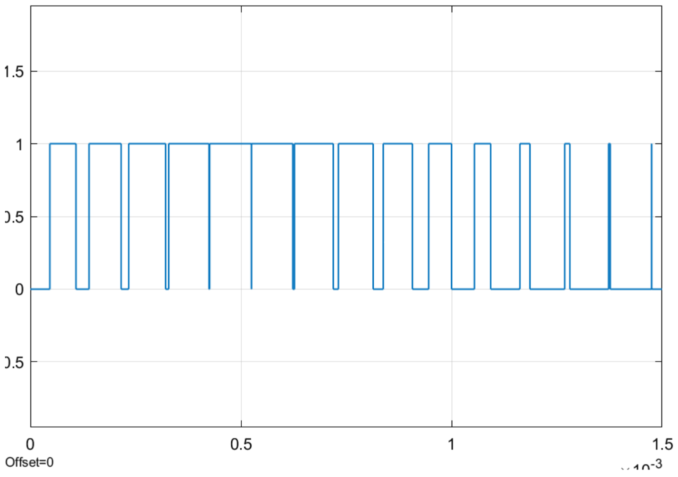


Interactions

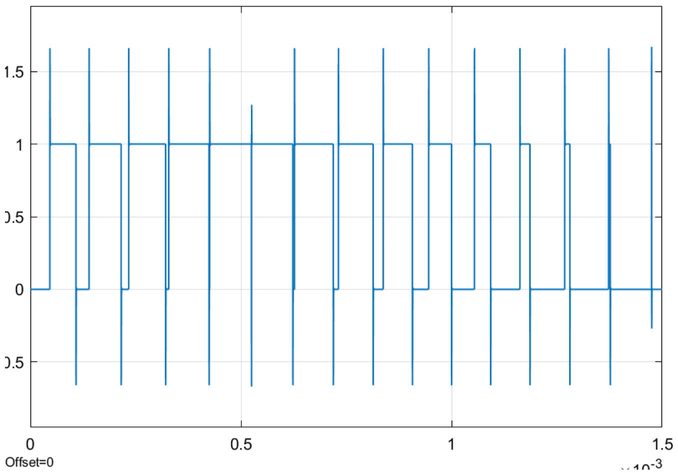
Motor-terminal voltages



Phase/phase voltage

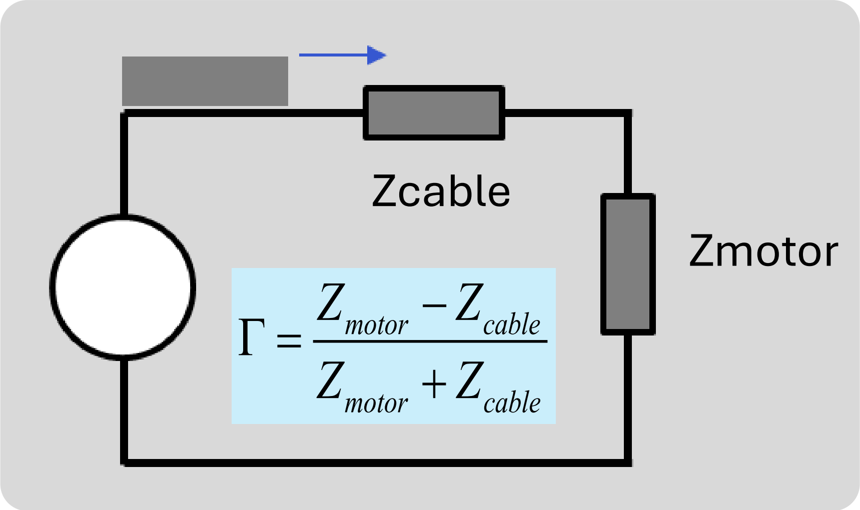


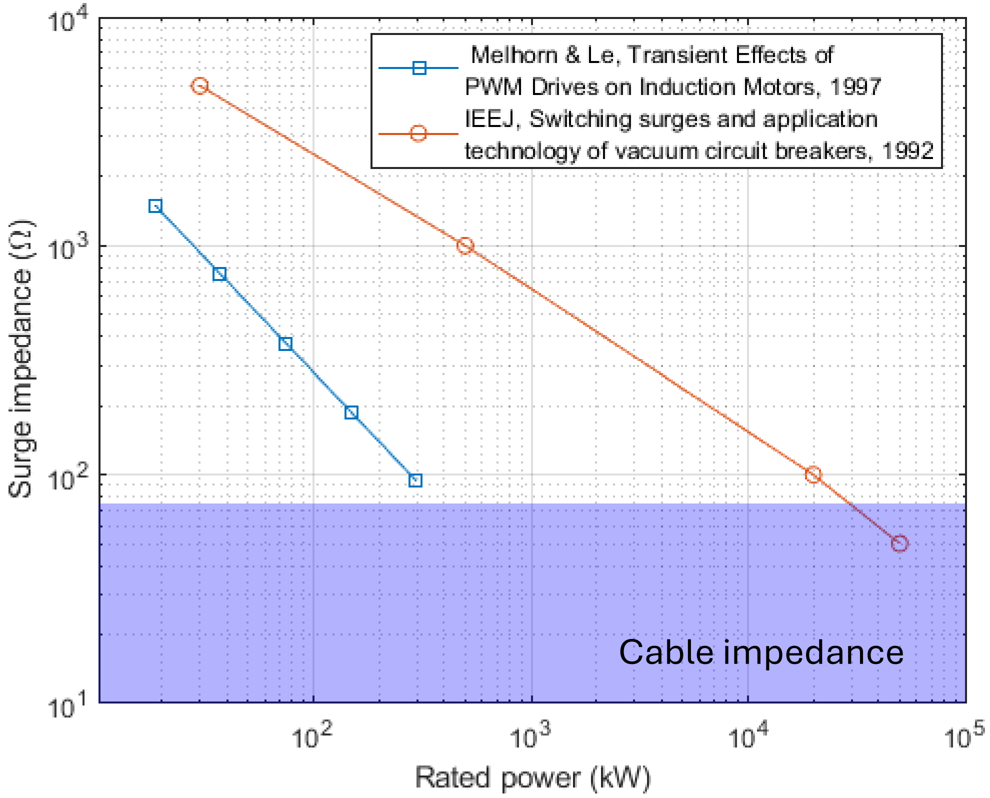
Inverter terminals

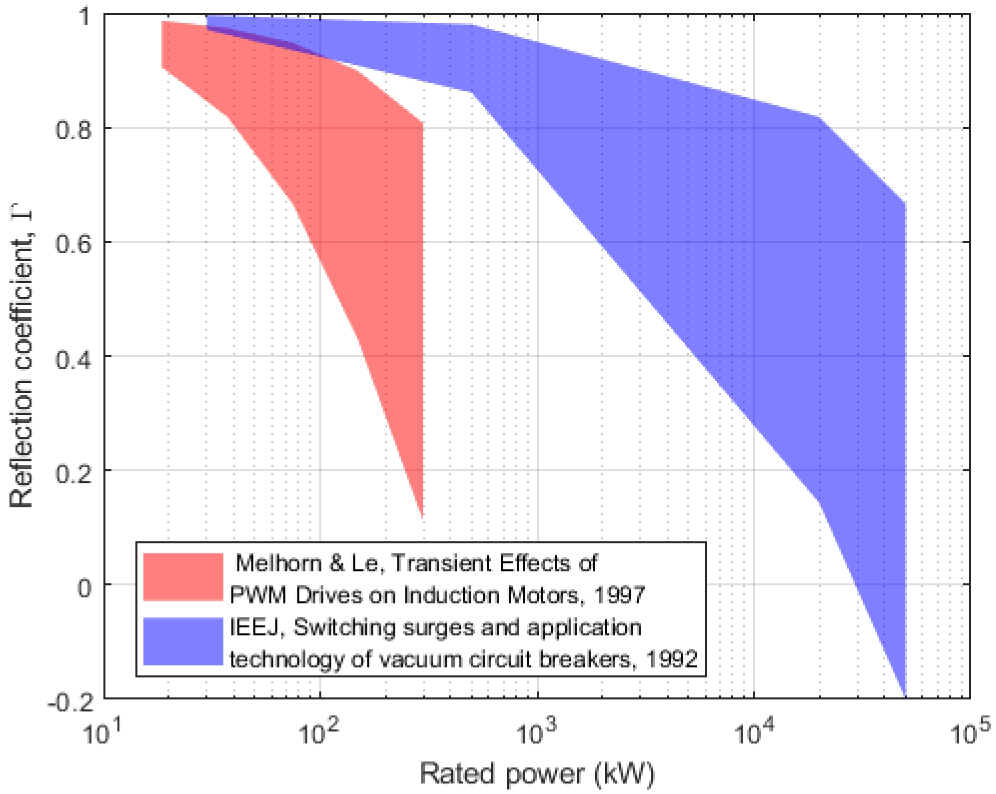


Motor terminals

Reflection coefficient







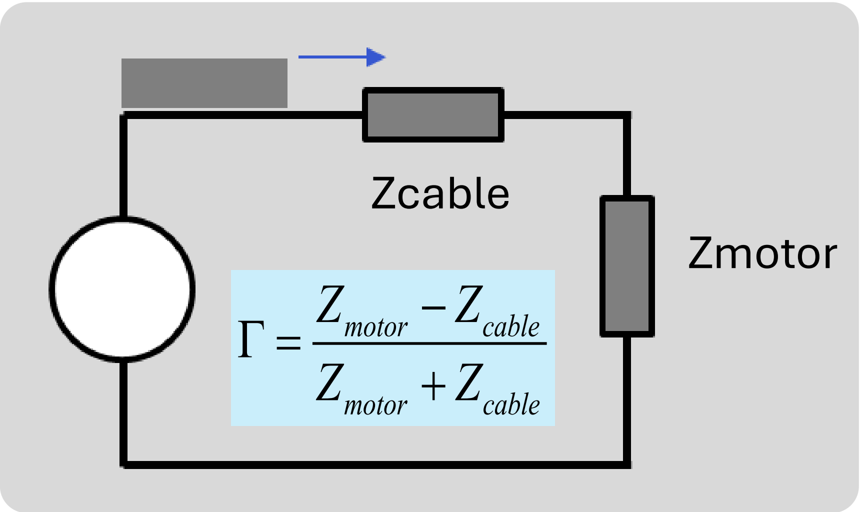
Overvoltage factor (IEC 60034-18-41)

Γ=1 $\rightarrow$ OF=2 $\rightarrow$ Full reflection

Reflection coefficient

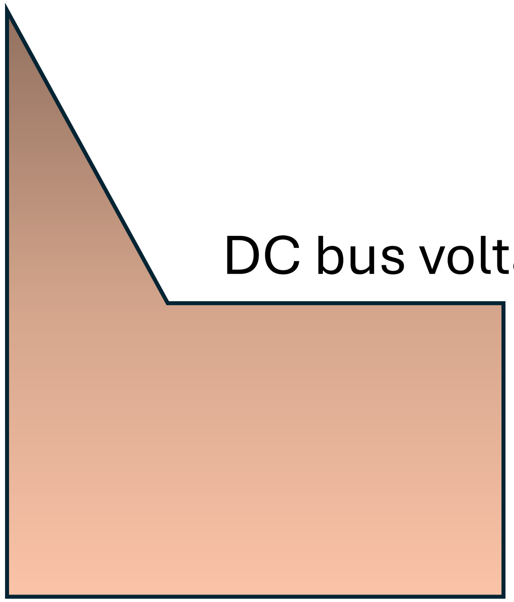
Overvoltage Factor

$$OF = \frac{V_P}{V_{dc}} = 1 + \Gamma \le 2$$



$$\Gamma = \frac{Z_{motor} - Z_{cable}}{Z_{motor} + Z_{cable}}$$

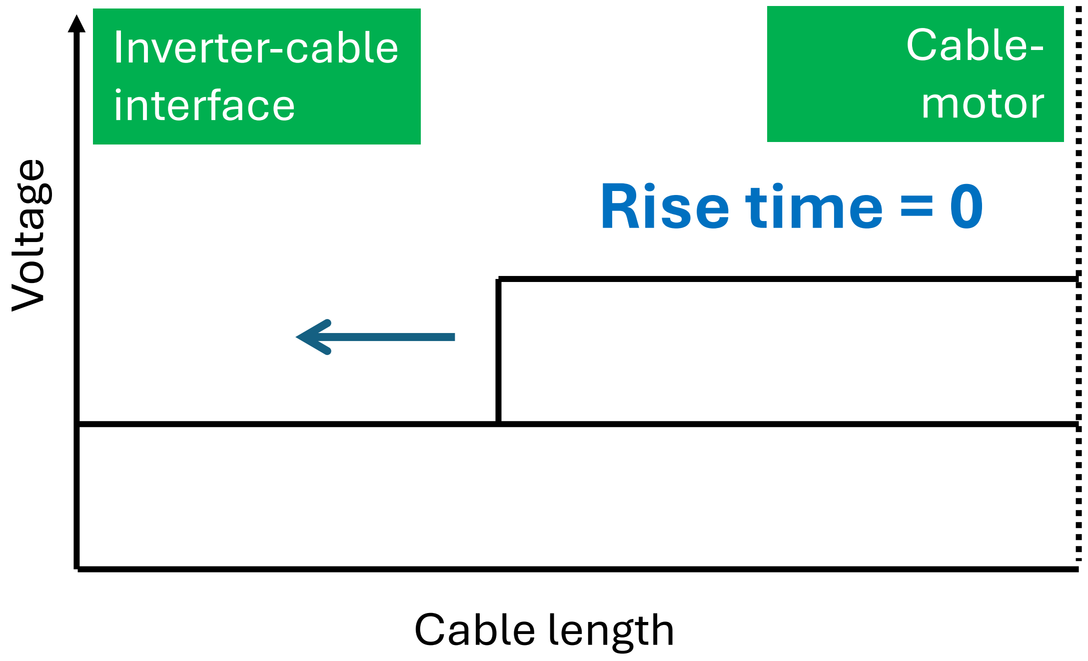
Peak voltage V_P = 2000 V

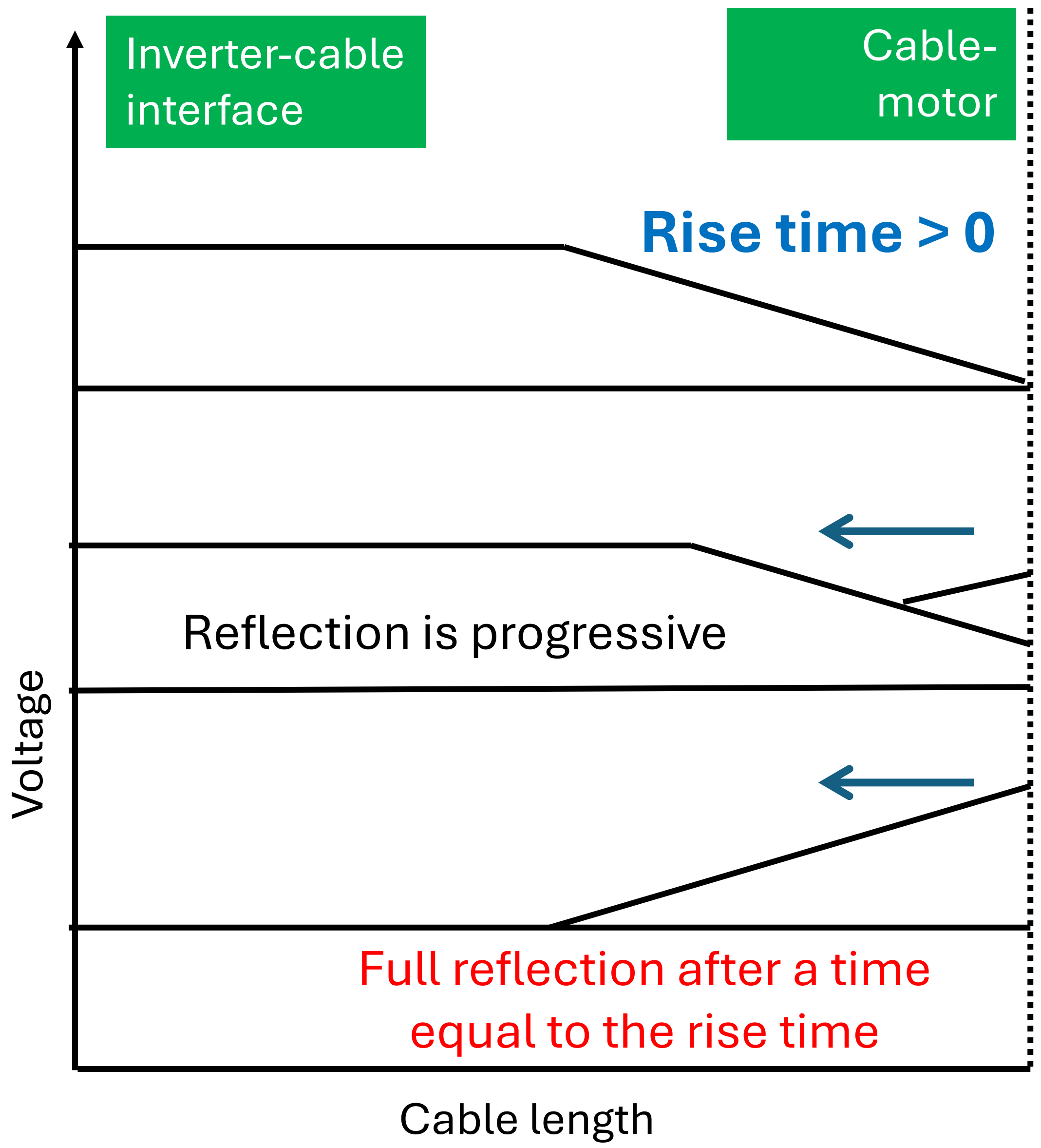


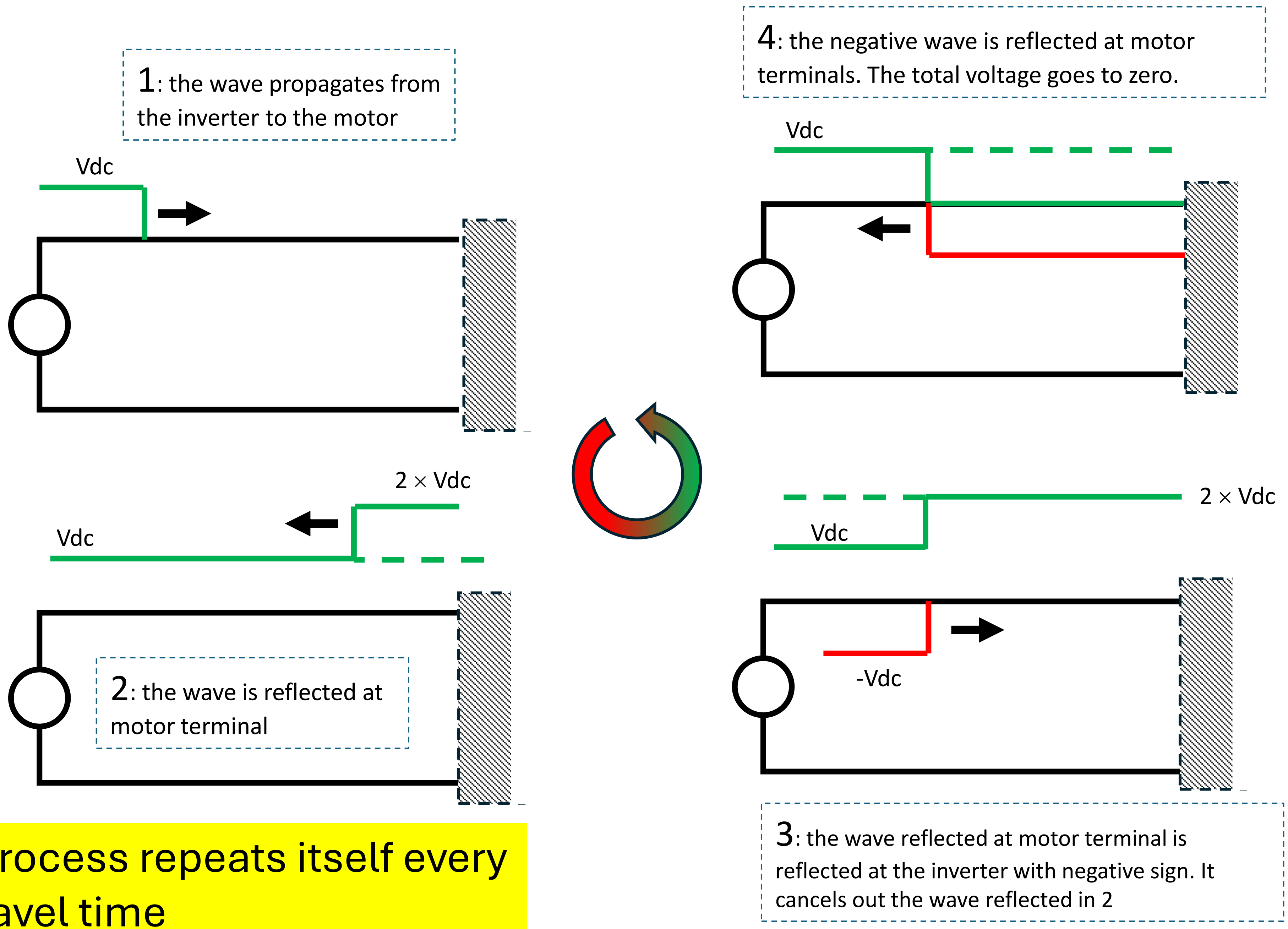
DC bus voltage V_{dc} = 1000

Effect of cable length

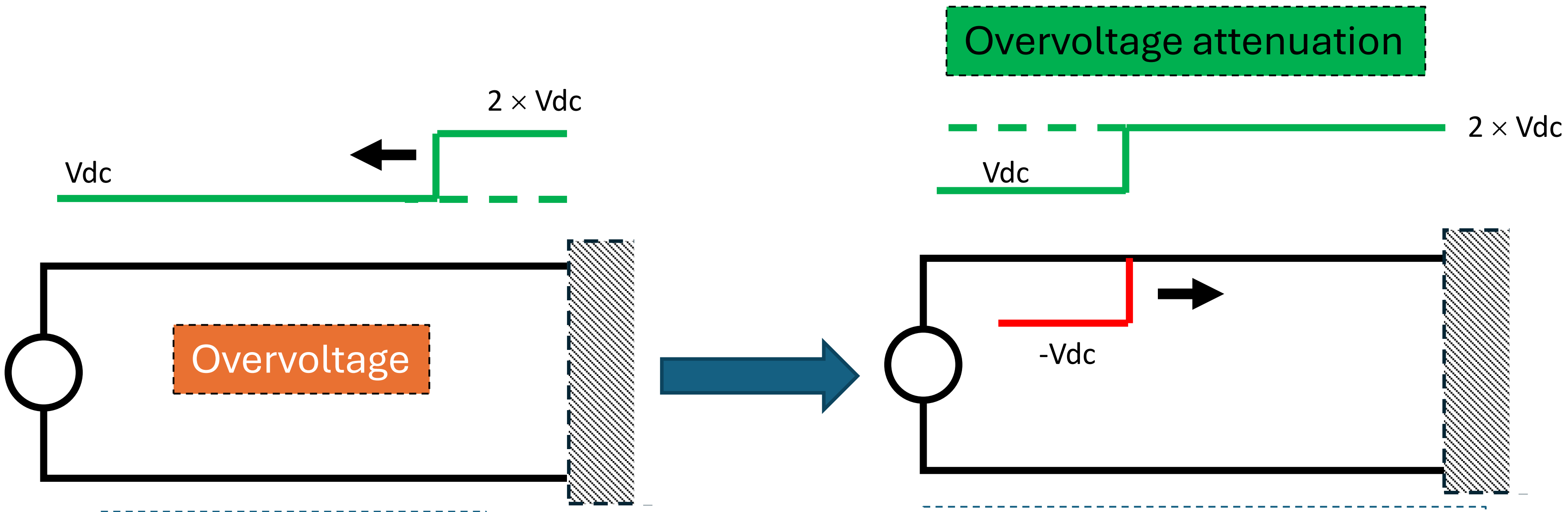
Influence of rise time on reflections







The process repeats itself every 4 x Travel time



2: the wave is reflected at motor terminal

3: the wave reflected at motor terminal is reflected at the inverter with negative sign. It cancels out the wave reflected in 2

cable lenght

$$t_{forth-back} = \frac{2 \times l_{cable}}{v_{prop}}$$

propagation speed

Time needed for overvoltage attenuation (after the overvoltage is observed)

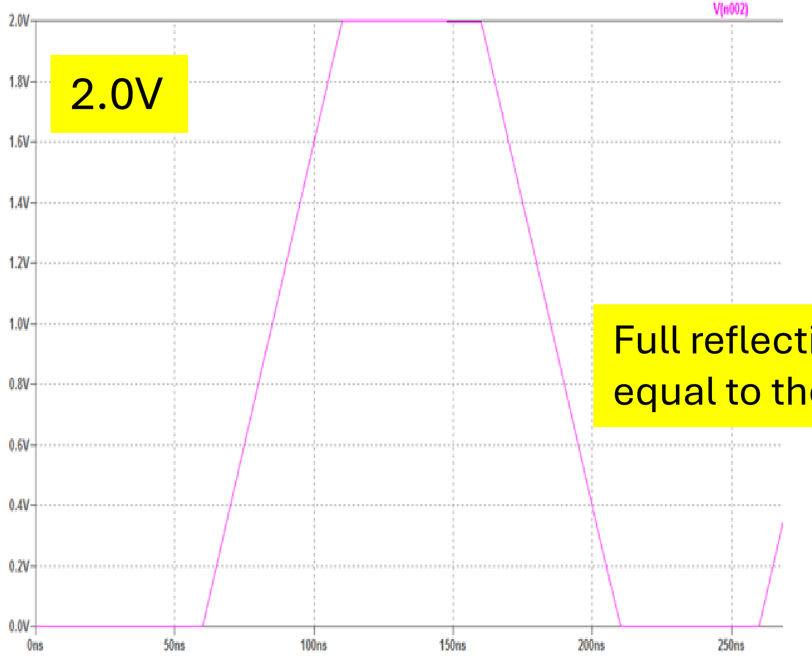
Time for the voltage surge to travel forth and back the cable

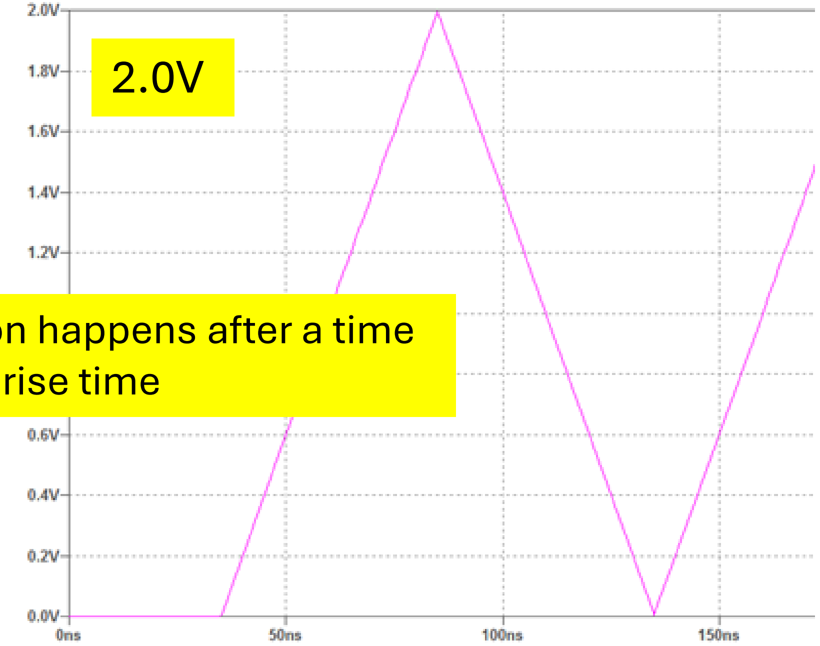
DC bus voltage = 1 V

t_{rise} = rise time
l_{cable} = cable lenght
v_{prop} = propagation speed

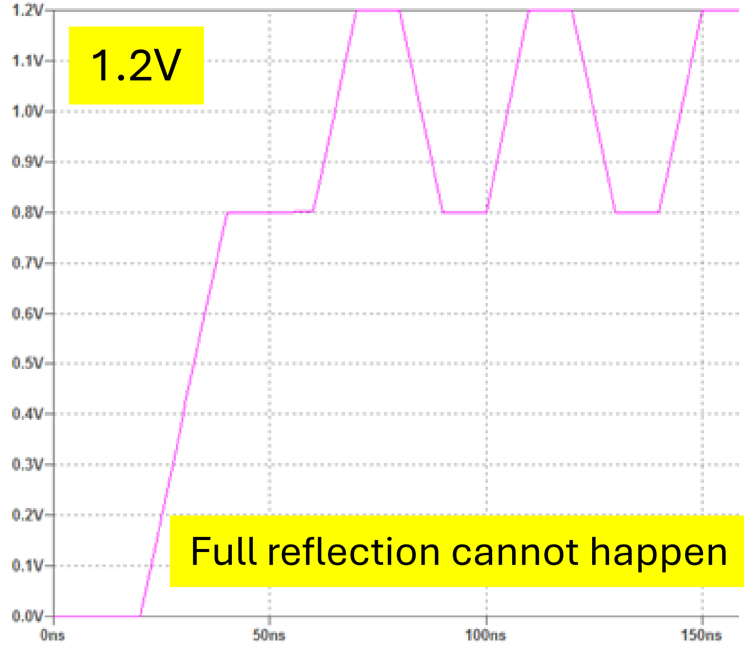
$$t_{forth-back} = 2\frac{l_{cable}}{v_{prop}}$$

Time needed for the voltage surge to travel forth and back the cable





Full reflection happens after a time equal to the rise time



Full reflection cannot happen

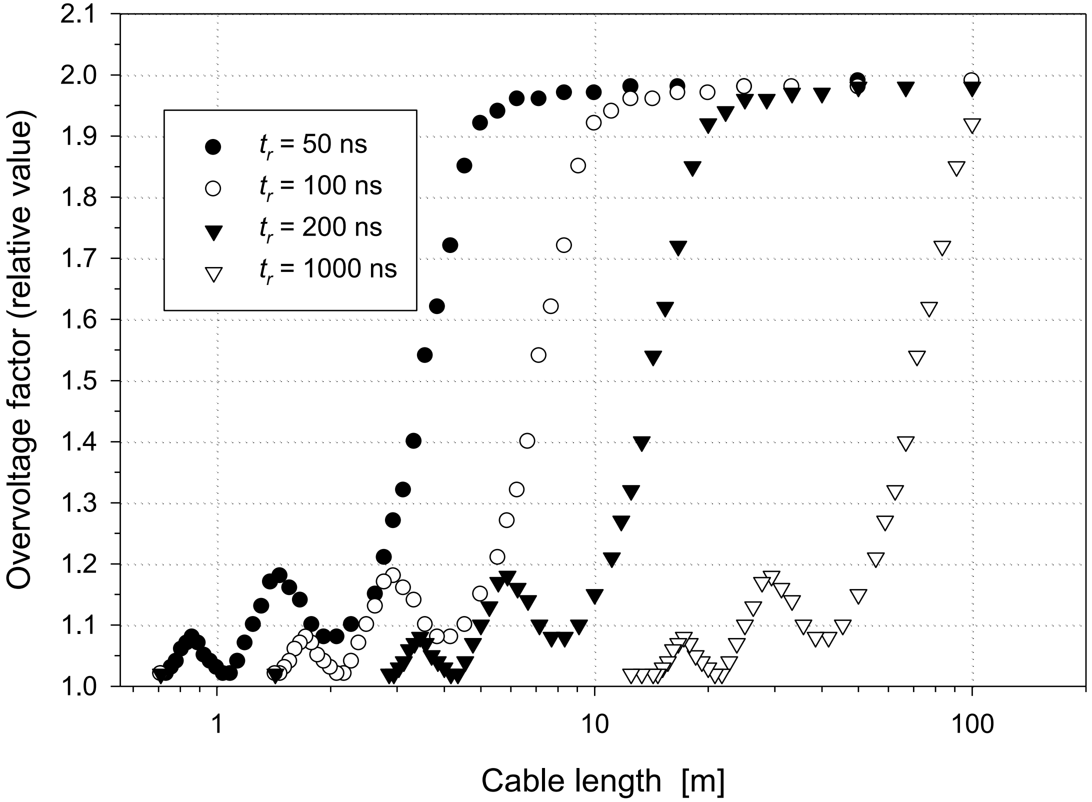
$$t_{forth-back} > t_{rise}$$

$$t_{forth-back} = t_{rise}$$

$$t_{forth-back} < t_{rise}$$

Overvoltages

Worst case ($\Gamma = 1 \rightarrow OF = V_p/V_{dc} = 2$)



V_P = Peak voltage
V_{dc}= DC bus voltage

t_{rise} = rise time
l_C= cable lenght

v_{prop} = propagation speed ⇨ 16 cm/ns

$$t_{forth-back} \geq t_{rise} \rightarrow \boxed{l_{cable} \geq v_{prop} \times \frac{t_{rise}}{2}}$$

Condition for complete reflection

Critical cable length @Trise=15 ns

v_{prop} = propagation speed ⇨ 0.16 m/ns

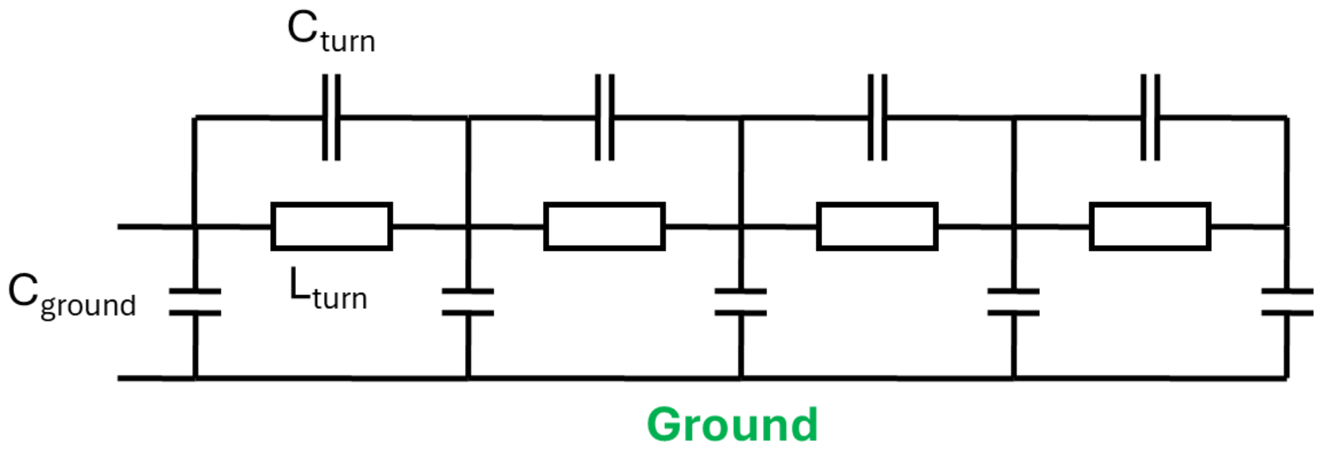
$$t_{rise} = 15\,\text{ns} \Rightarrow$$
$$l_{cable} \geq v_{prop} \times \frac{t_{rise}}{2} = 16 \cdot \frac{15}{2} = 120\,\text{cm}$$

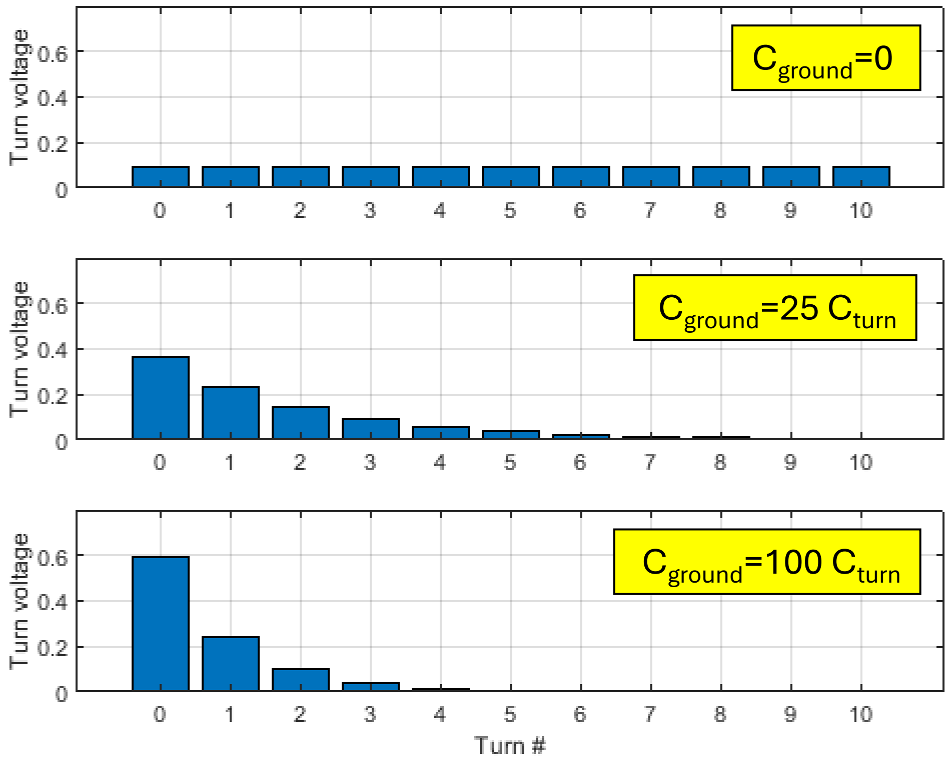
- With wide bandgap devices, reflections can become an issue also in EVs.
  - With GaN (4 ns), a 32 cm cable can be very long...

Effect of rise time

Besides the fact that shorter rise time give rise to larger reflections…

Turn/turn voltage



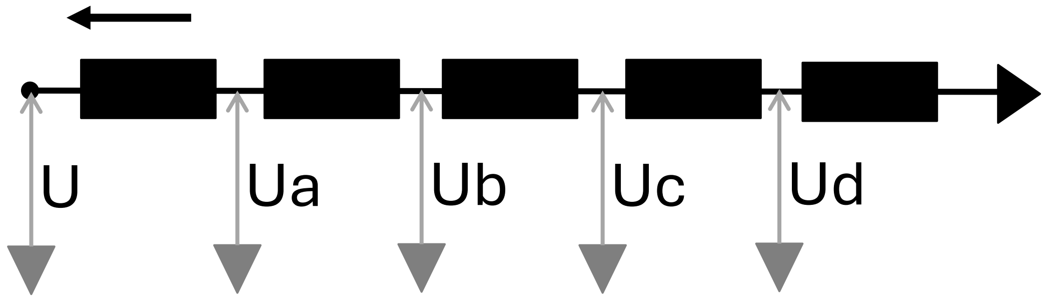


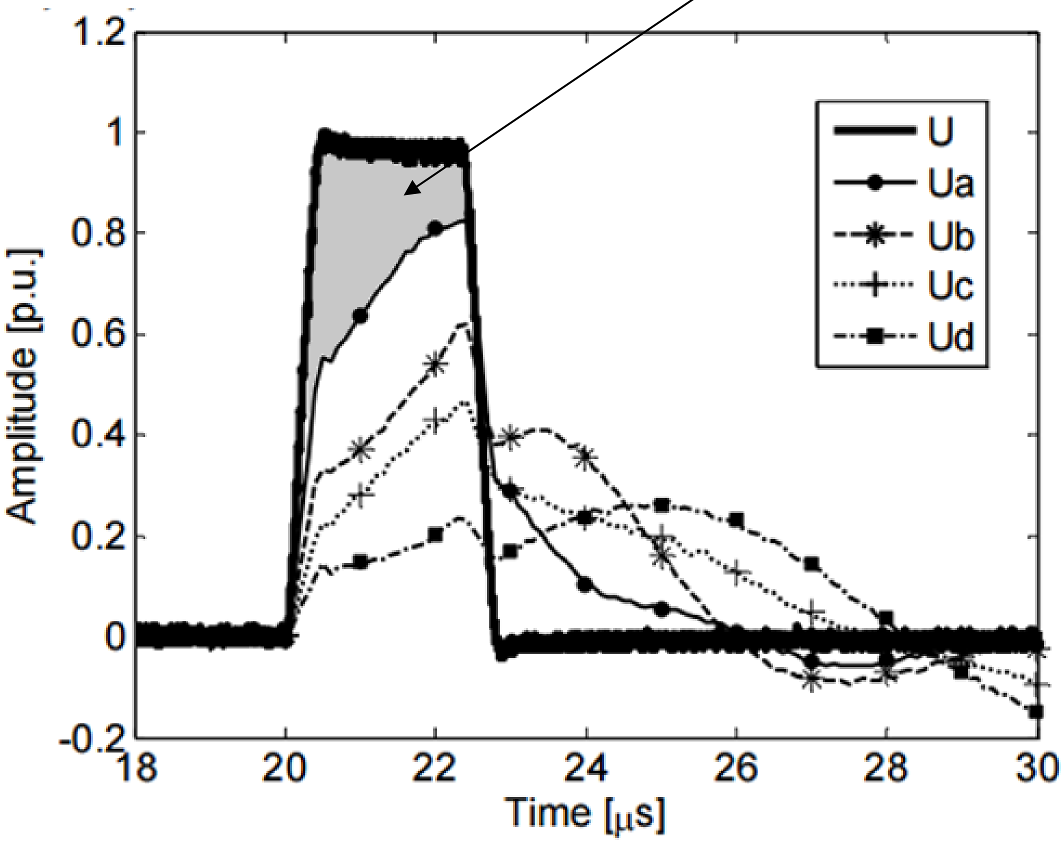
- Voltage distribution
  - The higher C_{ground} with respect to C_{turn} $\Rightarrow$
    - The higher the voltage drop on the first turns
- **Turn/turn insulation stress**

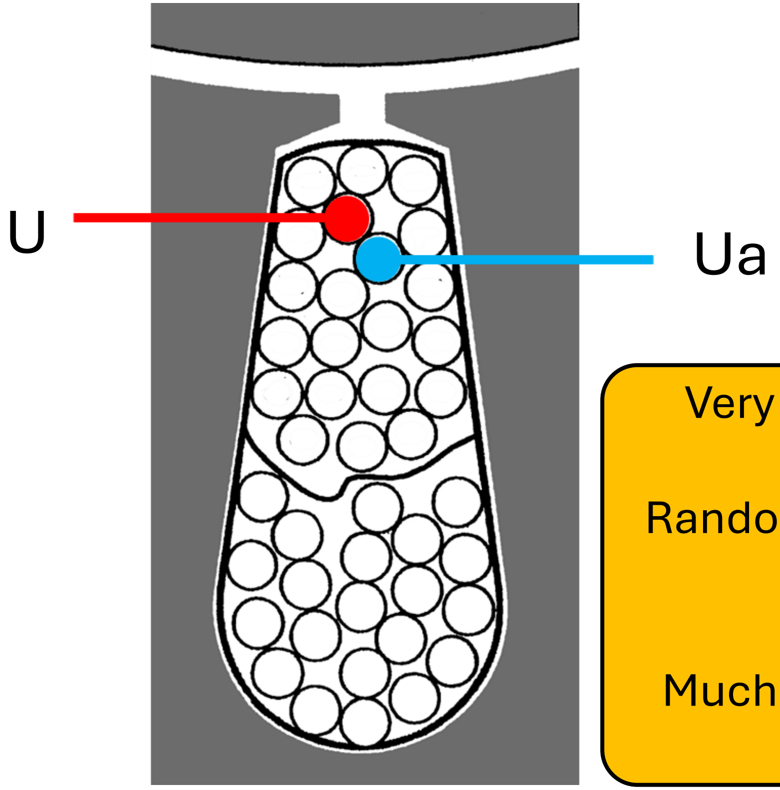
In reality, things can go far worse

U-Ua=Gray area in the figure

Turn/turn voltage



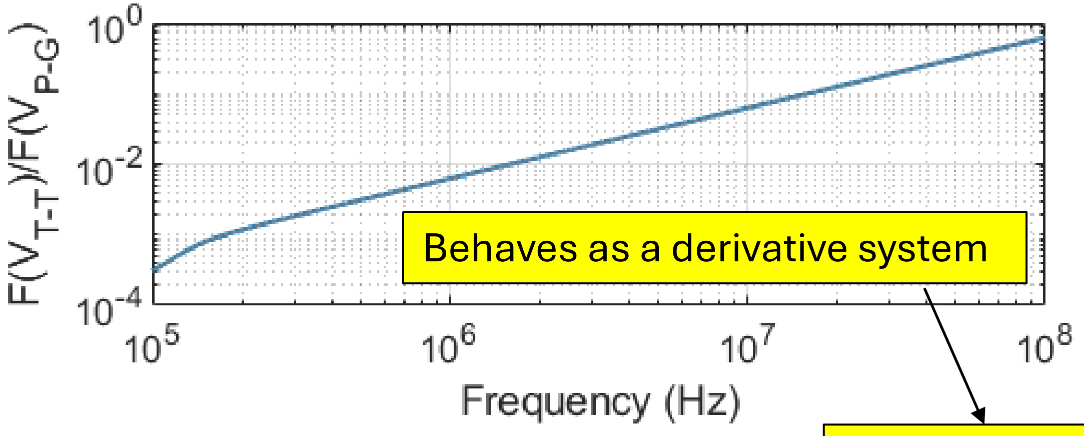


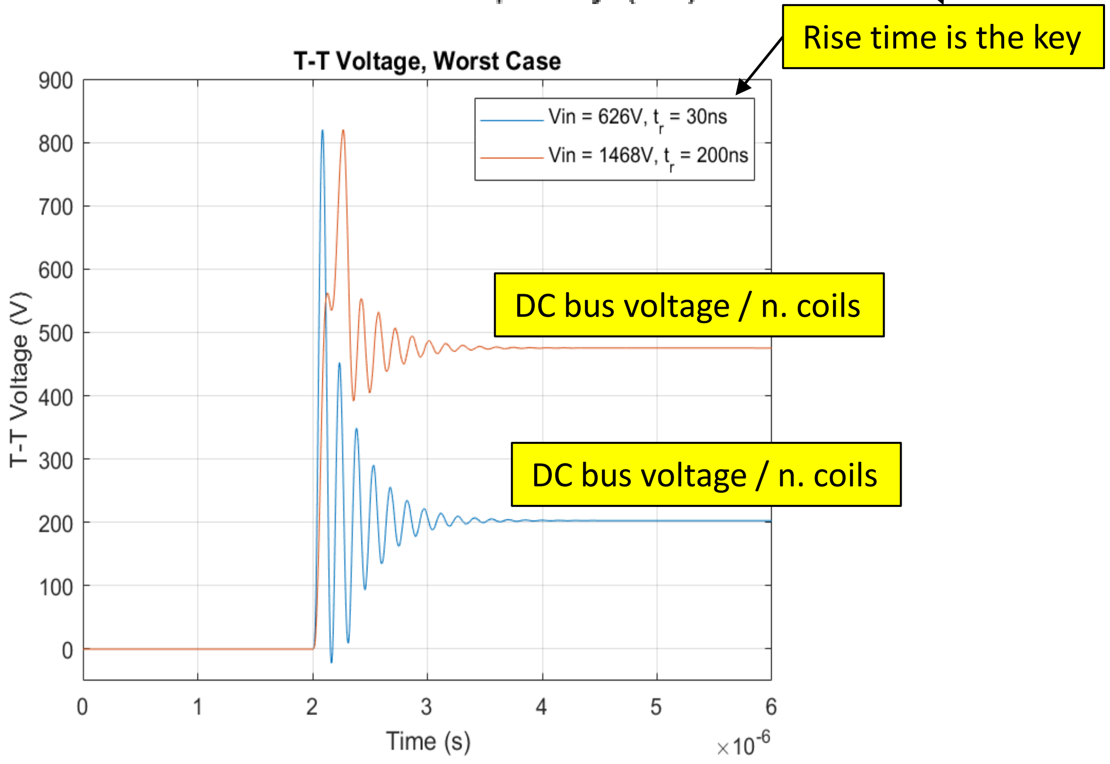


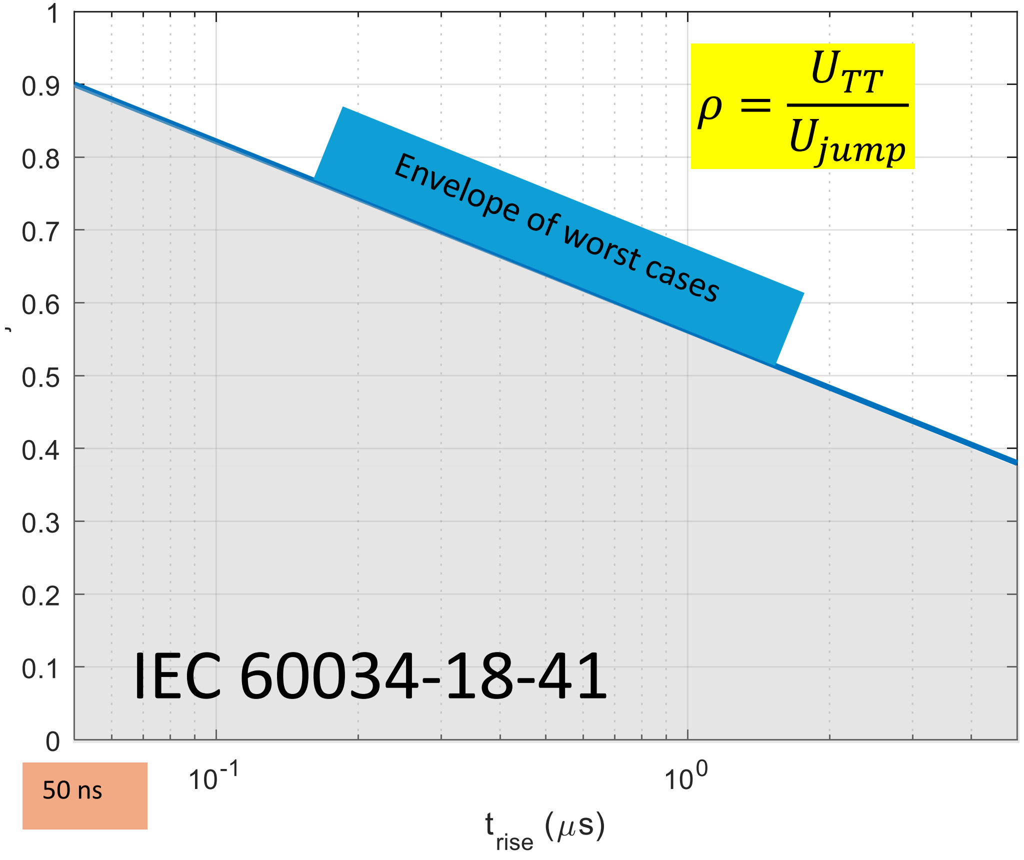
Very critical issue for random wound machines.
Random failures across machine population.

Much less important for hairpin machines

Uneven turn voltage distr.: Effect of rise time

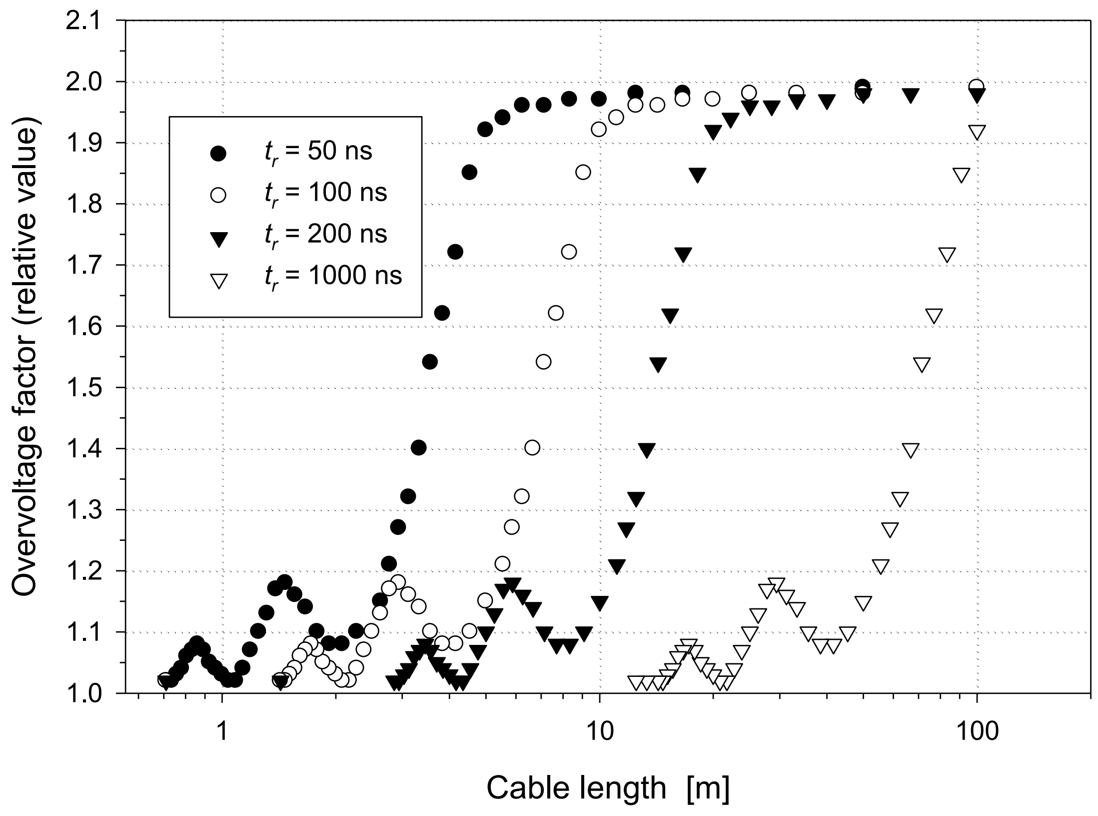




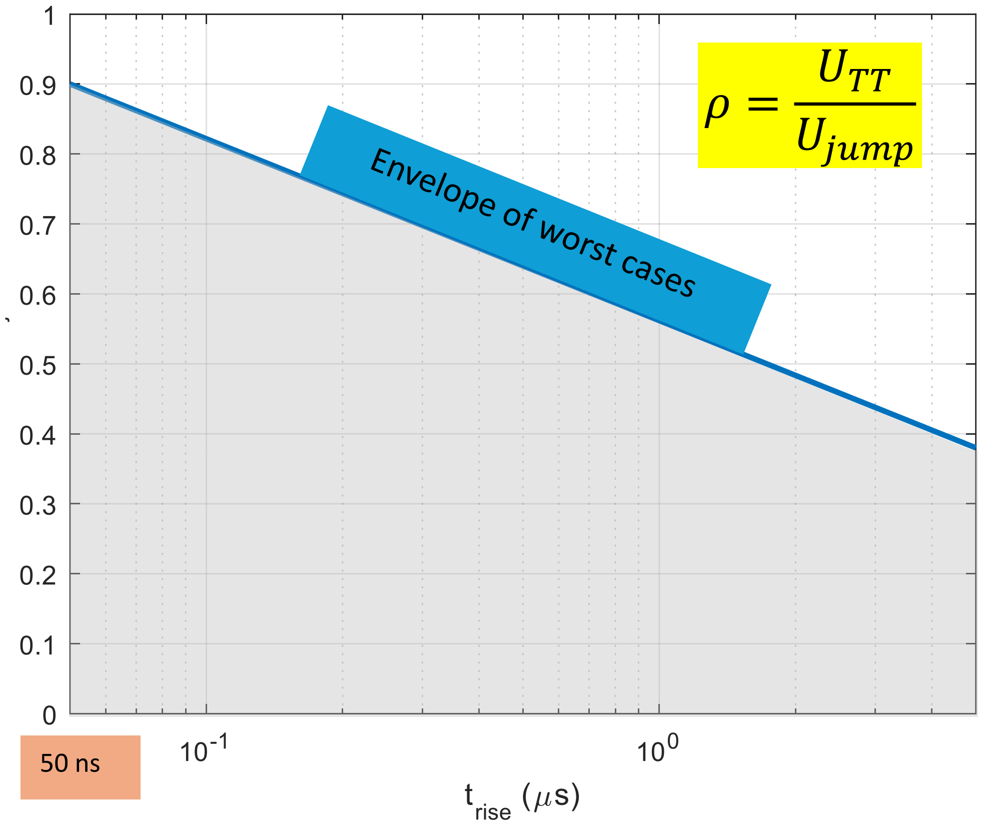


Summary

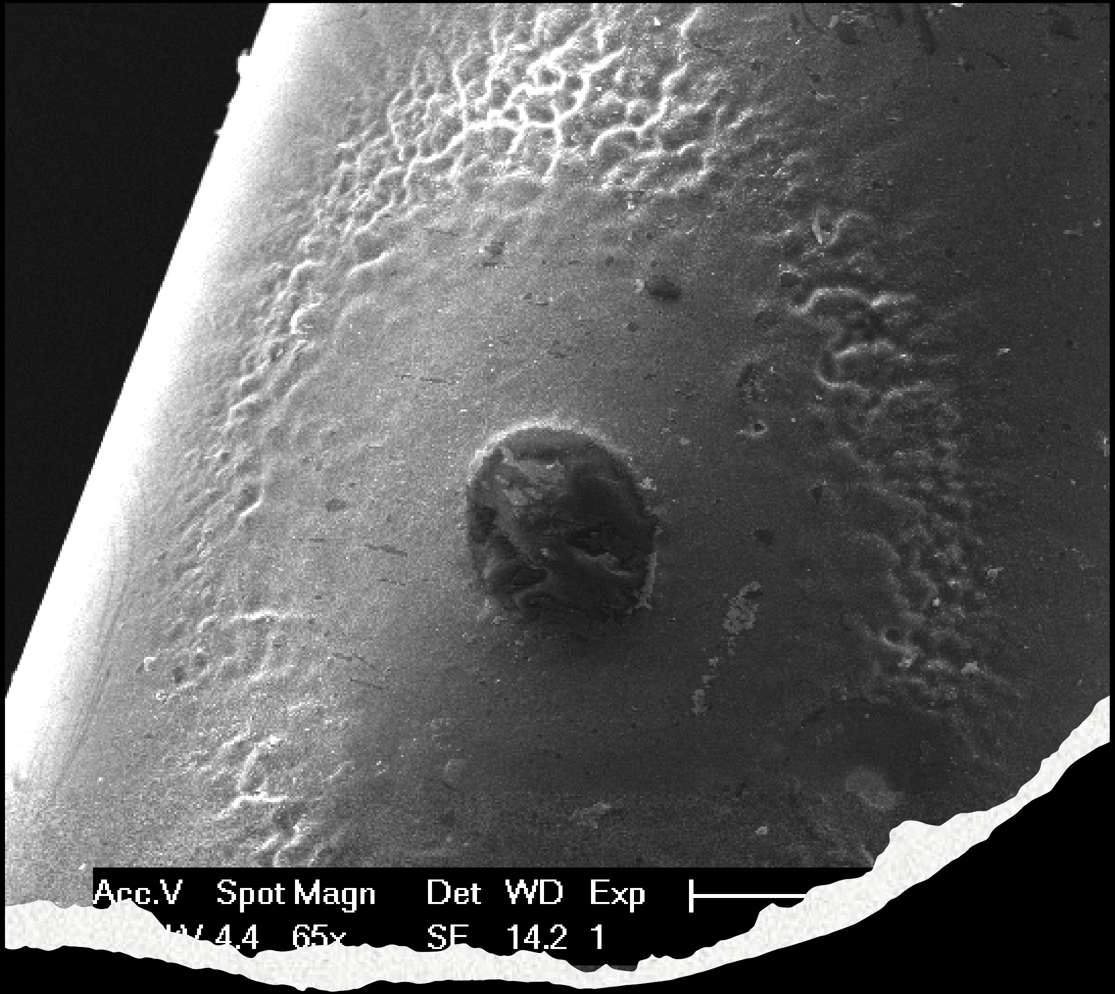
All insulation subsystems



Turn/turn insulation only



Partial Discharges



Voltage stress

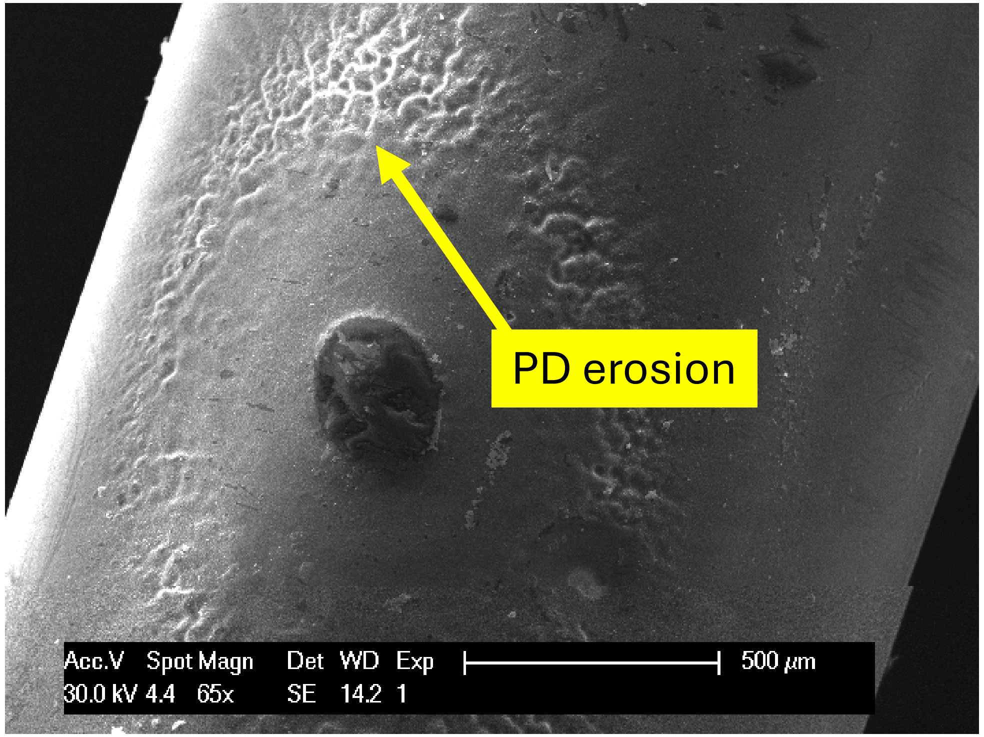
- Phase-to-phase
  - $U_{pk/pk} = 2 \times OF \times Udc$
- Phase-to-ground
  - $U_{pk/pk}=(2\times OF\text{-}1) \times Udc$
- Turn-to-turn (2-level inverter)
  - $U_{pk/pk}=(2\times OF\text{-}1) \times Udc \times \rho(Trise)\times 1.33$
- Voltage stress: phase-to-phase > phase-to-ground > turn-to.turn

- If OF$\rightarrow$2 and/or $\rho \rightarrow$1 there might be an excessive voltage on some parts of the insulation:
  - **Partial Discharges (PD) can be incepted**

Voltage stress

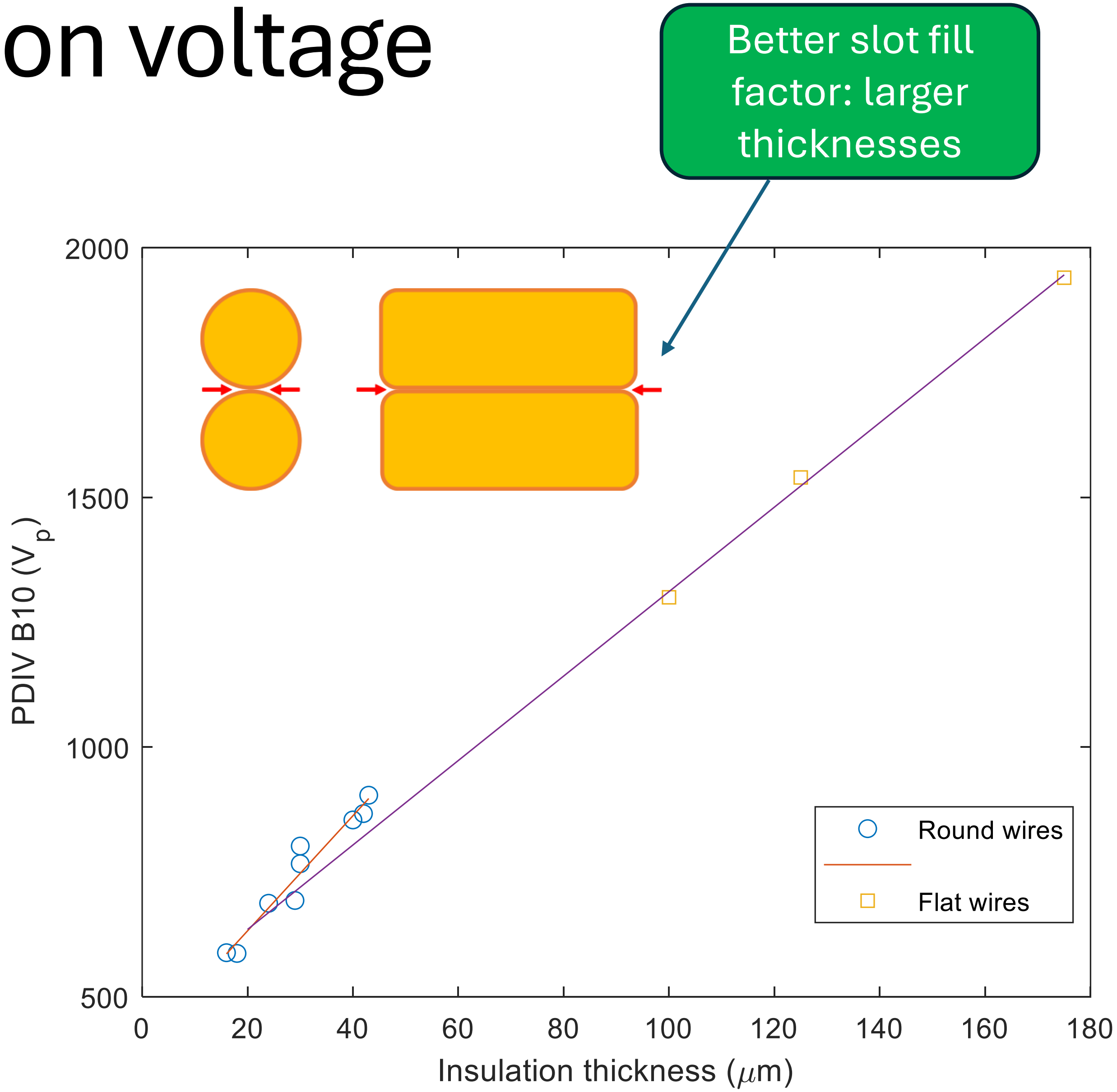
- PD: discharges that do not bridge the electrodes
  - deteriorate the insulation system over time

- **Under inverter waveforms, once PD are incepted the remaining life can be less than hours**
  - **Inverter switching frequency $\propto$ PD repetition rate**

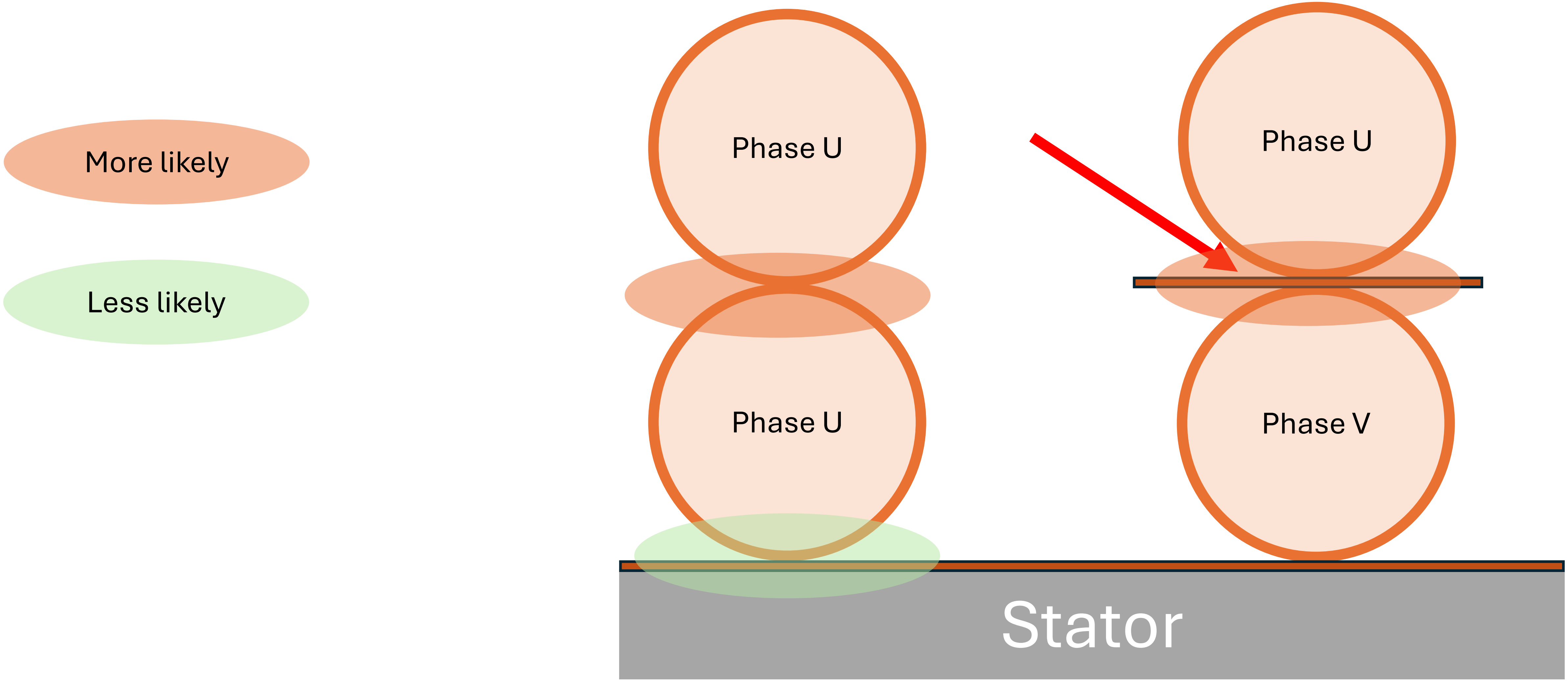


Partial discharge inception voltage

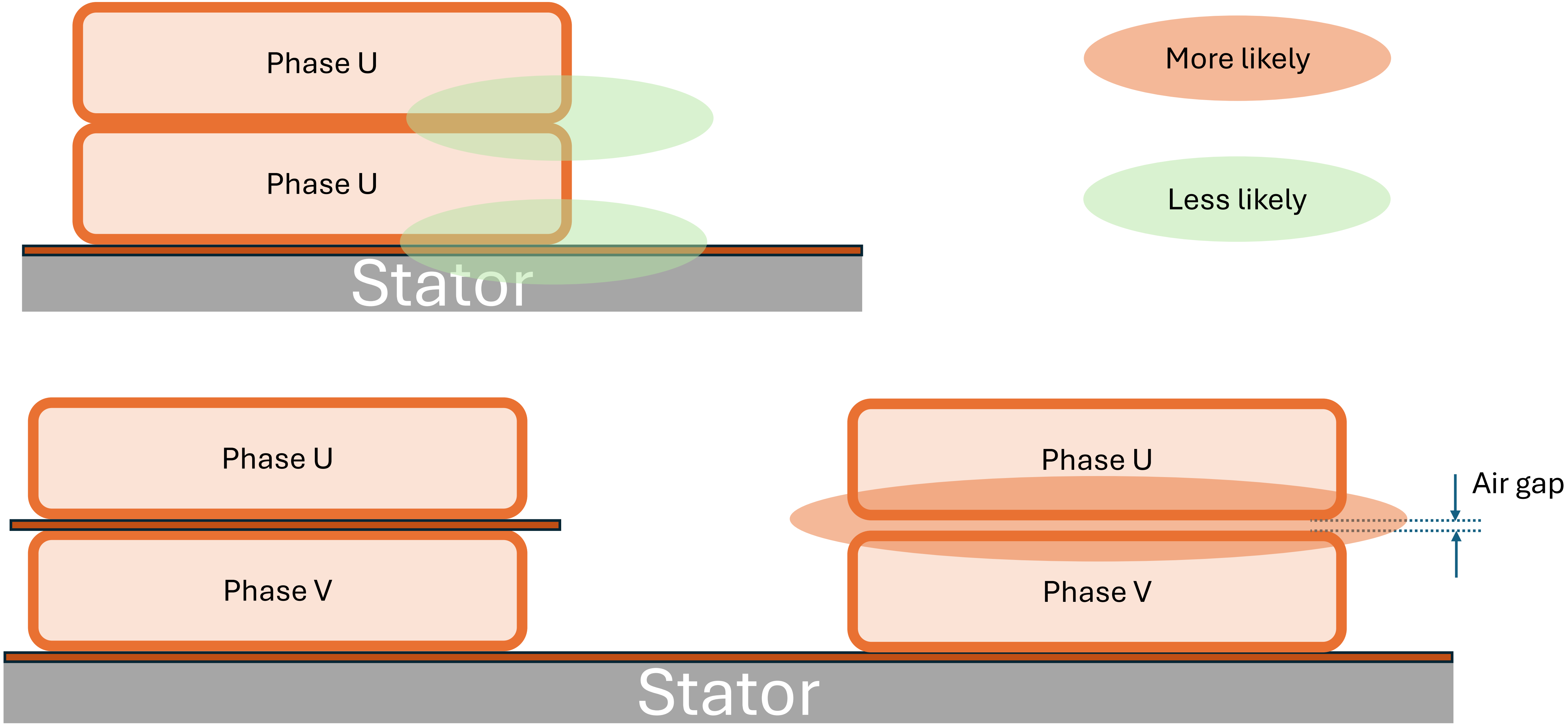
- The most important factor is insulation thickness
- Flat wires (hairpin stators) are typically thicker than round wires
    - Better slot fill factor
- The PDIV is much larger than that of round wires



Partial discharges in random wound machines



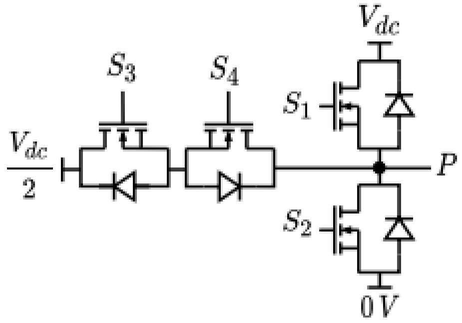
Partial discharges in hairpin machines

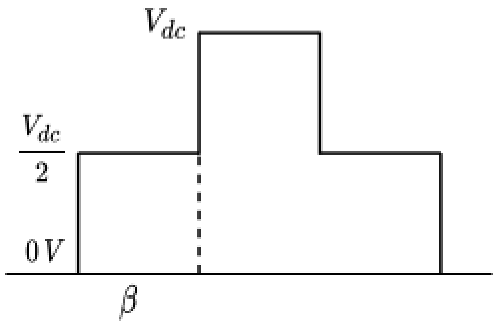


Solutions

System level

S_1	S_2	S_3	S_4	$Vout$
ON	OFF	ON	OFF	V_{dc}
OFF	ON	OFF	ON	$0V$
OFF	OFF	ON	ON	$V_{dc}/2$



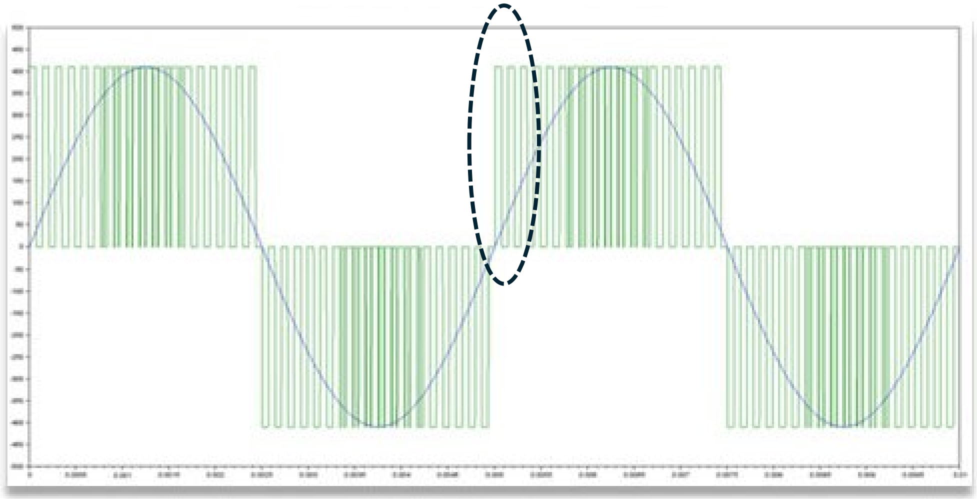


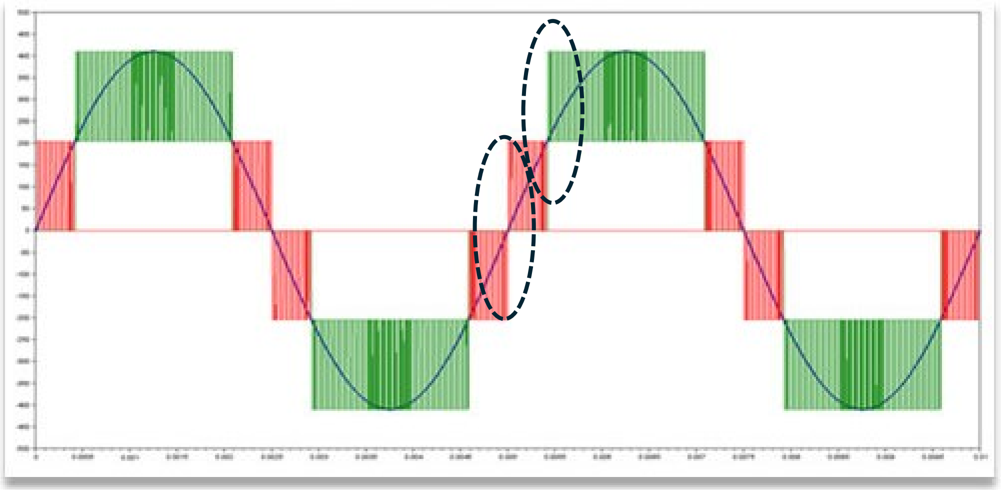
Drive-side solutions

- **Passive solutions**
  - Shorten the cables (if feasible)
  - Use filters (increase rise time at motor terminals)
- **Limit DC bus voltage**
  - SCR AC/DC bridges to limit
  - Limit regeneration (e.g., cranes)

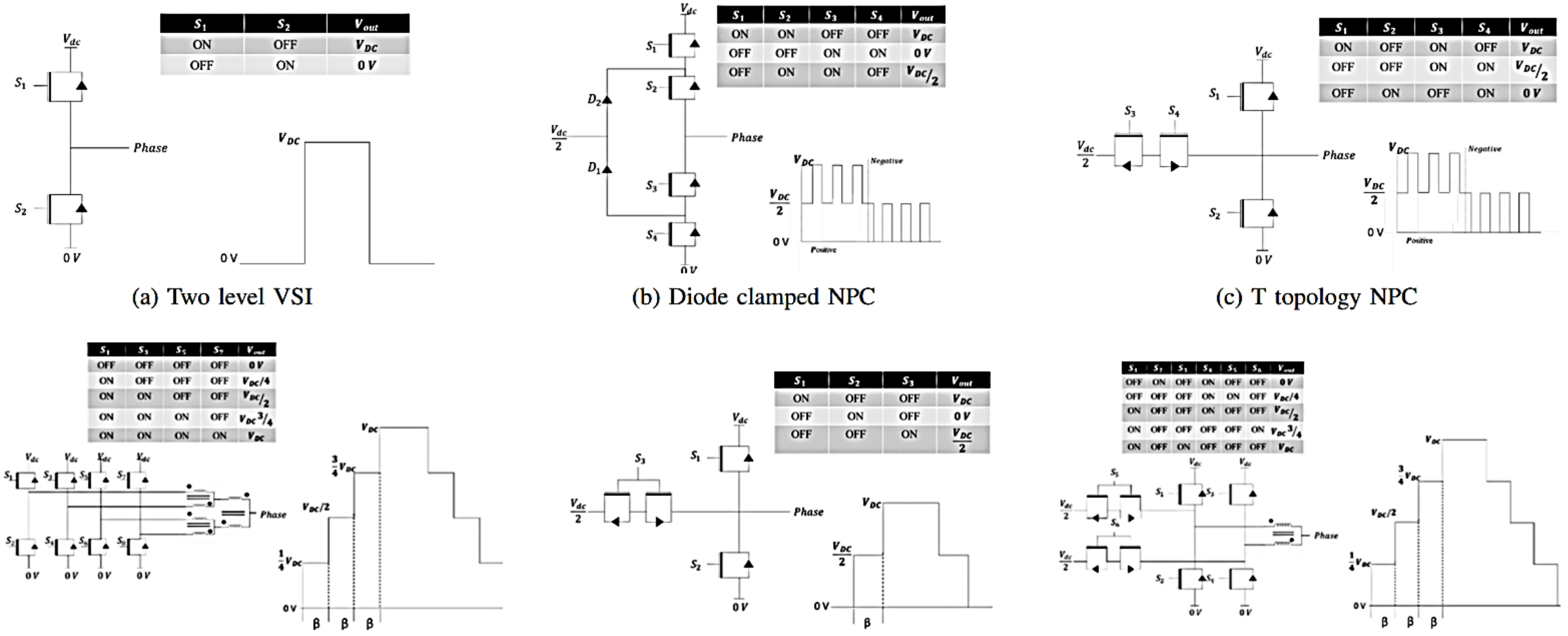
Drive-side solutions: power electronics

- Reducing the “jumps”:
  - Reduce the OF factor
  - Lower the stress on T/T insulation
    - Derivative system





Drive-side solutions: power electronics



S_1	S_2	V_{out}
ON	OFF	V_{DC}
OFF	ON	$0\,V$

(a) Two level VSI

S_1	S_2	S_3	S_4	V_{out}
ON	ON	OFF	OFF	V_{DC}
OFF	OFF	ON	ON	$0\,V$
OFF	ON	ON	OFF	$V_{DC}/2$

(b) Diode clamped NPC

S_1	S_2	S_3	S_4	V_{out}
ON	OFF	ON	OFF	V_{DC}
OFF	OFF	ON	ON	$V_{DC}/2$
OFF	ON	OFF	ON	$0\,V$

(c) T topology NPC

S_1	S_3	S_5	S_7	V_{out}
OFF	OFF	OFF	OFF	$0\,V$
ON	OFF	OFF	OFF	$V_{DC}/4$
ON	ON	OFF	OFF	$V_{DC}/2$
ON	ON	ON	OFF	$V_{DC}\,3/4$
ON	ON	ON	ON	V_{DC}

(d) Staggered switching

S_1	S_2	S_3	V_{out}
ON	OFF	OFF	V_{DC}
OFF	ON	OFF	$0\,V$
OFF	OFF	ON	$\frac{V_{DC}}{2}$

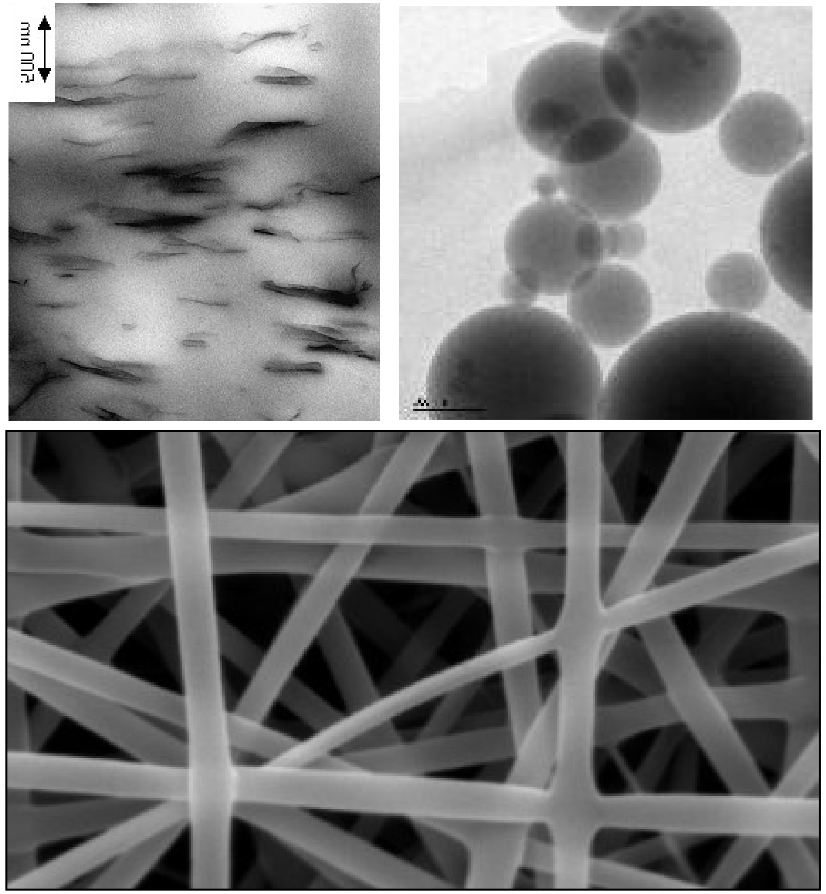
(e) Two level VSI with gradient reduction

S_1	S_2	S_3	S_4	S_5	S_6	V_{out}
OFF	ON	OFF	ON	OFF	OFF	$0\,V$
OFF	OFF	OFF	ON	ON	OFF	$V_{DC}/4$
ON	OFF	OFF	ON	OFF	OFF	$V_{DC}/2$
ON	OFF	OFF	OFF	OFF	ON	$V_{DC}\,3/4$
ON	OFF	ON	OFF	OFF	OFF	V_{DC}

(f) Multileg with gradient reduction

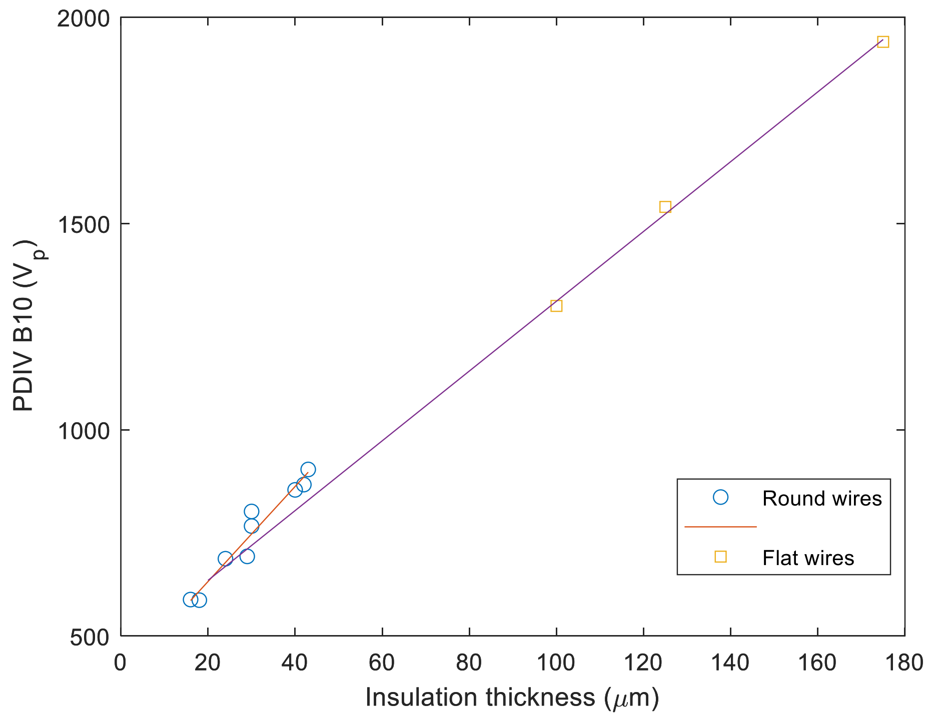
F. Savi, D. Barater, S. Nuzzo and G. Franceschini, "Evaluation of Inverter Architectures for Output Voltage Overshoot Reduction in WBG Electric Drives," *2021 IEEE 30th International Symposium on Industrial Electronics (ISIE)*, Kyoto, Japan, 2021

Insulation level



Machine-side solutions

- ***Increase insulation thickness***
  - Reinforce first coil/turns
- Cons:
  - Low power density of the machine
    - Low heat exchange capabilities
  - High total cost of ownership
    - High repair costs
    - Low maintainability
    - Low availability
  - Noise
  - Vibrations



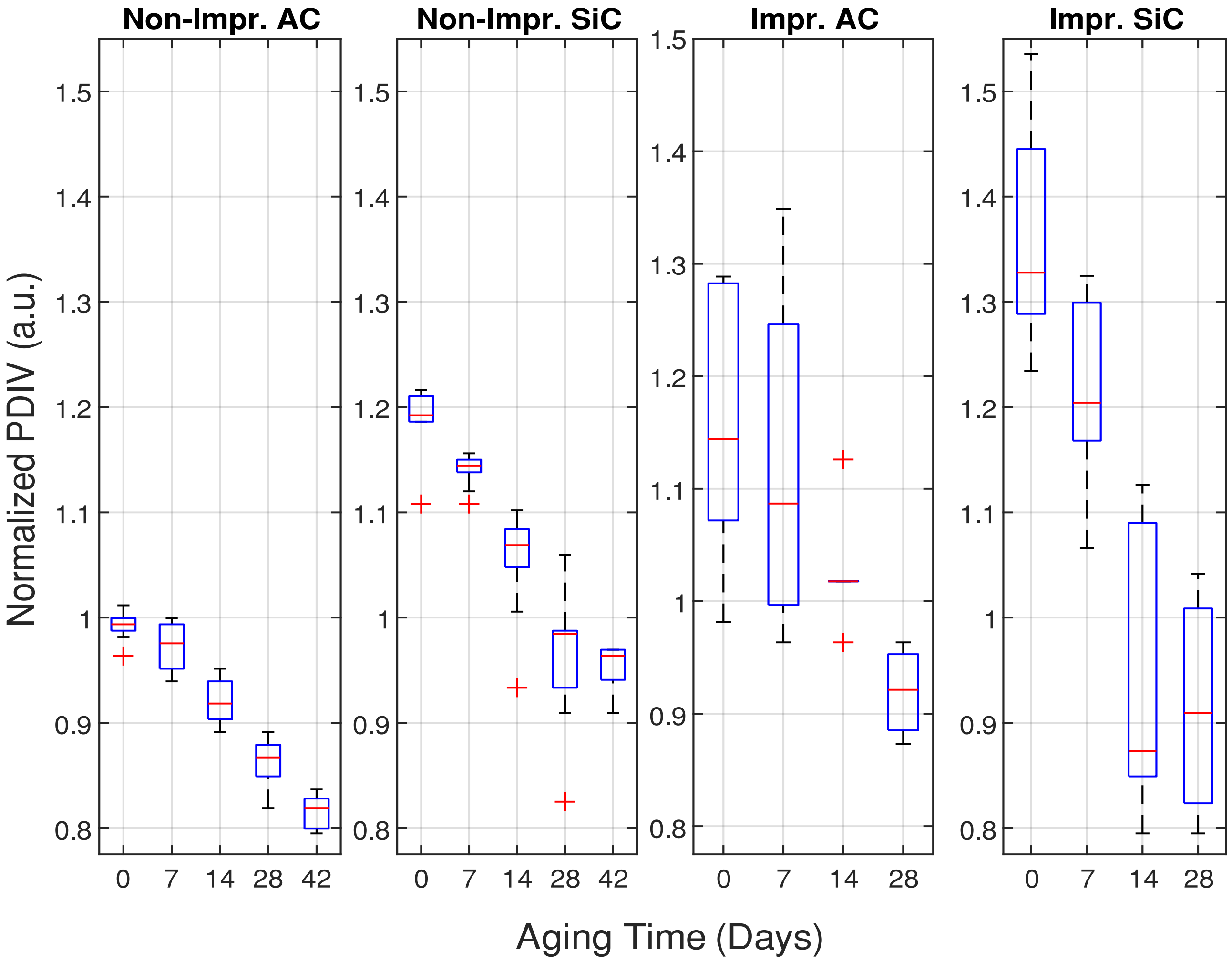
Machine-side solutions

- Thermal stress reduce PDIV over time
  - Accounted for in the design phase

- Reduce thermal stress

  - Use materials with a higher thermal class

  - Improve cooling



Machine-side solutions

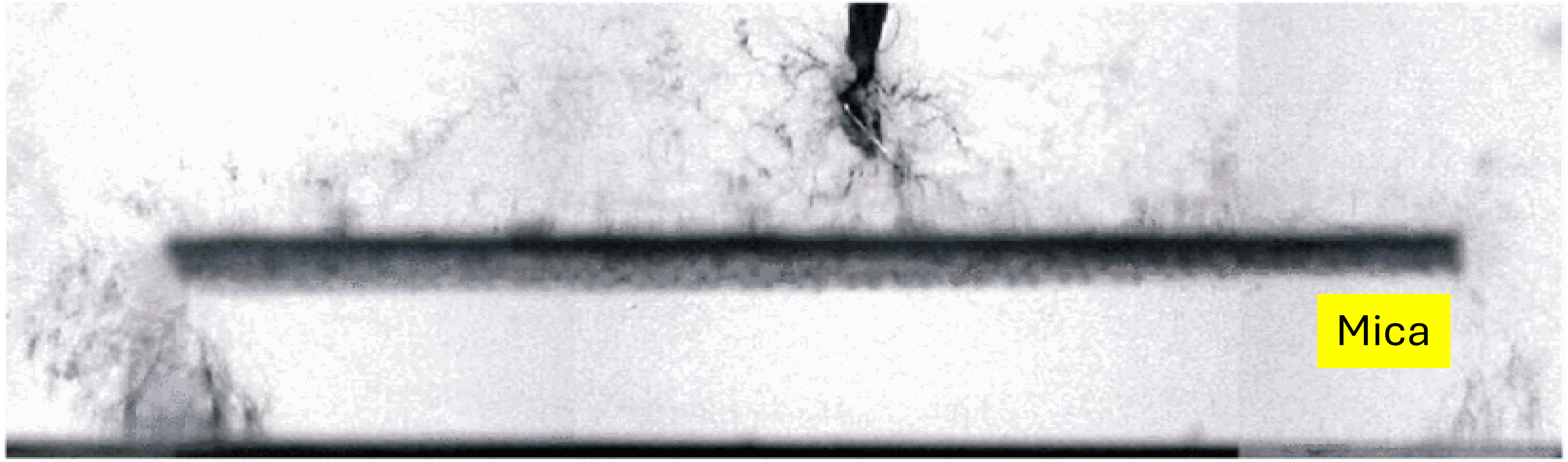
- Improve impregnation
  - Pros:
    - Avoid cavities (random wound machines)
    - Improve thermal exchange
  - Cons:
    - Longer times for manufacturing
      - Pre-heat the stator
      - Impregnate
      - Cure

Corona-resistant magnet wires

Corona-resistant materials

- Dielectrics loaded with nanoparticles
  - Inorganic nanoparticles, mostly metal oxides
    - Alumina, Titania, Magnesia,...
- Insulation system that have been nanostructured
  - Enamels (Corona-Resistant Magnet Wires)
  - Liners
  - Resins

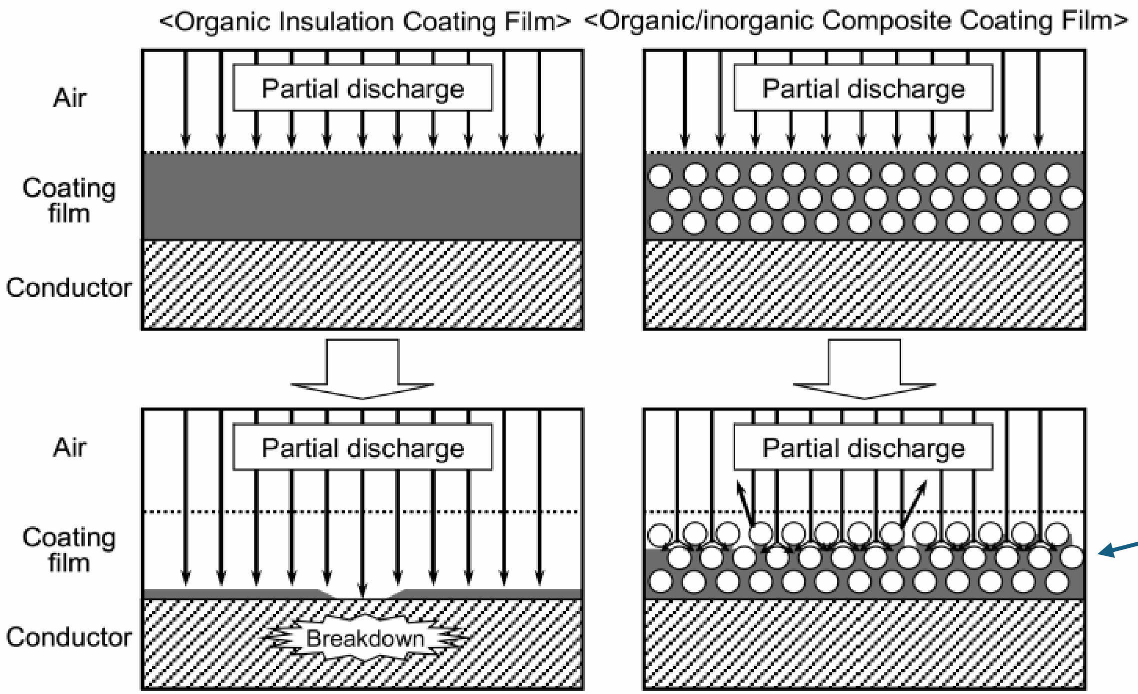
Inorganic materials act as barriers for PD erosion



- Treeing in the needle-plane arrangement. The mica tape acts as barrier for electrical trees

R. Bruetsch, M. Tari, K. Froehlich, T. Weiers and R. Vogelsang, "High Voltage Insulation Failure Mechanisms," Conference Record of the 2008 IEEE International Symposium on Electrical Insulation, Vancouver, BC, Canada, 2008, pp. 162-165, doi: 10.1109/ELINSL.2008.4570301.

Protection mechanisms: ceramic layer



What happens with vibrations?

H. Kikuchi and H. Hanawa, "Inverter surge resistant enameled wire with nanocomposite insulating material," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 1, pp. 99-106, February 2012, doi: 10.1109/TDEI.2012.6148507

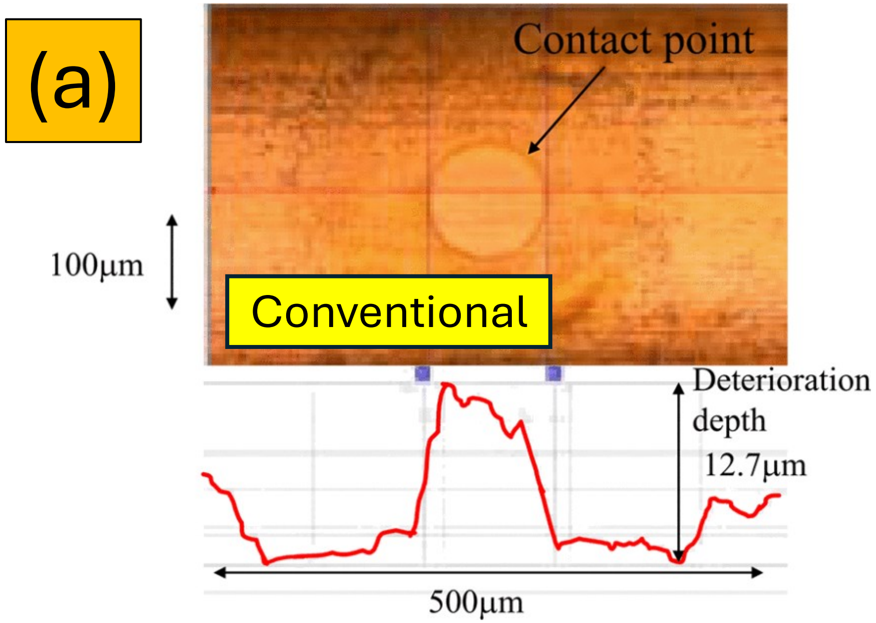
Erosion by PD and CR

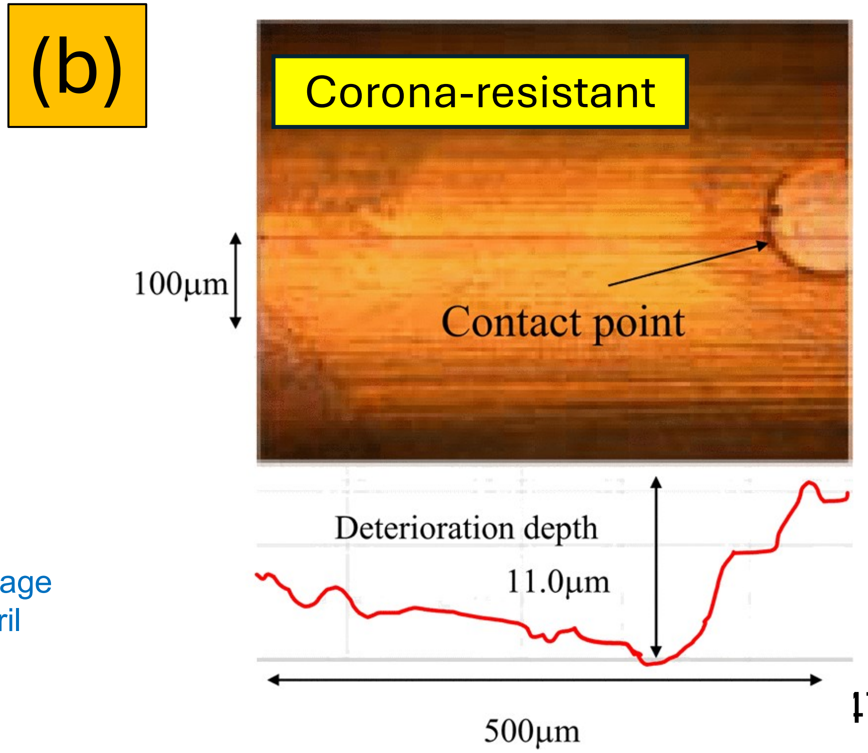
- Similar erosion depth, but time doubles

a. Conventional enameled wire
    - Surge voltage application: 0.22 h

b. CR enameled wire (wt%=1)
    a. Surge voltage application: 0.5 h

N. Hayakawa and H. Okubo, "Lifetime characteristics of nanocomposite enameled wire under surge voltage application [Feature article]," in *IEEE Electrical Insulation Magazine*, vol. 24, no. 2, pp. 22-27, March-April 2008



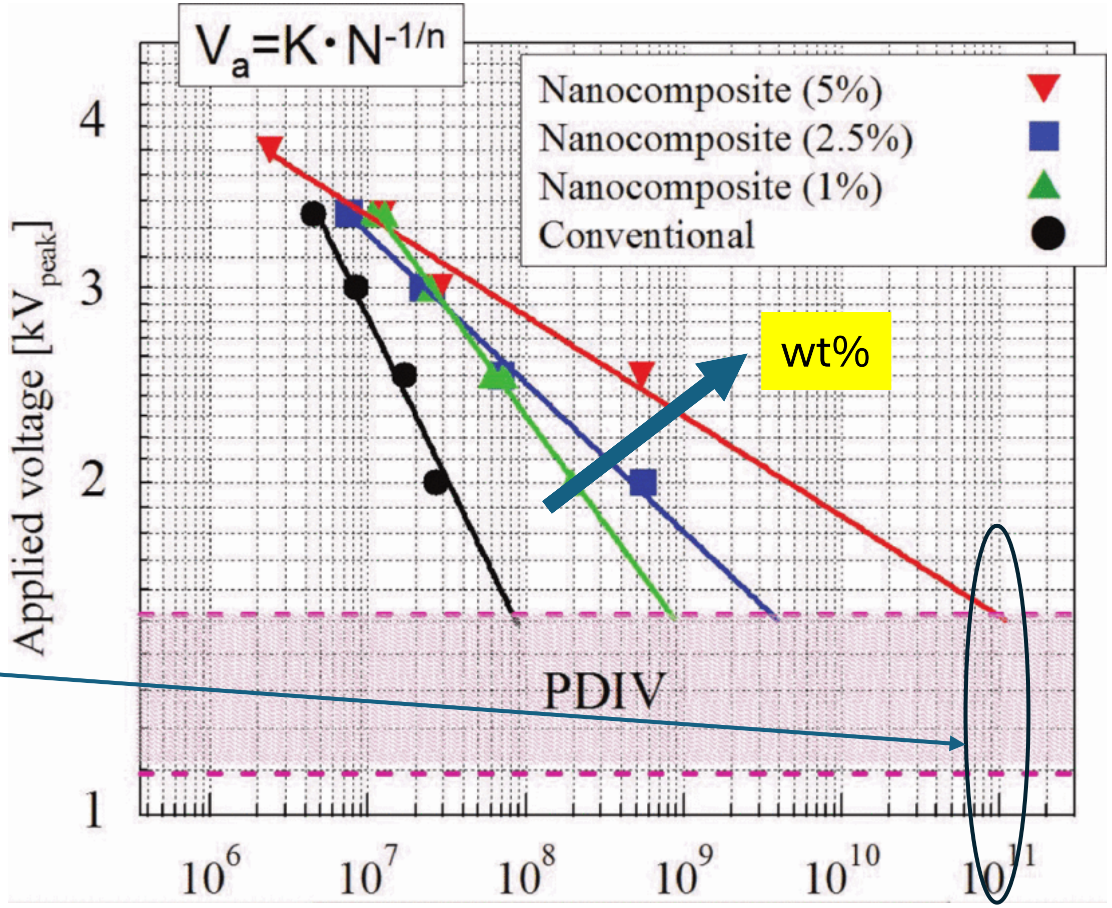


Lifetime

Hitoshi Okubo *et al.*, "Lifetime characteristics of nanocomposite enameled wire under surge voltage application," *2007 Annual Report - Conference on Electrical Insulation and Dielectric Phenomena*, Vancouver, BC, Canada, 2007, pp. 13-16,

- Lifetime increases by ~3 order of magnitudes
    - Insulation thickness: 20 μm
    - Pulse repetition rate: 10,000 pps

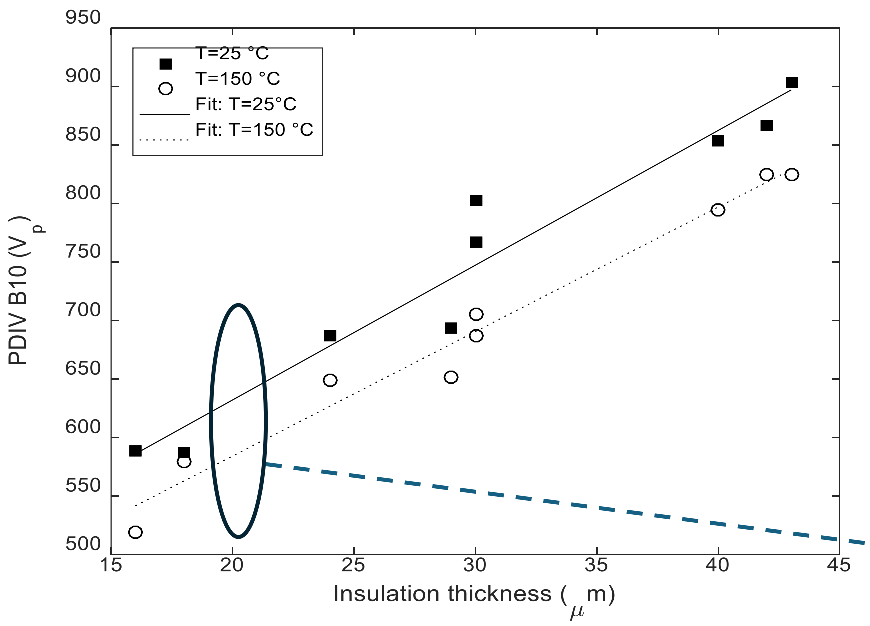
- My doubt.
    - Modern inverters: 40,000 pps
    - Assume $N = 10^{11}$
    - $t_{failure} = \frac{10^{11}}{4 \cdot 10^4} = 2{,}500{,}000\ s \sim 29\ days$



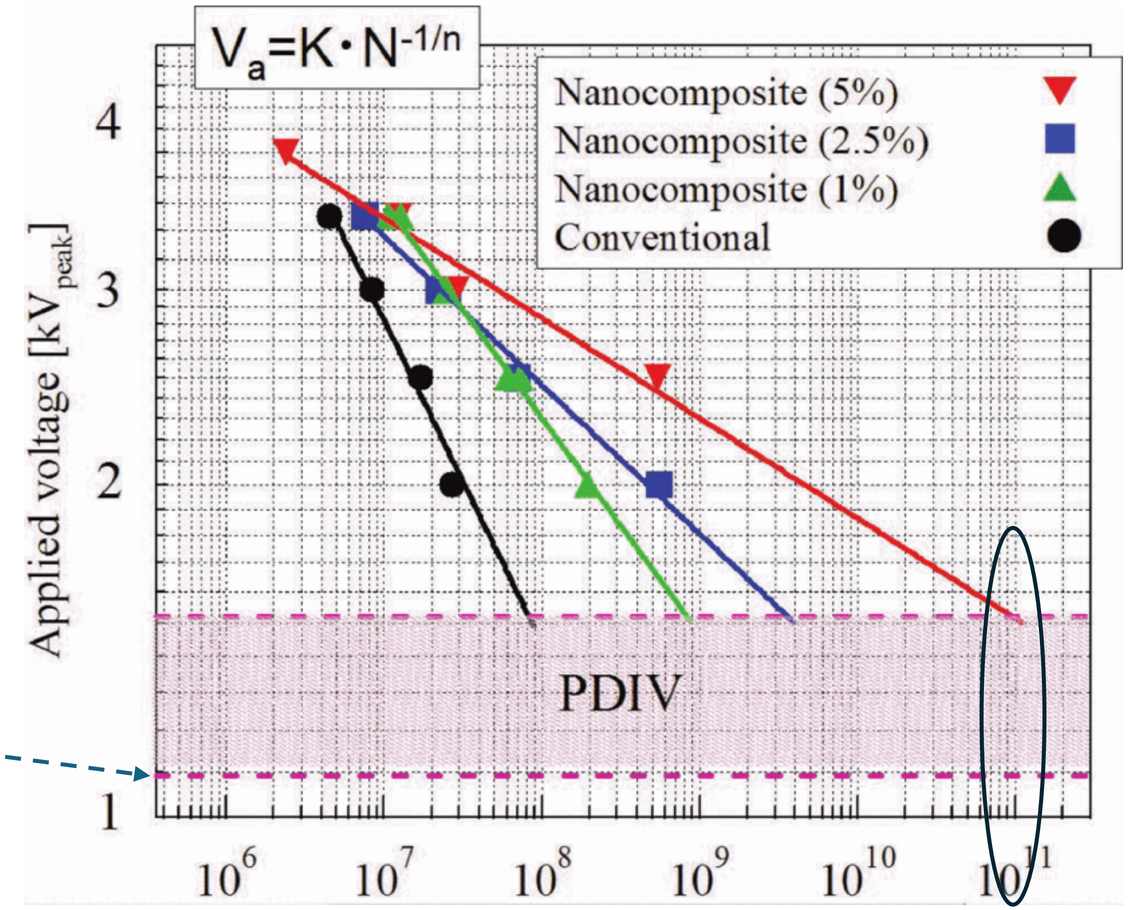
Number of cycles before breakdown

Lifetime, Okubo et al.

Hitoshi Okubo *et al.*, "Lifetime characteristics of nanocomposite enameled wire under surge voltage application," *2007 Annual Report - Conference on Electrical Insulation and Dielectric Phenomena*, Vancouver, BC, Canada, 2007, pp. 13-16,

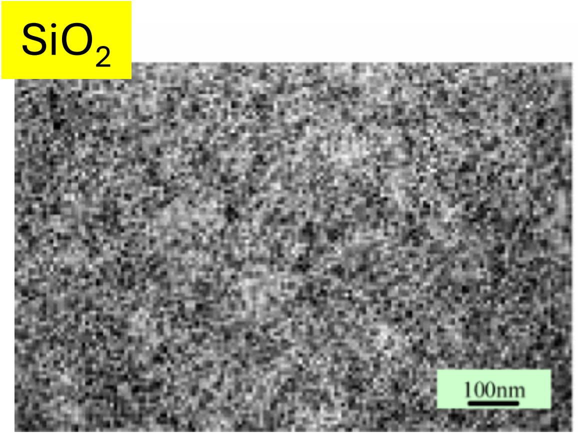


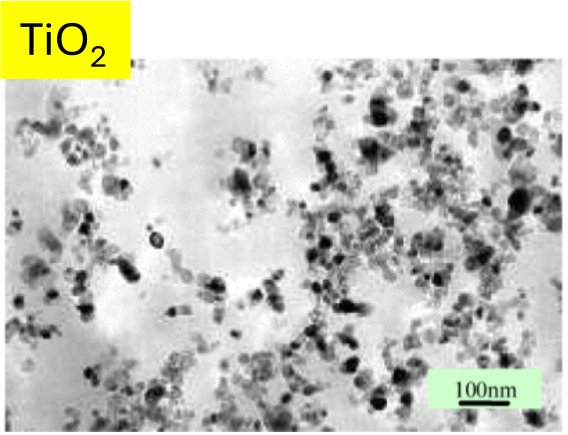
Probably PDIV is much lower

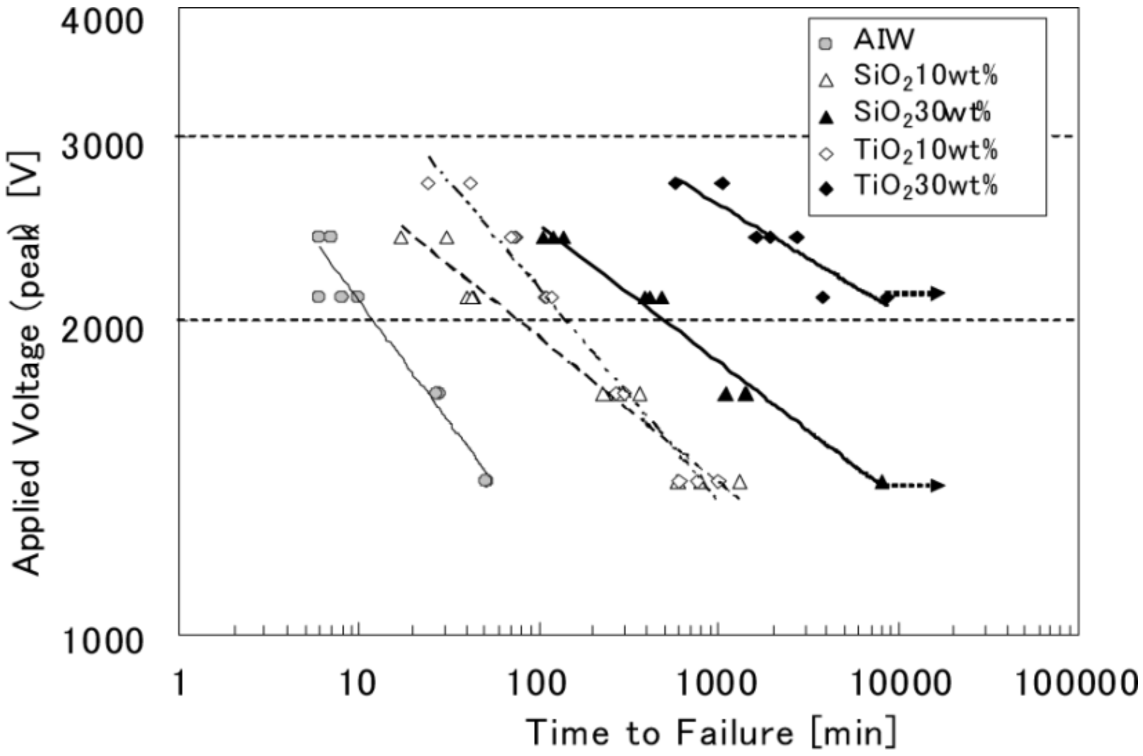


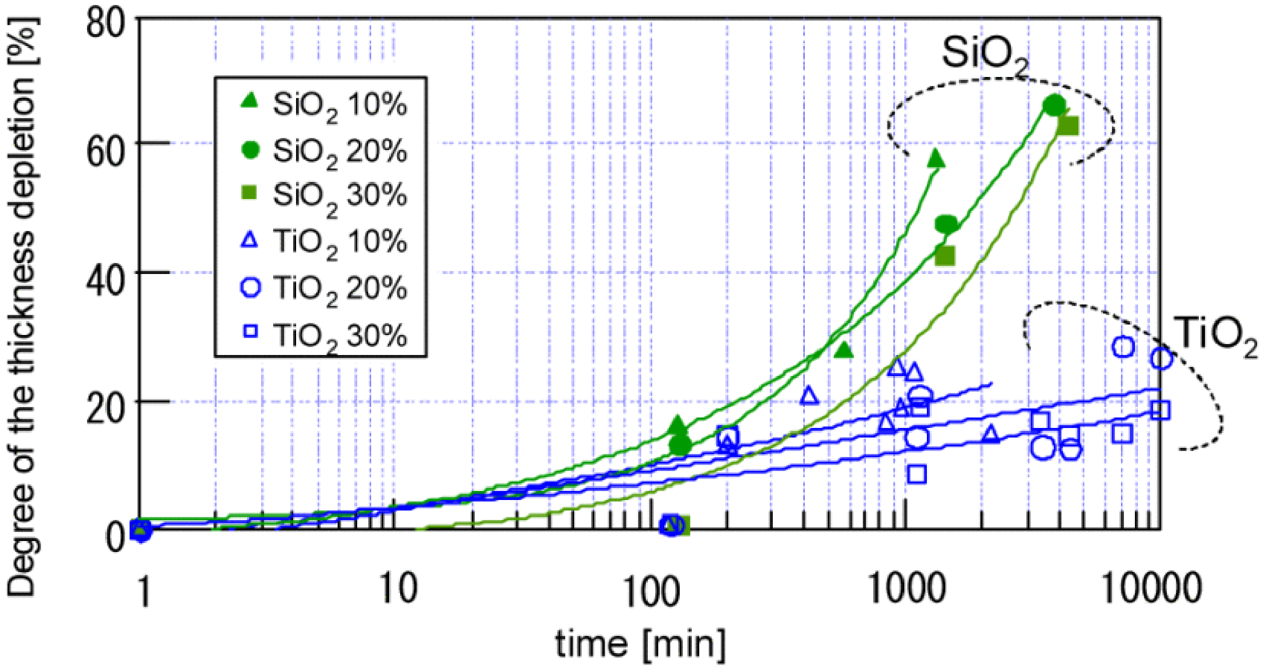
Number of cycles before breakdown

Lifetime, Hikita et al.



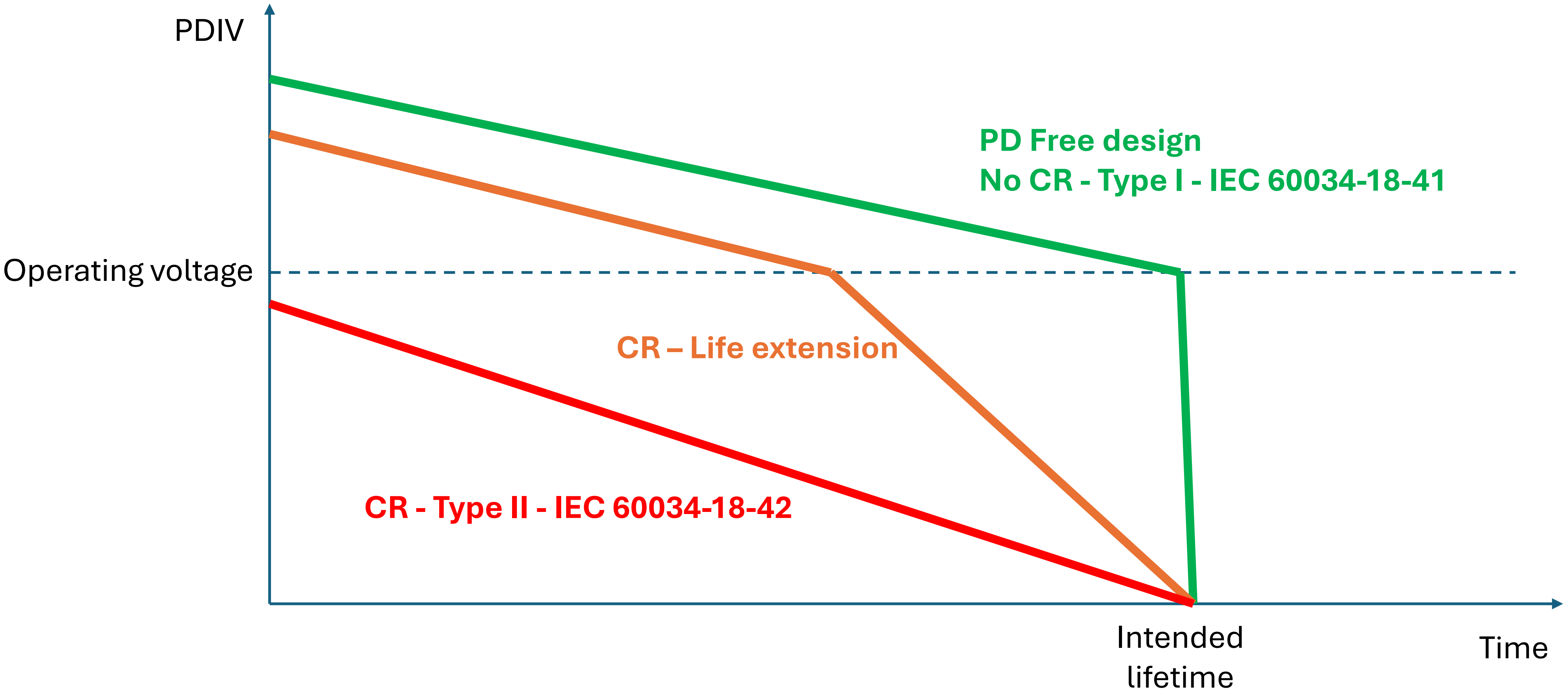






- M. Hikita et al., "Partial discharge endurence test on several kinds of nano-filled enameled wires under high-frequency AC voltage simulating inverter surge voltage," 2009 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Virginia Beach, VA, USA, 2009, pp. 719-722,

Scenarios



PDIV
Operating voltage
PD Free design
No CR - Type I - IEC 60034-18-41
CR – Life extension
CR - Type II - IEC 60034-18-42
Intended lifetime
Time

Conclusions

Conclusions

- Inverters increase the electrical stress on the machine insulation

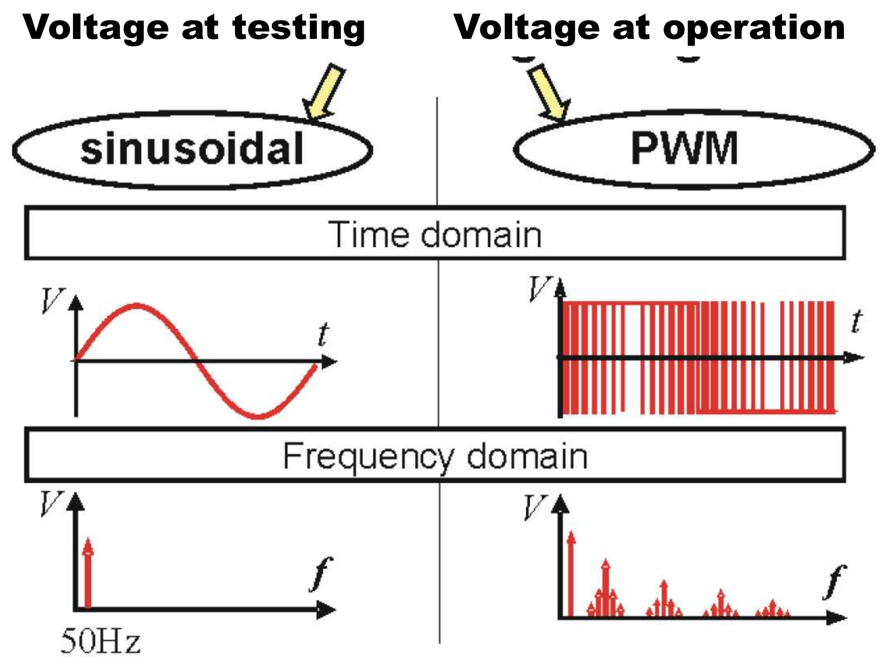
- Main parameters:
  - Cable length
    - The longer the larger the stress
  - Rise time
    - The shorter the larger the stress
  - Inverter frequency
    - the larger the shorter the remaining life after PD inception

- SiC or GaN inverters are an issue for the machine insulation

- Solutions
  - Drive side
    - More complex inverter
    - Lower reliability

  - Machine side
    - Thicker insulation
    - CR magnet wires

- How to properly design with CR magnet wires remains an open point



High voltage power electronic converters: Dielectric performance: stresses and testing

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SINTEF Energi AS
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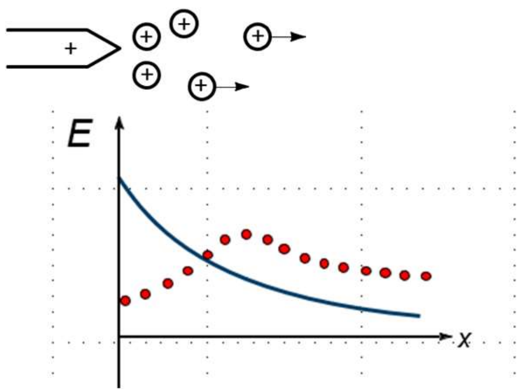
Topics

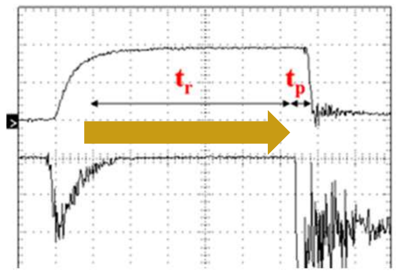
- Partial discharges
- Defects
- Sine vs switched voltages
- Effect of slew rate
- Partial discharge signatures
- Space charge and electric fields
- PD detection at switched voltages

A discharge is an electron avalance: What governs inception?

- The electric field has to be above E_{crit}:
  - Field is high at sharp edges
  - Space charge can reduce field
  - Timeconstant of charging depend on conductivity
  - For fast slew rate time for getting space charge may be too short



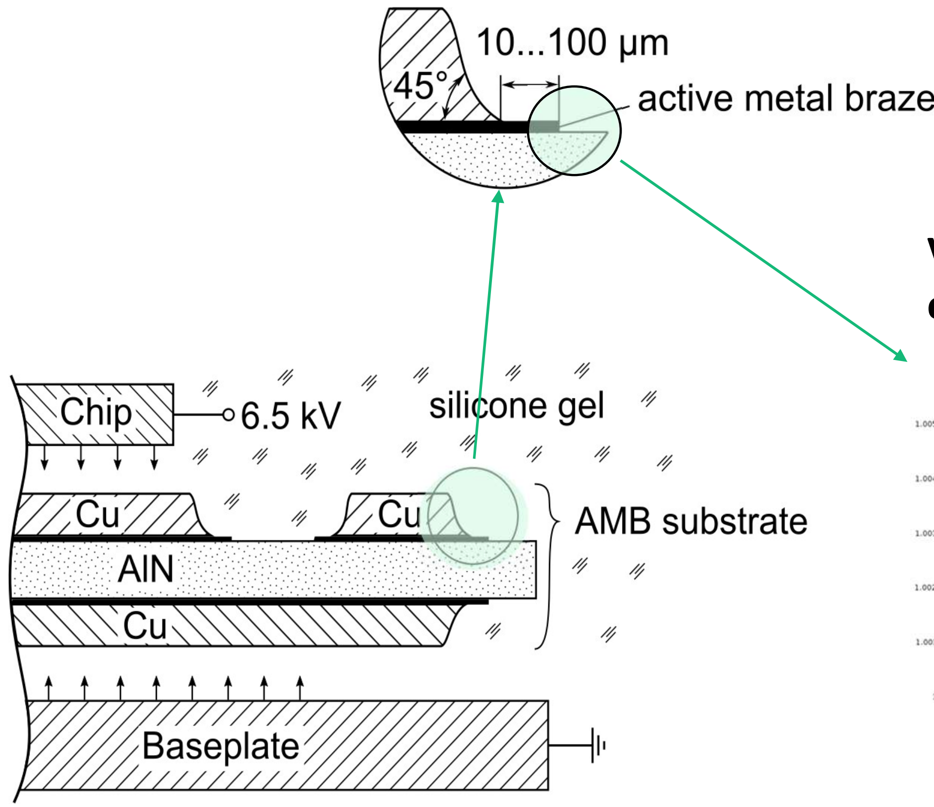
- There has to be an electron in the high field region
  - When electron becomes available the discharge starts
  - Waiting time is a statistical parameter



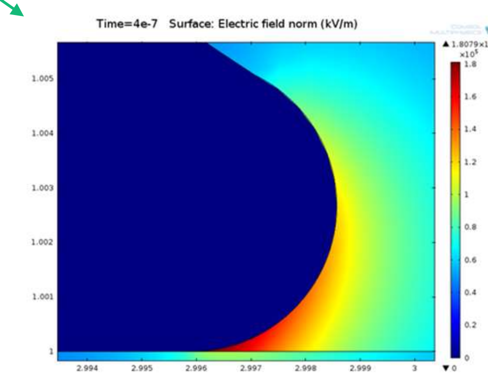
Converter insulation
Defects and diagnostics at sine and switched voltages

Electrical insulation of IGBT modules

- Ceramic substrates (AlN, Al_2O_3, Si_3N_4)
- Silicone gel
- Polymer case



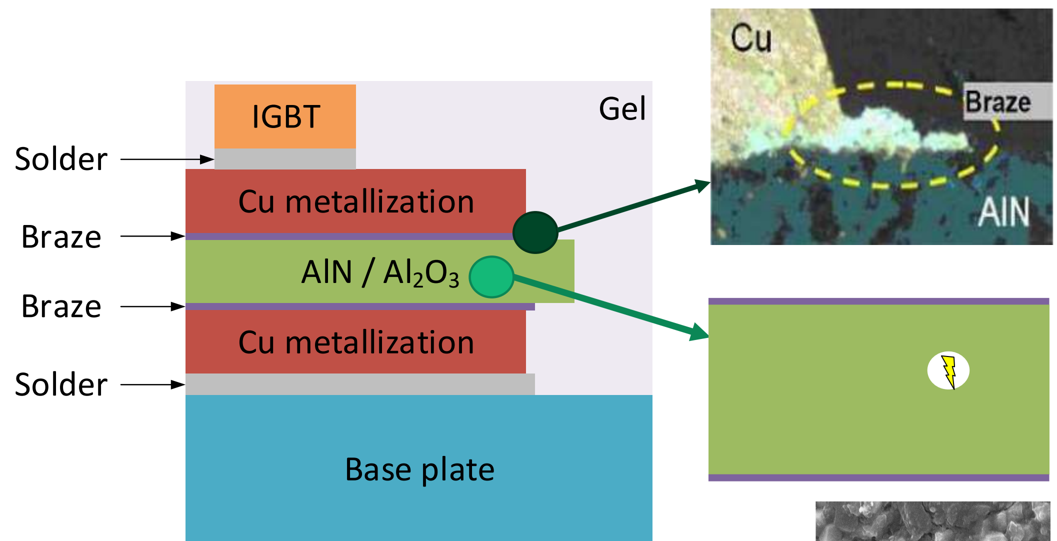
Very high electric fields:
e.g. at 7 kV -> 180 kV/mm

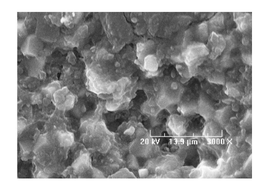


Partial discharge may occur at «defects» in power modules

- Field enhancement at sharp edges at tripple points ($Cu/Al_2O_3/Gel$)
- Delamination of varnish at triple points
- Voids inside substrates (AlN, Al_2O_3)

Ghassemi, M., Geometrical Techniques for Electric Field Control in (Ultra) Wide Bandgap Power Electronics Modules, EIC 2018.

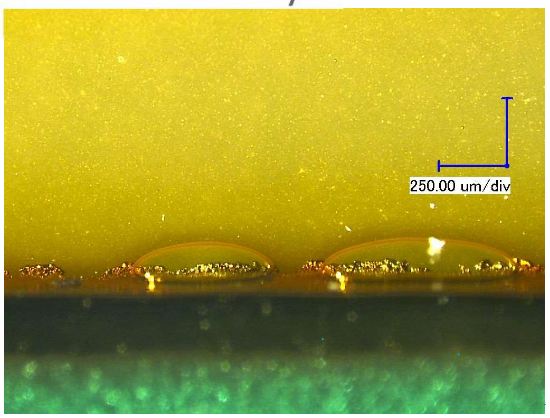




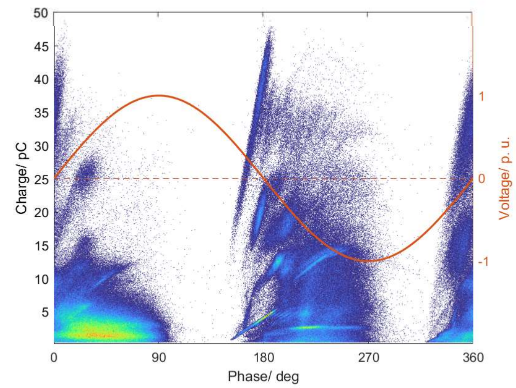
J.-L. Augé et al.: Partial Discharges in Ceramic Substrates Embedded in Liquids and Gels, TDEI 2013

Different defects has different characteristics:
May be identified by phase resolved PD measurement

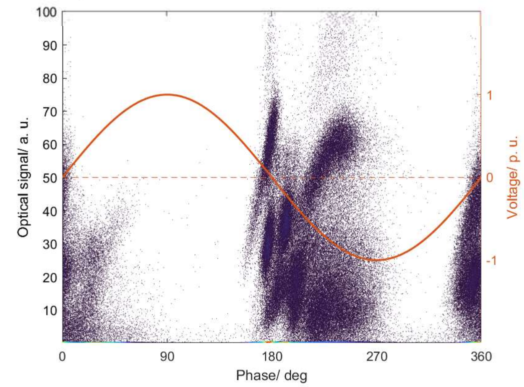
Gas filled cavity



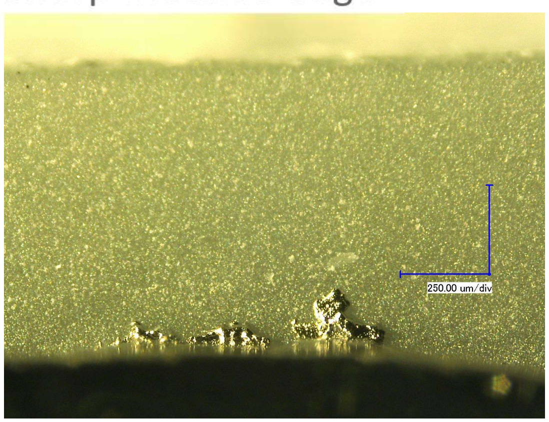
Electrical measurement



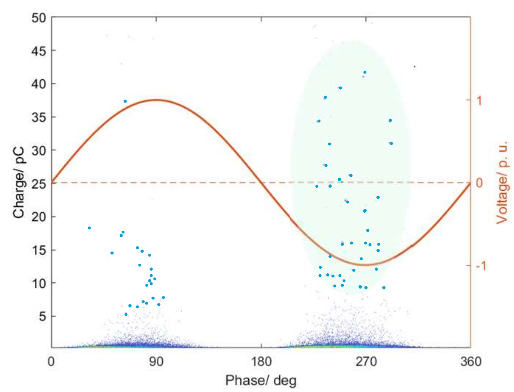
Optical measurement



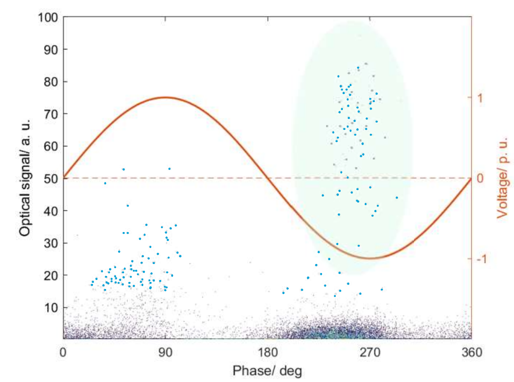
Sharp metallic edge



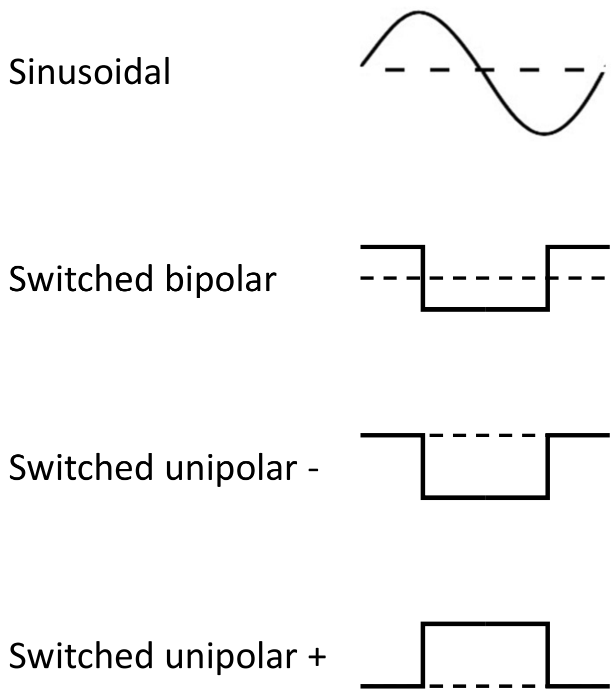
Electrical measurement

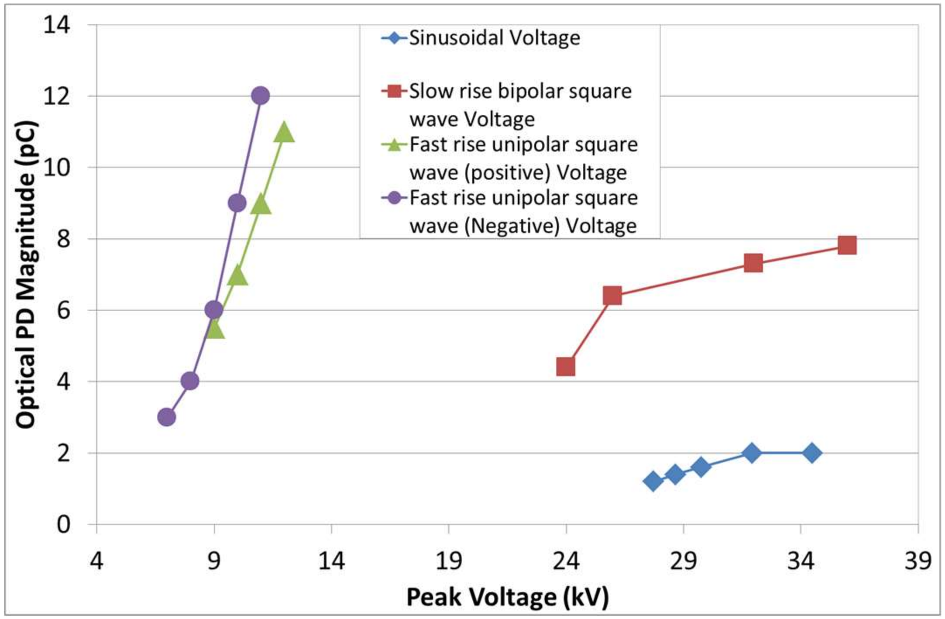


Optical measurement



PD inception and magnitude for sine and switched voltages - measured at triple point with photomultiplier

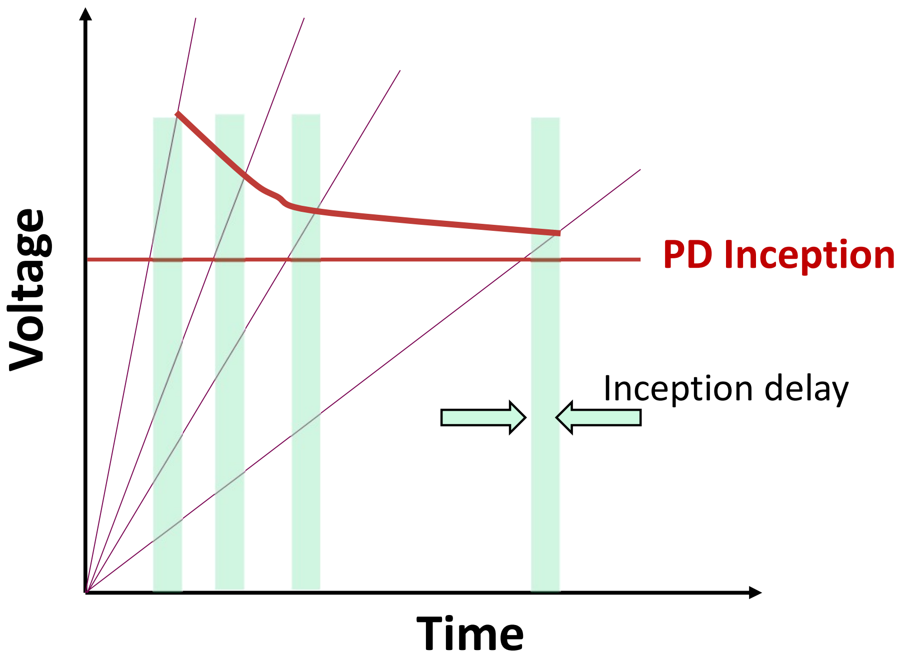




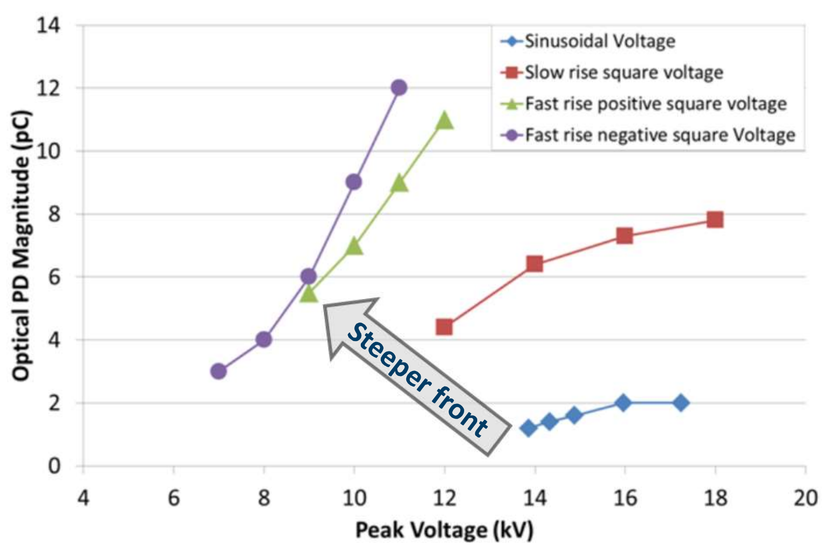
- ✓ **Large reduction of Inception voltage at fast rise time**
- ✓ **Increased PD magnitude**

Discharge level increases at increasing slew rate

Increasing overvoltage

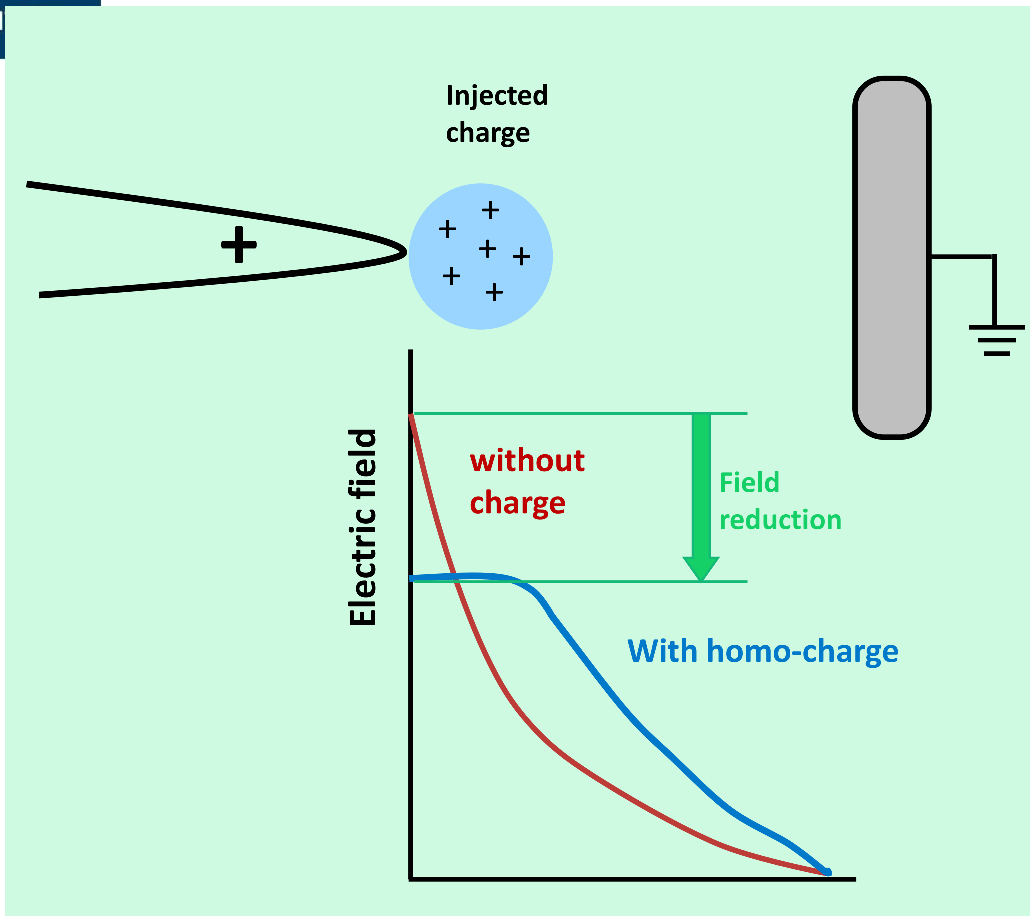


Increasing discharge magnitude



Electric field - spacecharge & field distortion

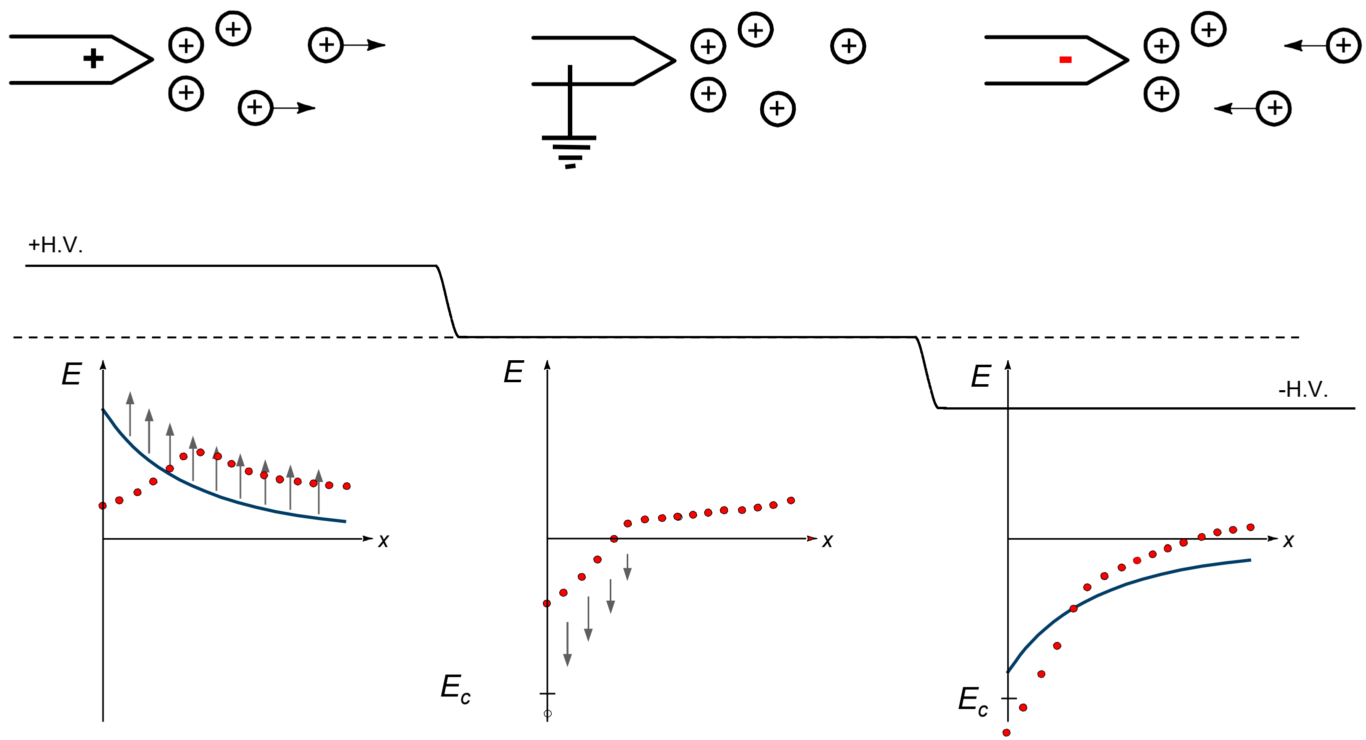
Space charge of same polarity will reduce maximum field



- It takes time to transport charge, depending on ion mobility of gel
- With increasing slew rate field reduction from space charge will diminish and electric field increase

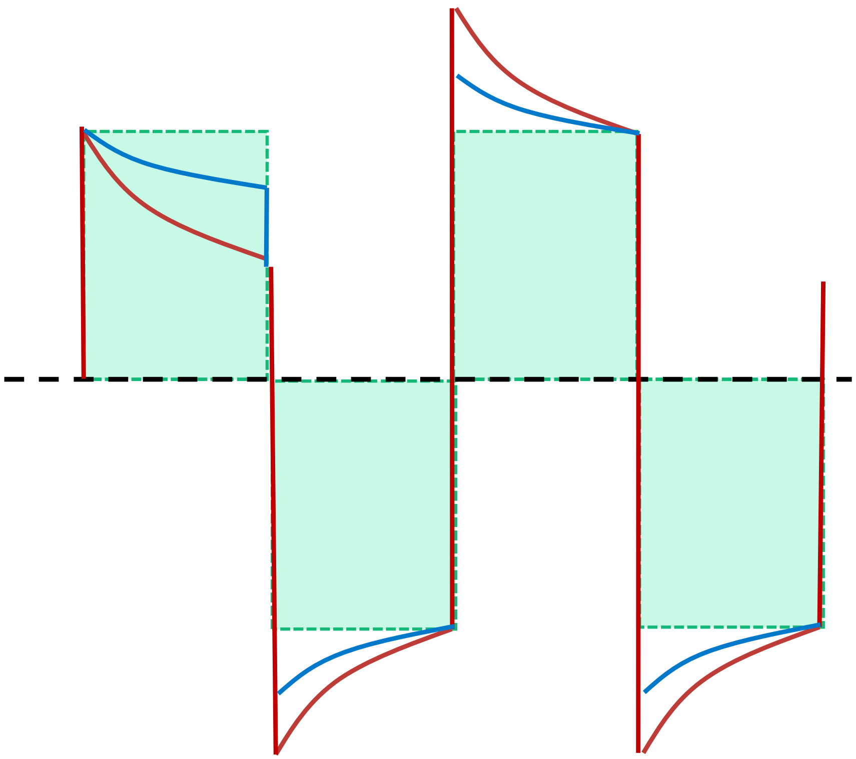
Polarity reversal on DC pre-stressed insulation

Field-enhancement from space-charge

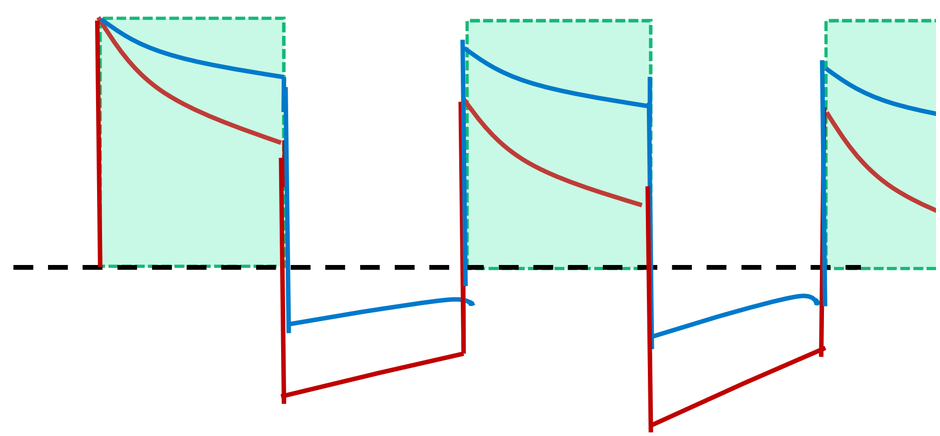


Space charge governed electric field at conductor edge at switched voltages

Bipolar -> field uncrease



Unipolar : field reduction



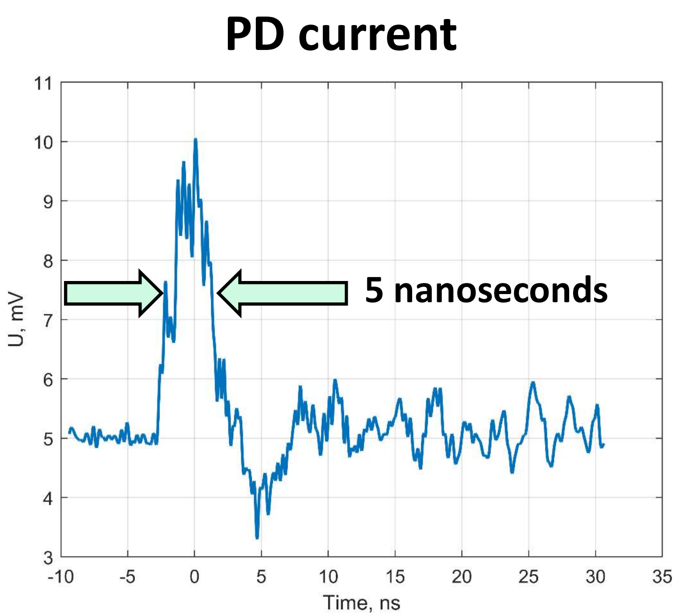
Space charge effects governed by gel conductivity:

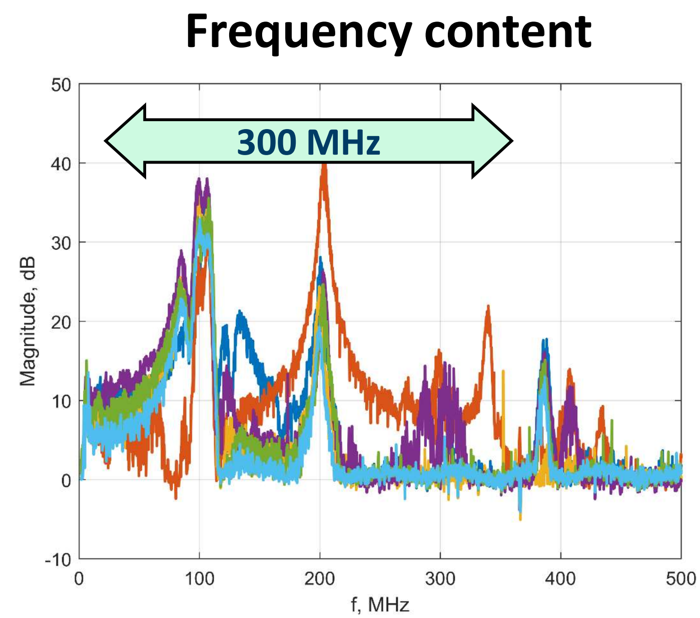
High conductivity

Low conductivity

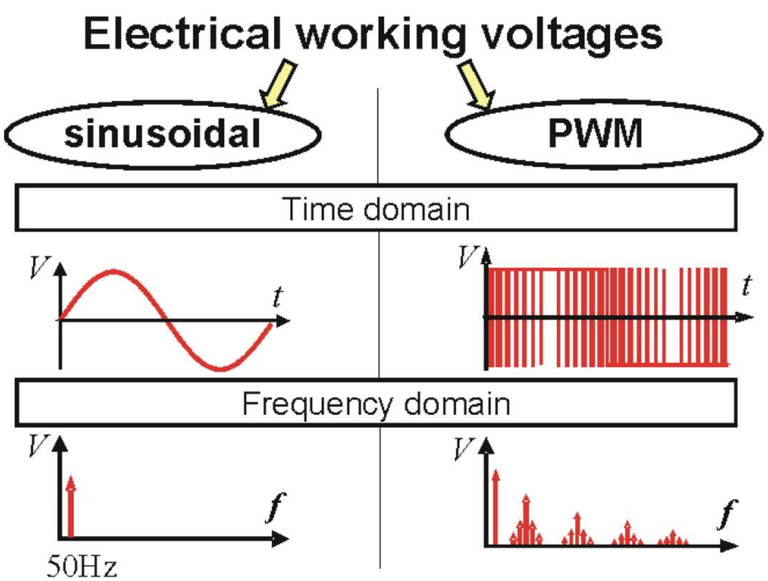
PD detection – conventional and VHF/UHF

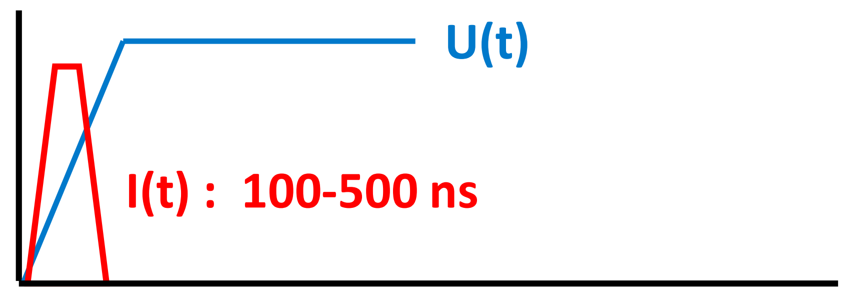
A PD current represent a charge displacement and contain compoinents over a wide frequency range

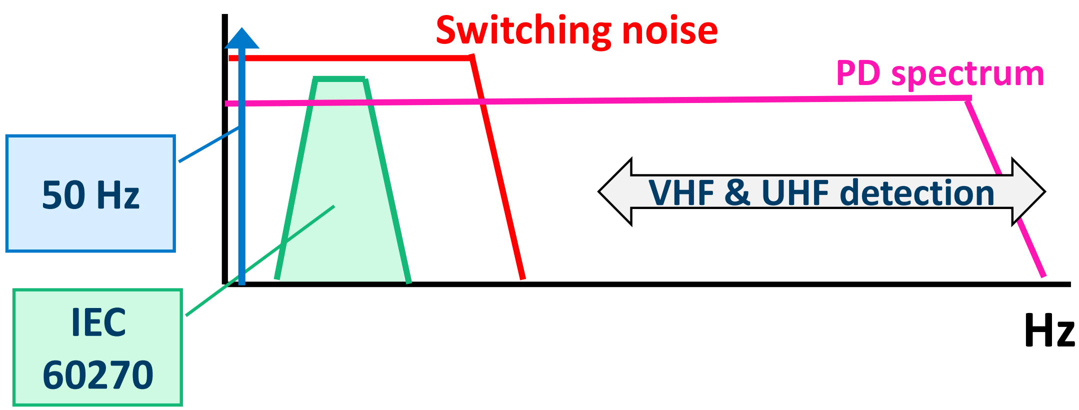




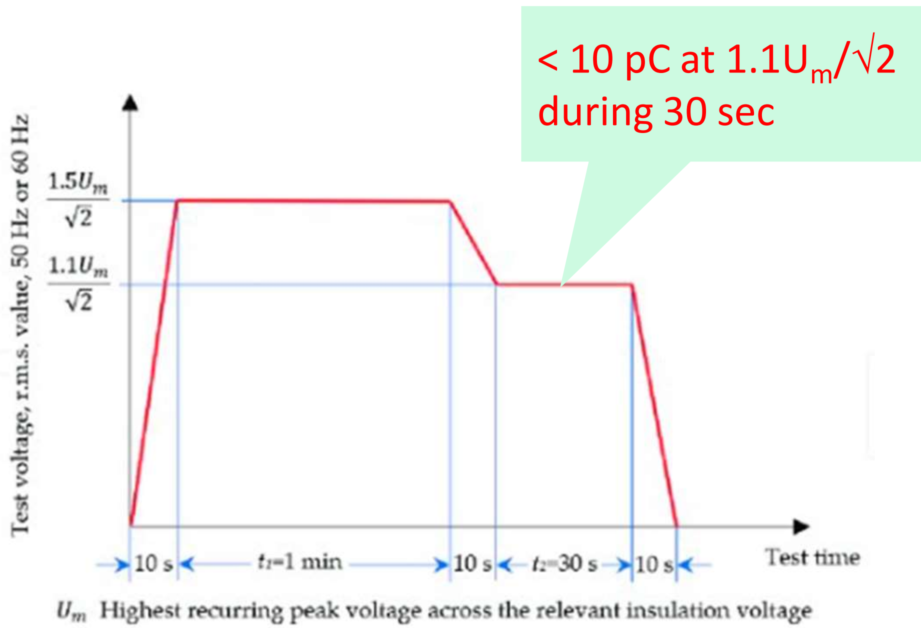
Conventional PD-detection (IEC 60270) not possible at switched voltages







Acceptance test for HV power converter modules:
Sinusoidal voltage and partial discharge measurement



- **IEC 61287 Railway applications** – Power converters installed on board rolling stock – Part 1: Characteristics and test methods
- **IEC 60270 Charge based PD measurement** at low frequency

versus

- **IEC TS 62478** High voltage test techniques - Measurement of partial discharges by **electromagnetic** and acoustic methods

X-ray supply seed electrons -> initate discharges

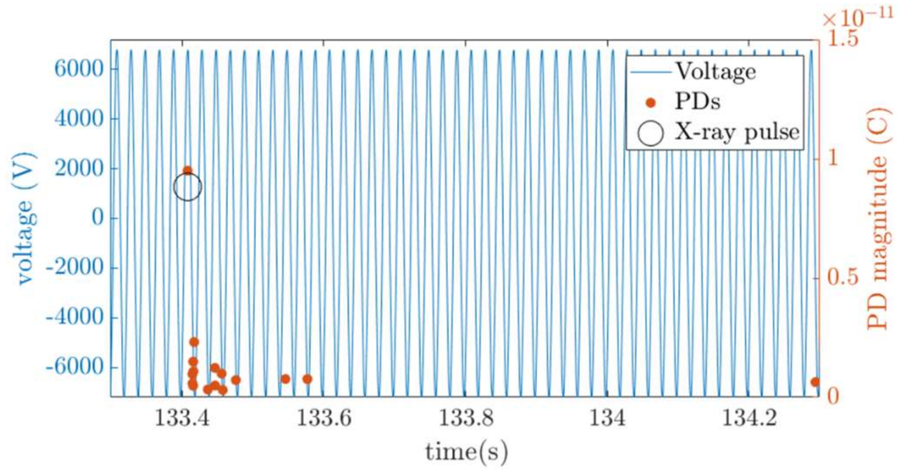
Supressing statistical uncertainties in QC
Revealing PD sources during short time tests

Pulsed X-ray source

- 270 kV acceleration
- 50 nsec pulse
- Triggerable

Al_2O_3 model substrate

X-ray induced partial discharges



Conclusions - Electric stresses

- Electric field stress will depend on space charge formation/relaxation & gel conductivity.
- Inside IGBT, unipolar voltage with high repetition rate may be less stressing than bipolar voltages

Conclusions – discharge detection

- Stresses used in todays test methods are not representative for stresses experienced in service
- PD detction is not possible with classic methods (IEC 60270) at switched voltages
- Feasible to detct PD at switched voltages using high frequency band detection (IEC TR 62478).
- X-rays used to activate «sleeping» defects during short test duration
- PD sources can be recognized using pattern recognition

Some background literature

- A.A.Abdelmalik, A.Nysveen, L.E. Lundgaard: "Influence of Fast Rise Voltage and Pressure on Partial Discharges in Liquid Embedded Power Electronics", IEEE TDEI, Vol.: 22, Issue: 5 , Pages: 2770-2778, Oct 2015
- I. Semenov, I. Folkestad Gunheim, K. Niayesh, H. K. Hygen Meyer, L. E. Lundgaard: "Investigation of Partial Discharges in AlN Substrates Under Fast Transient Voltages", IEEE Transactions on Dielectrics and Electrical Insulation, Vol.29, No. 2, 2022
- I. Semenov, T. G. Aakre, I. G. Folkestad, I. Smisethjell, K. Niayesh and L. Lundgaard, "Partial Discharge Inception in Ceramic Substrates Embedded in Silicone Liquid, Silicone Gel, and Mineral Oil at Fast Voltage Rise and Sinusoidal Voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*

Thank you for the attention