Dielectric response and partial discharge measurements on stator insulation at varied low frequency

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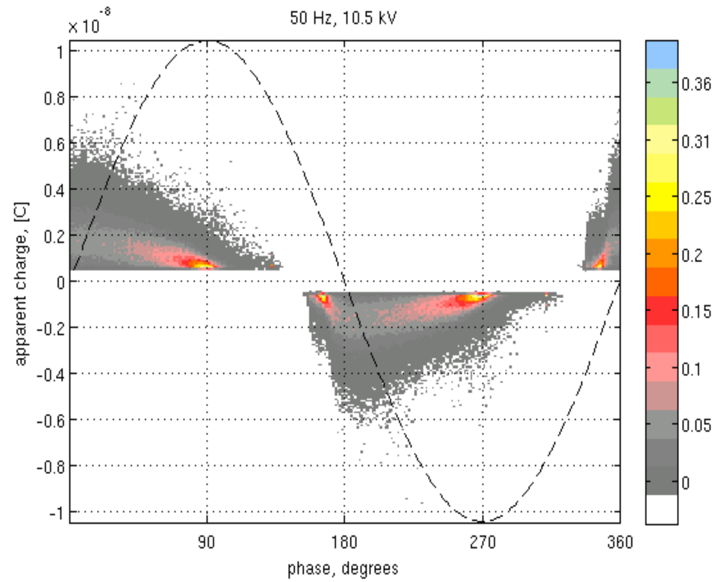
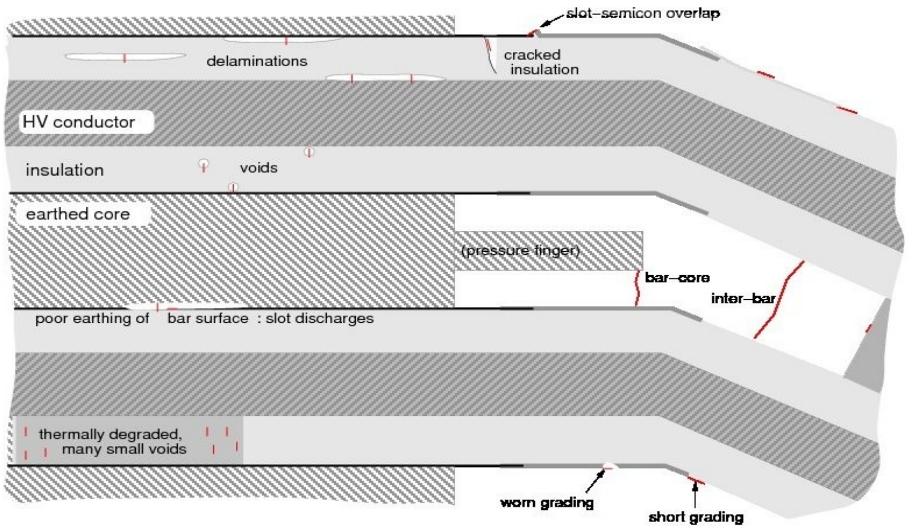
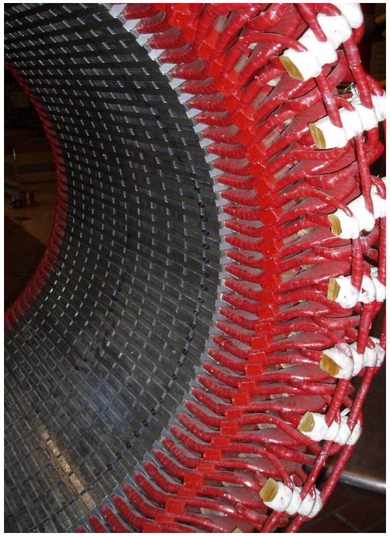
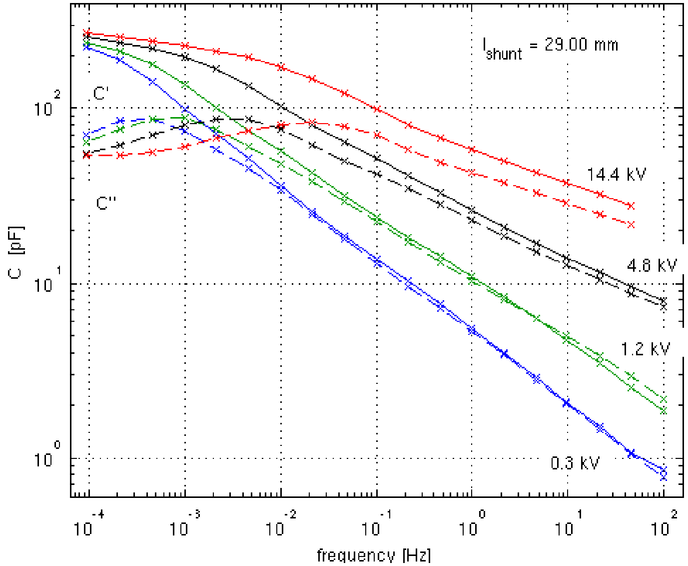
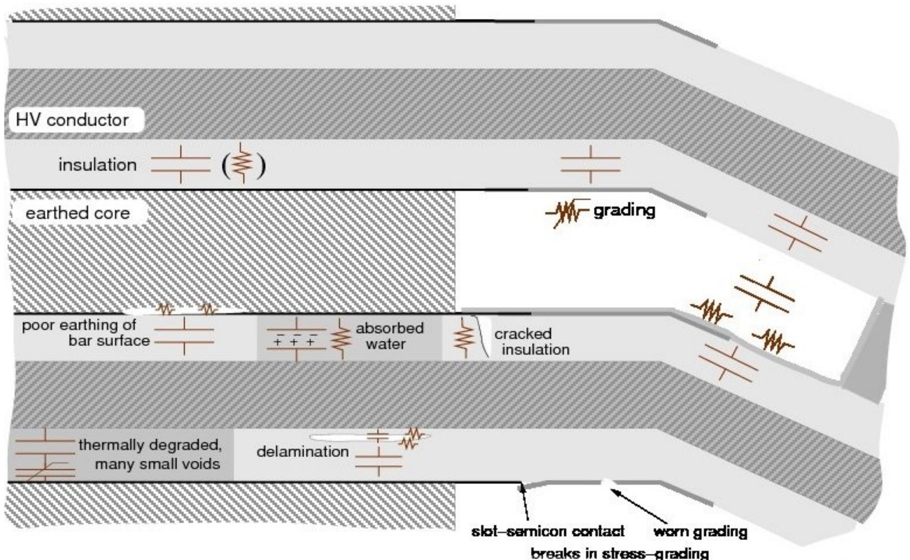




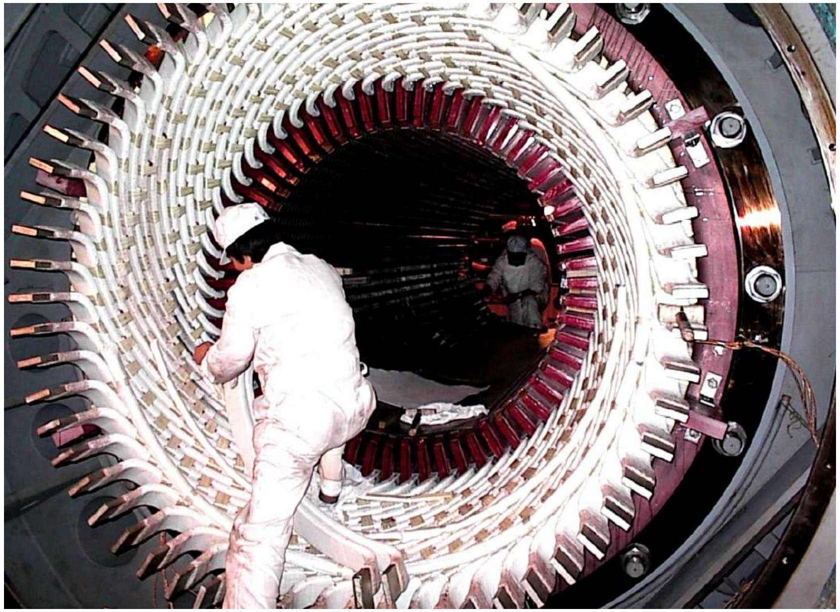




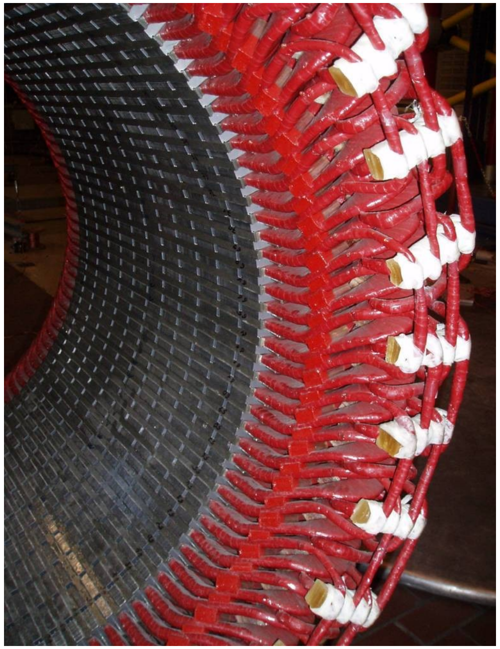


“Rotating Electrical Machines”: The Stator and its Windings

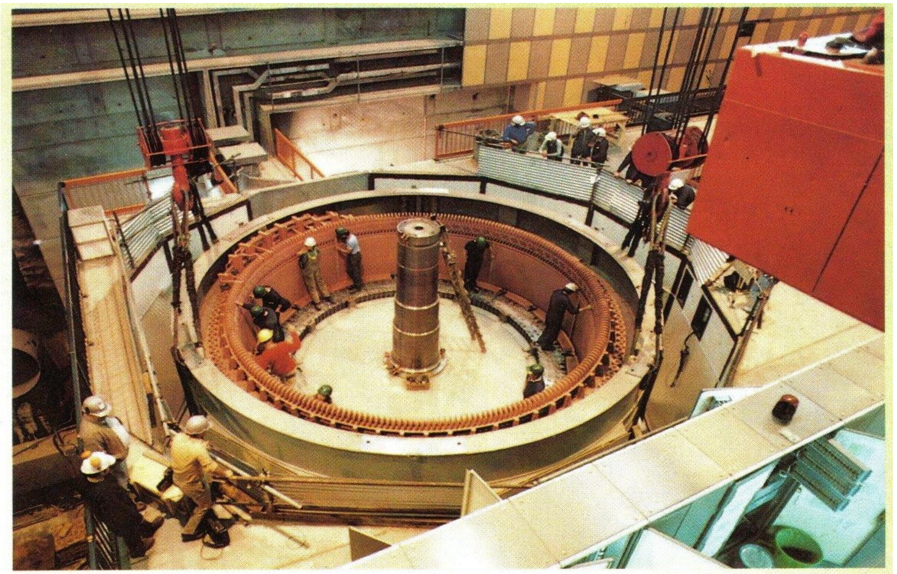
turbo-generator



motor



hydro-generator

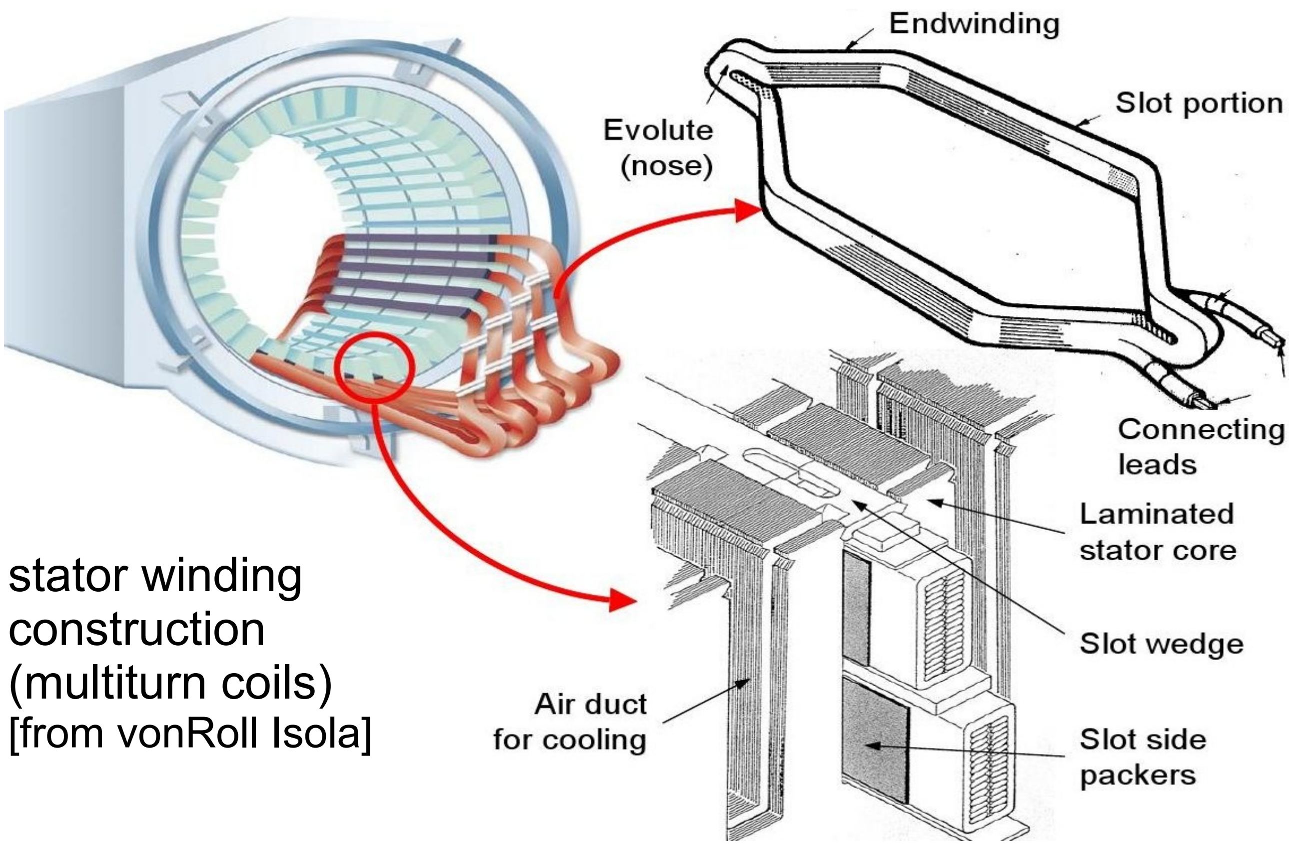


Vast range of power ratings,
<1 MW to >1 GW

Voltage generally below 30 kV.
Very compact insulation
-- mica based, hard-wearing

Often expensive and critical:
diagnostics and monitoring

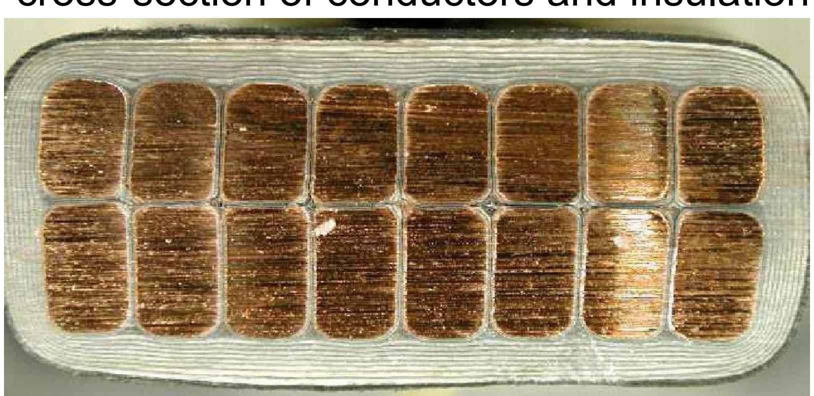
High-voltage Stator Insulation



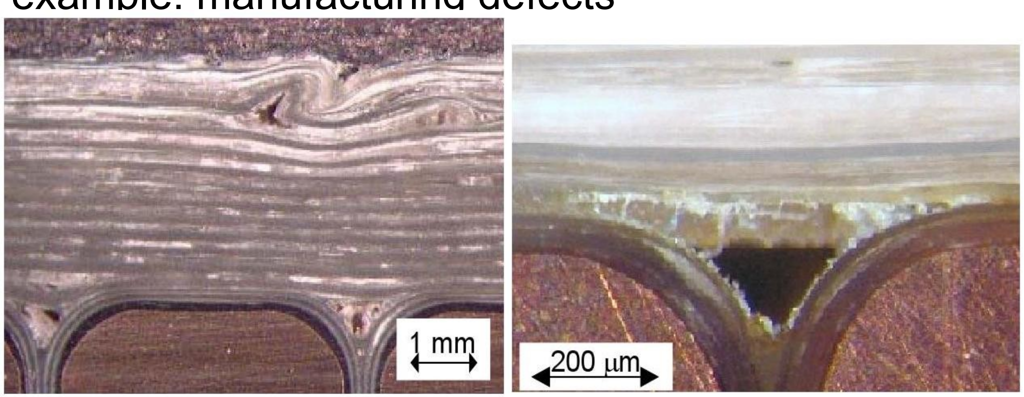
stator winding
construction
(multiturn coils)
[from vonRoll Isola]

example: end-winding discharges

cross-section of conductors and insulation



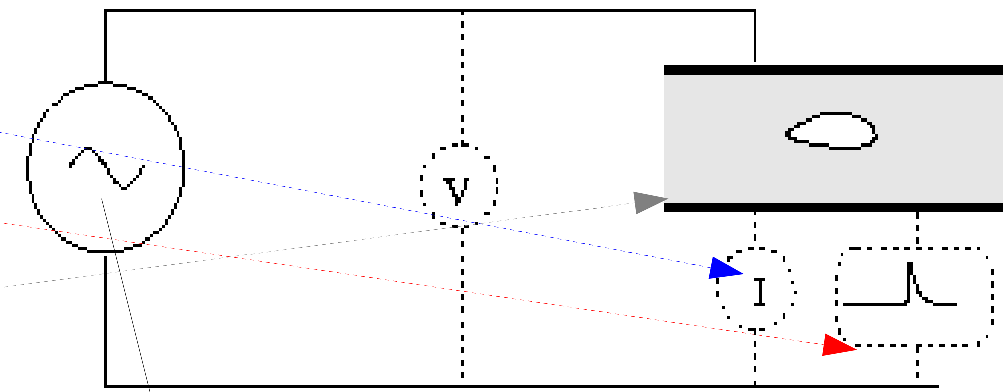
example: manufacturing defects



Initial Aims

Measurement types:

Dielectric response (FDDS) (smooth)
PD-pulse measurement (pulses)

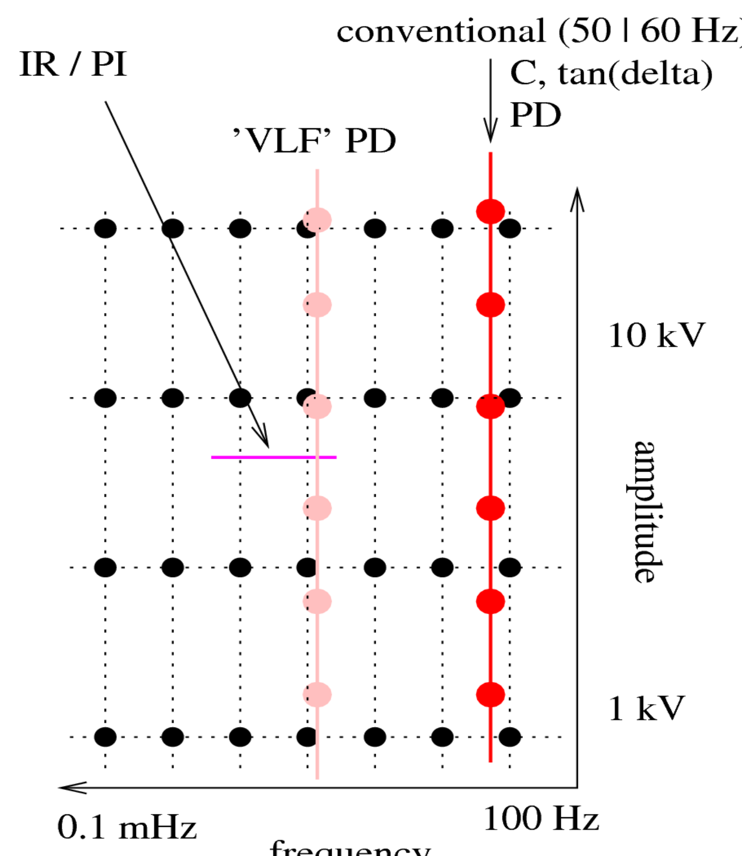


Applied to:

Stator insulation
(relatively neglected in earlier projects)

Special features:

Amplitude and frequency of applied voltage



Varied frequency

earlier work: VF-PRPDA, HV-FDDS on XLPE-cables
greater information from frequency-dependence

Low-frequency range

apart from the information, savings in voltage-source

Harmonics in DS measurement

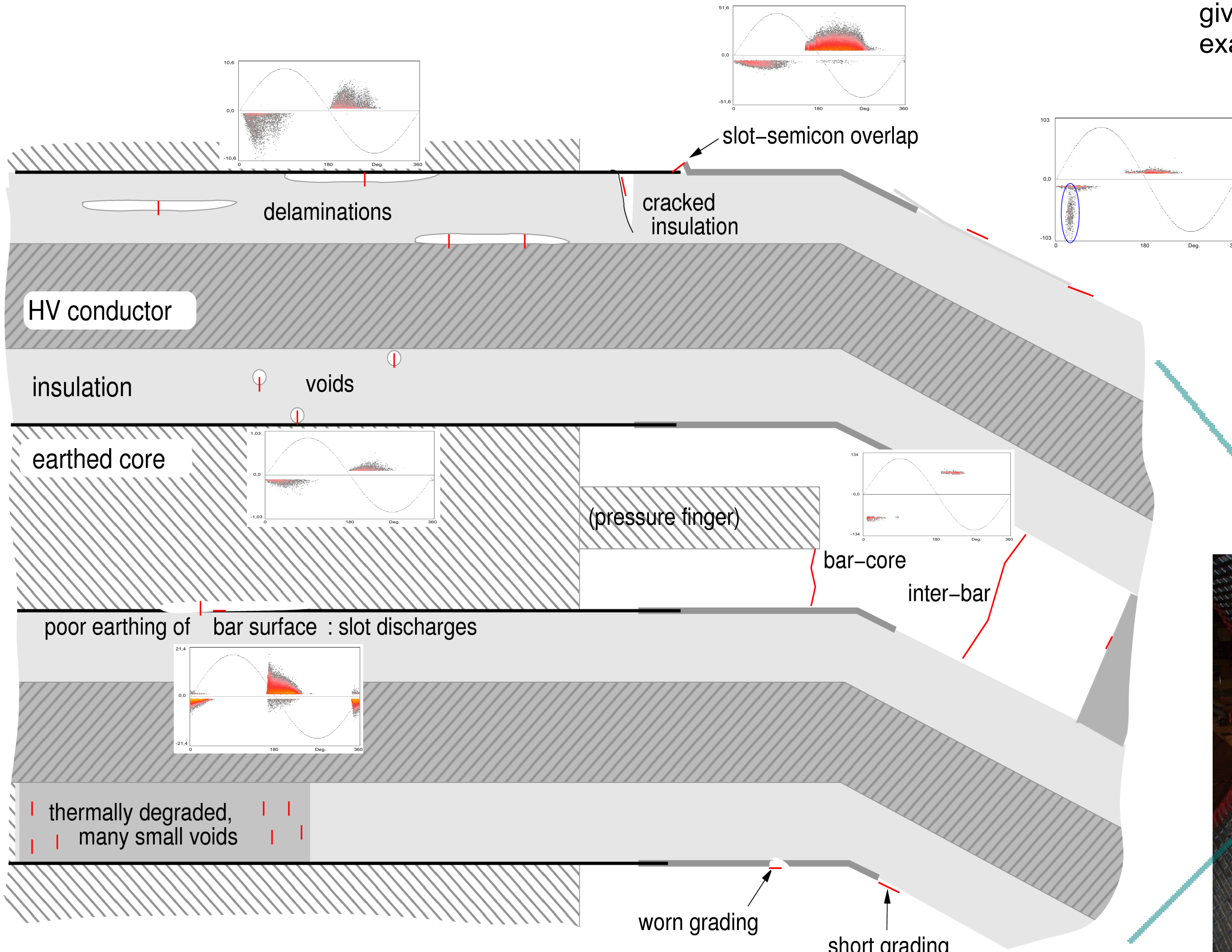
more detail of mean waveform,
distinction between linear/nonlinear current-sources

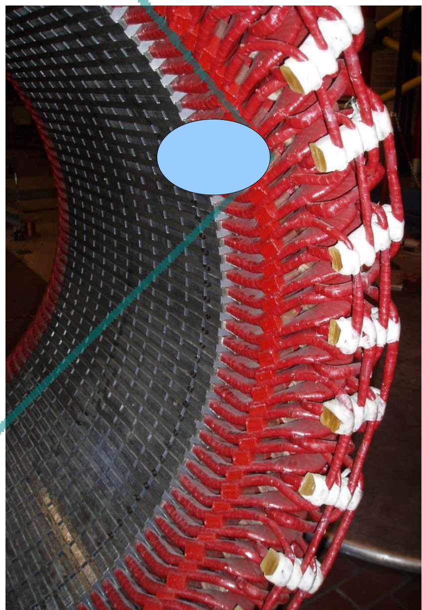
Combination of DS+PD

save time if doing both; compare results;
PD measurement within DS current; substitute?

Stator PD sources

Note: example PD patterns are from an IEC-60034-27 appendix, not from the machine whose photograph is given below as an example.





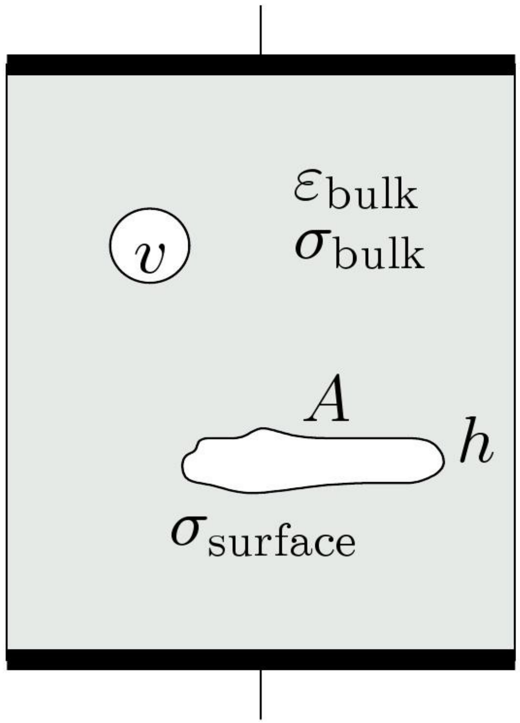
Frequency-dependence of PD

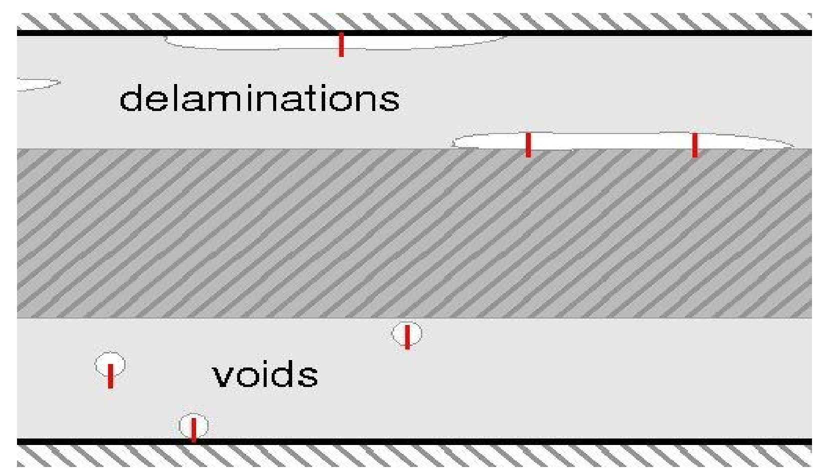
Perhaps one of the most interesting points of all... the pure “VF-PRPDA”.

BUT: not studied much here: general PD and frequency dependence was looked at by other projects.

Detailed work with different stator-insulation defects would be interesting.

For example: a useful distinction of voids from delaminations?





Frequency-dependence also of stresses in end-winding, from R-C circuits of grading and contamination.

Reasonable frequency-range

Lower limit comes from acceptable measurement-time

usually much less time available in an industrial situation than in laboratory

remember: probably several voltage amplitudes and combinations of phases

DS in the laboratory is generally fine with just two cycles

PD: need several cycles to begin to approach a representative pattern

perhaps 10 mHz is industrially acceptable -- even this is optimistic

Upper limit comes from acceptable demands on the voltage-source

the HV amplifier used in this work has maximum current of 20 mA

typical ~ 1000 nF stator winding, at 10 kV and 50 Hz $\longrightarrow$ ~ 3 A

upper frequency-limit for this object, voltage and amplifier is < 1 Hz

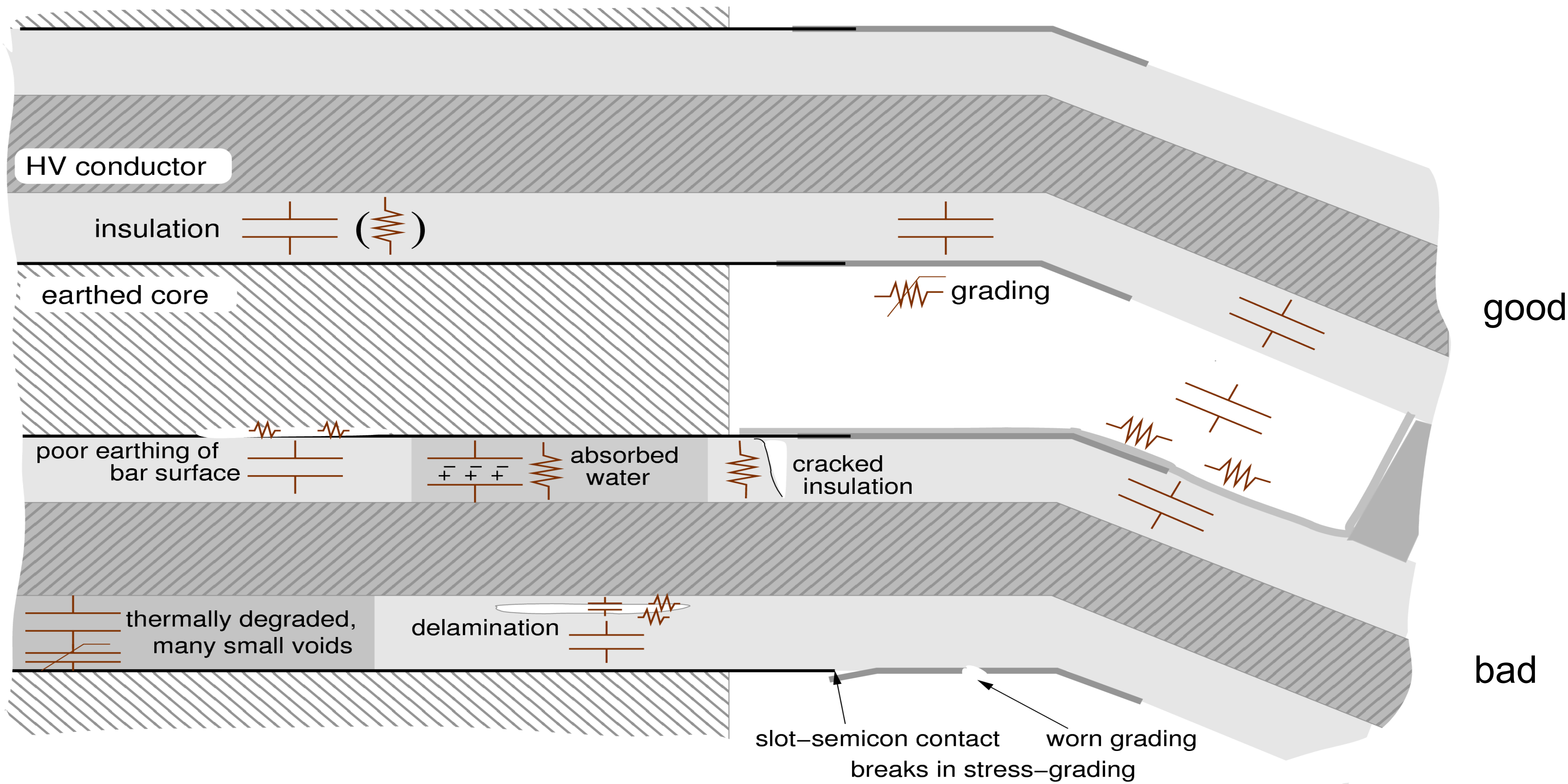
(side-issue: could instead do non-PD measurement at LV e.g. 100 V, including ~100 Hz)

Sources of DS currents

Large contribution of 'bulk insulation' (hundreds of nF/phase).
Often assumed to be linear. Approximately power-law functions ΔC'(f) and C"(f).

Thermal aging: reduction in capacitance

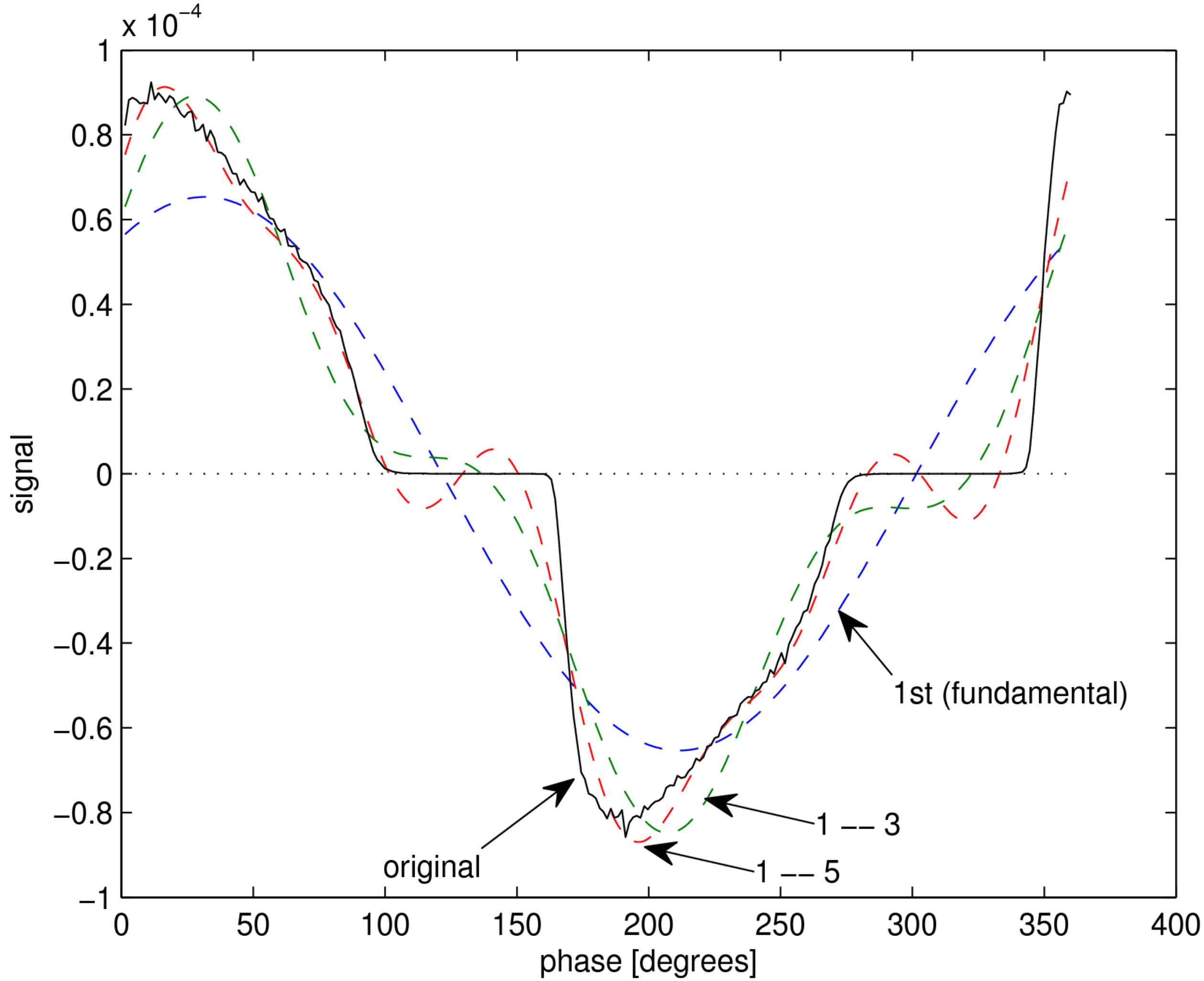
Water absorption: increase in capacitance and loss, possible polarity-dependence.



Defects: increased loss through series resistance; nonlinearity; currents from PD.
Nonlinearity is a useful distinction between many normal and bad parts.
BUT: end-winding grading...

(FD)DS measurements, including harmonics

current waveforms for insulation nonlinearities (PD, stress-grading) are rather smooth, well represented by just a few harmonics (although PD mean current has higher-frequency variations too)



Harmonics:

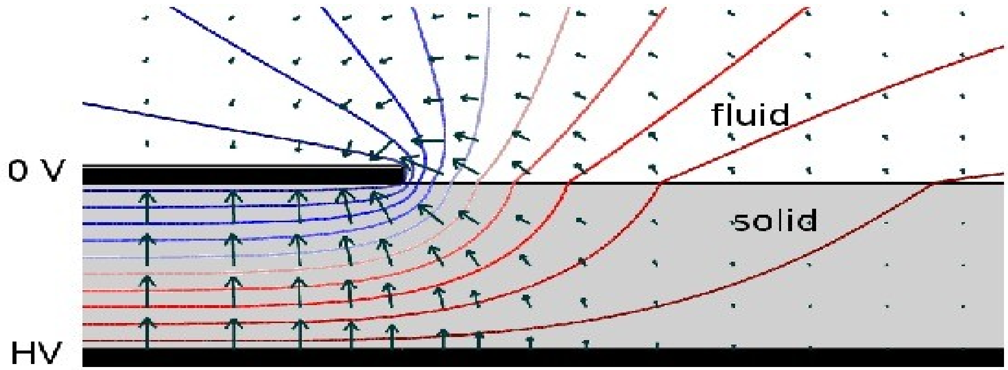
reveal the waveform

sensitive measure of just the nonlinear parts of the current

Stress-grading: nonlinear SiC-based material

A severe disturbance to voltage-dependent and frequency-dependent variations in C' and C'' and to harmonics.

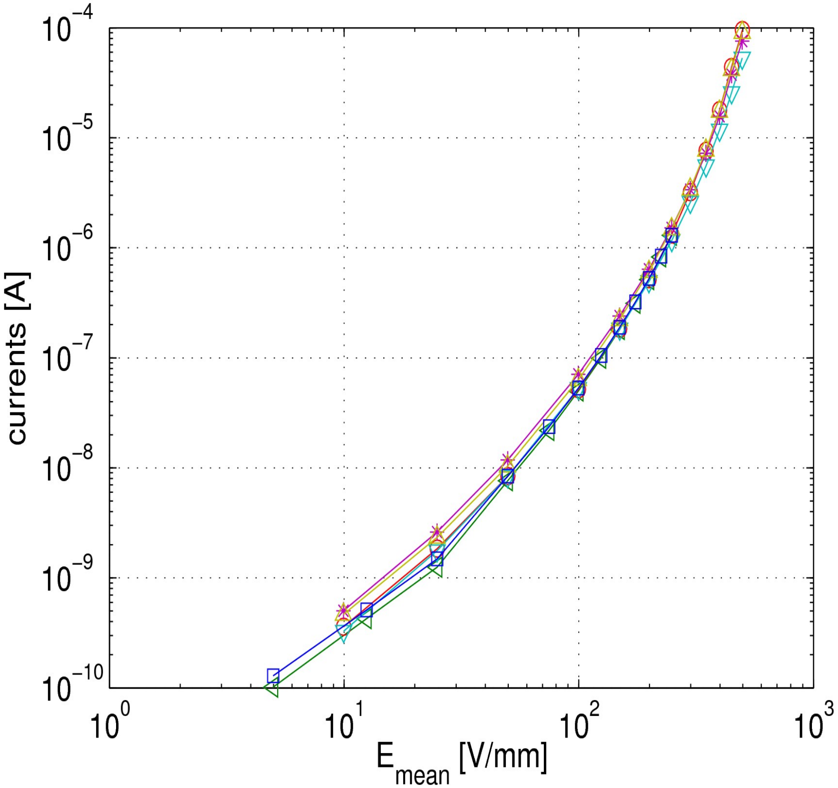
“truncated electrode dielectric” with no grading: high field



nonlinear-conductive material extending the truncated conductor

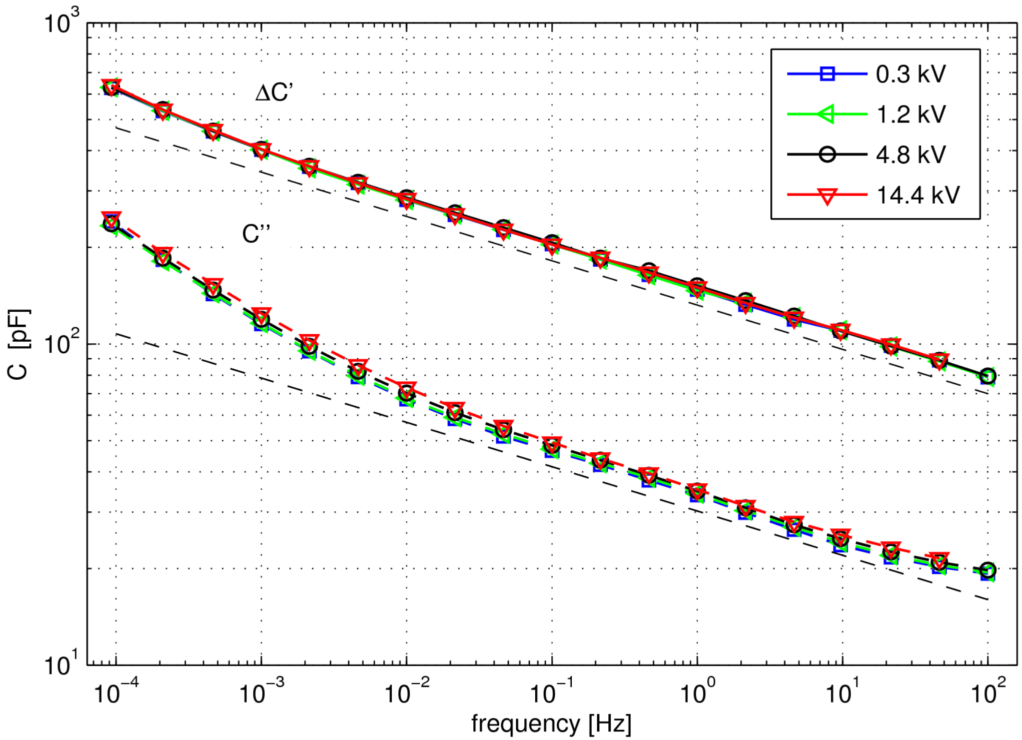
the potential for this situation in a stator, at “slot exit” considered a problem above about 5kV (even 3kV with IFD)

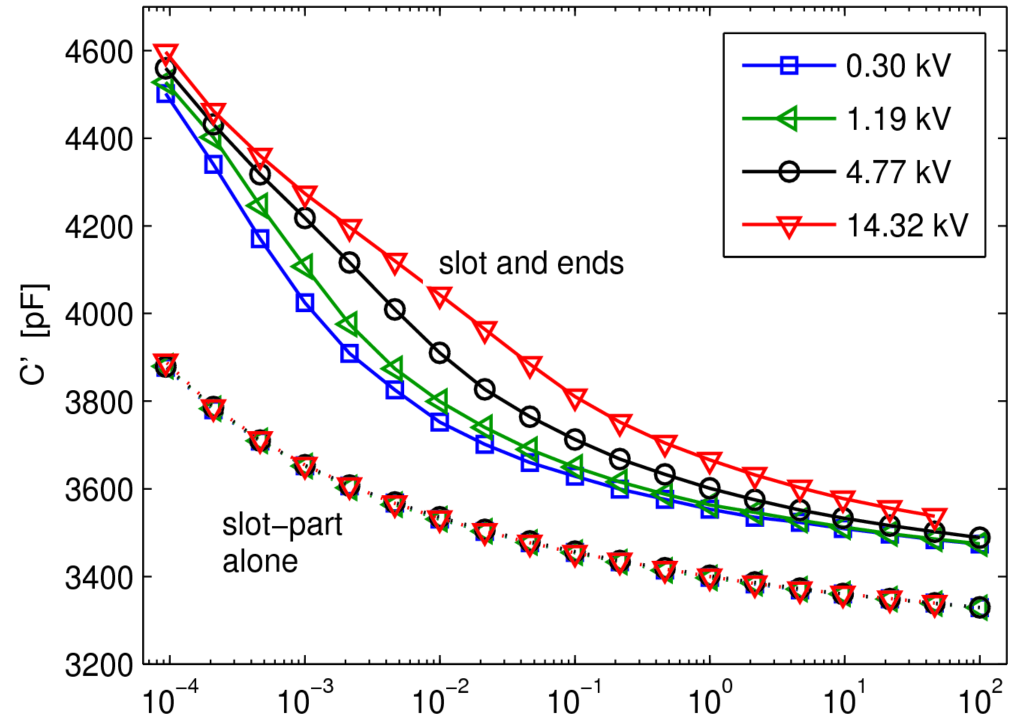
example of the nonlinearity of I/V

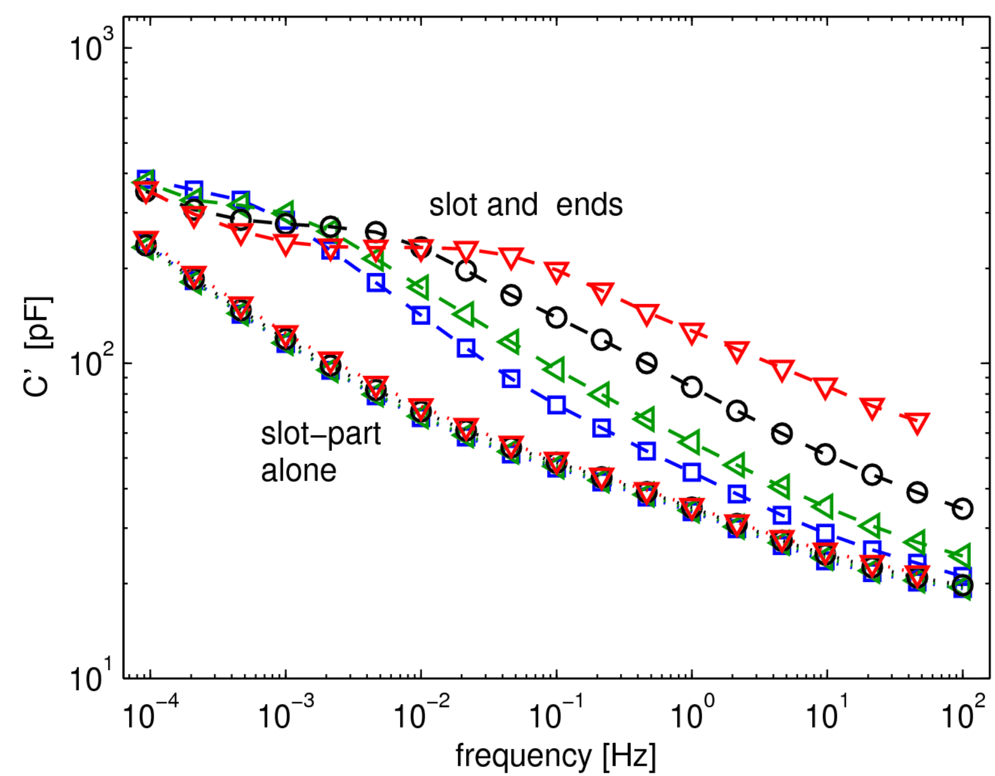


C',C" for healthy insulation, with and without end-winding stress-grading

pure material response (guarded, subtraction of C_\infty)







In these bars:

slot-semiconductor is about 1400 mm long

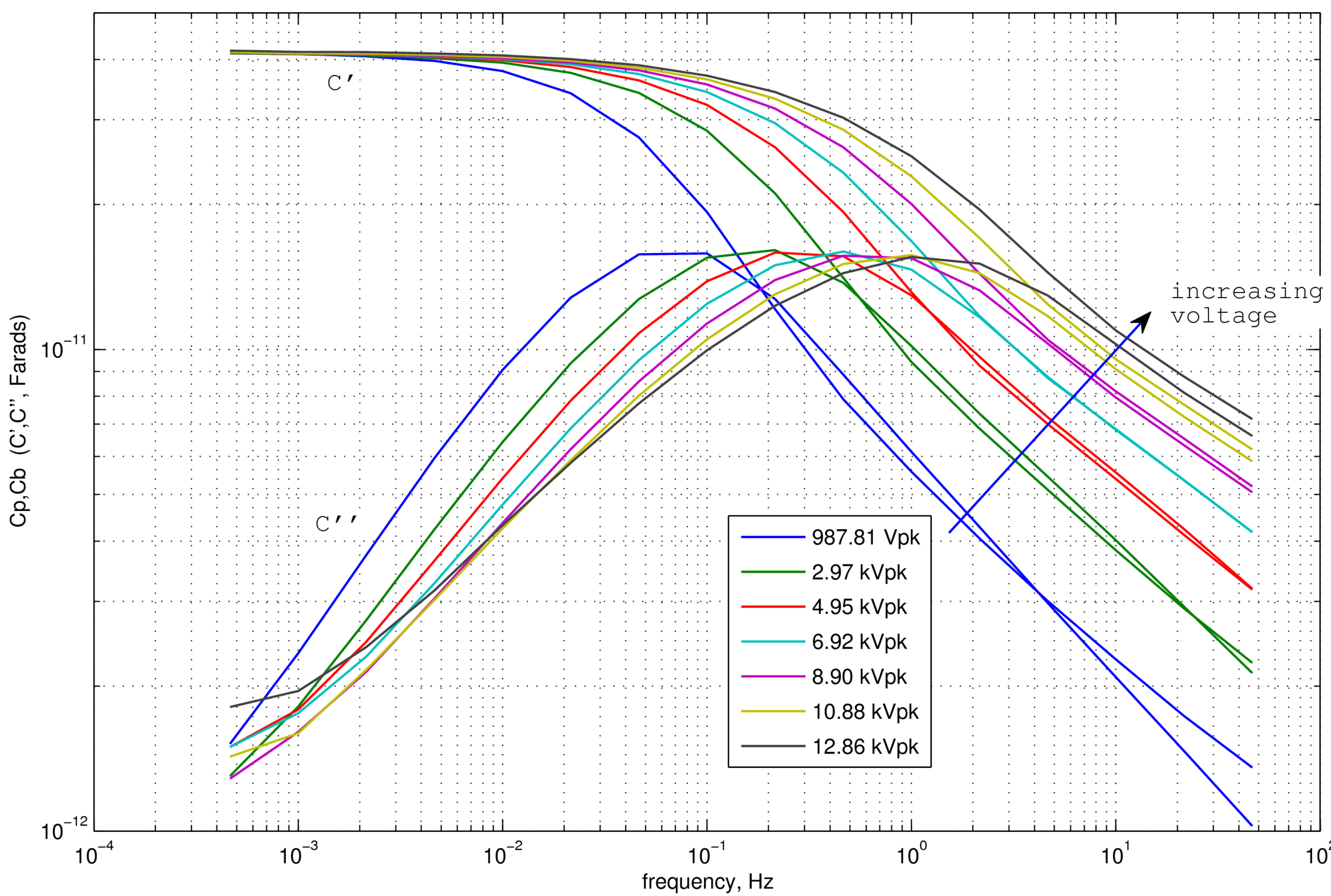
active regions of end-grading are 2 x 90 mm

Simple physical model of stress-grading

PTFE insulation (low dispersion).
Commerical SiC-based grading material.

Special features of C' C'' ---

- HF: parallel: superposed at LV
- LF: C' reaches a maximum
- MF: loss-peak shifts with voltage

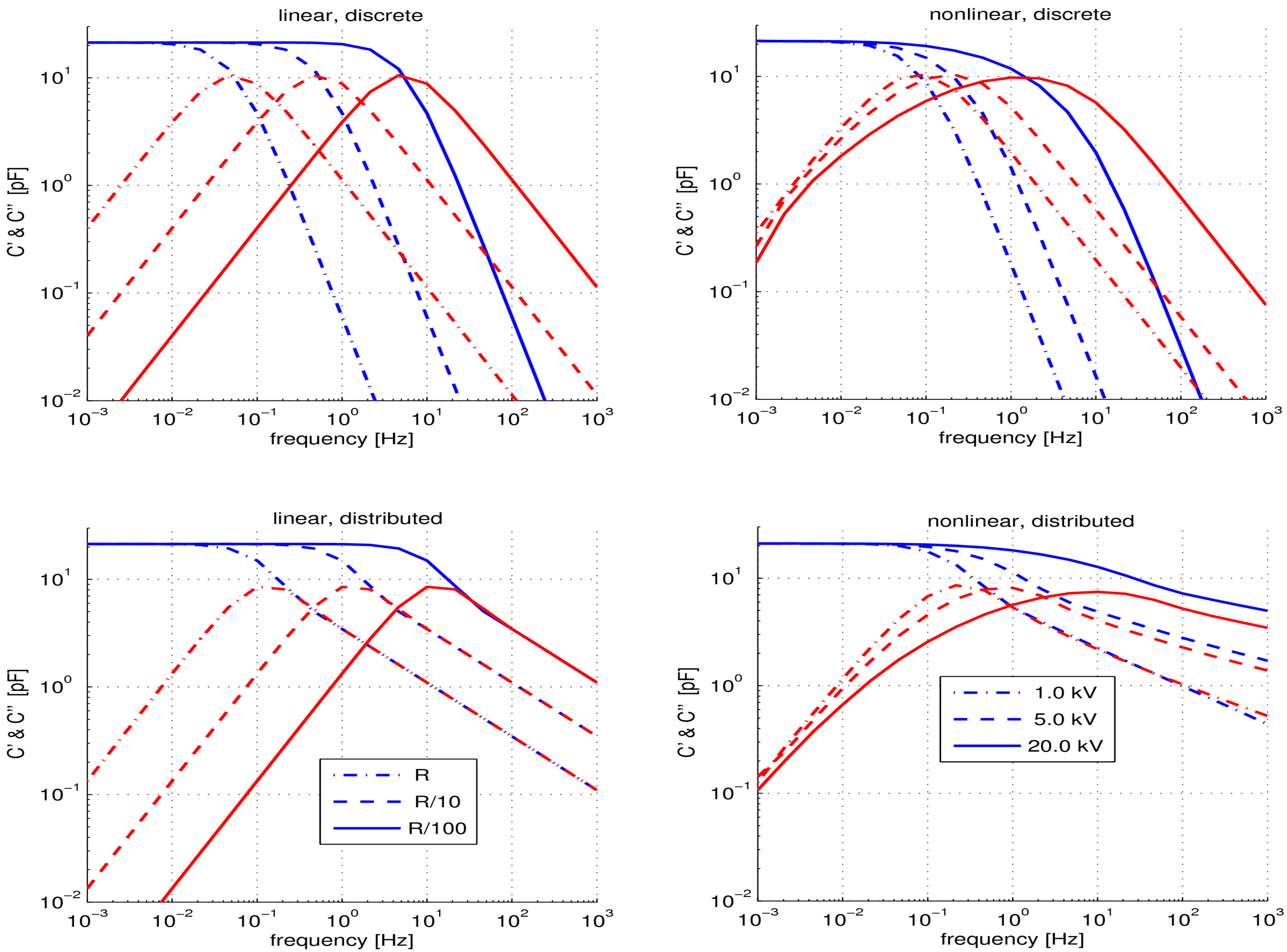


Simple numerical models of stress-grading

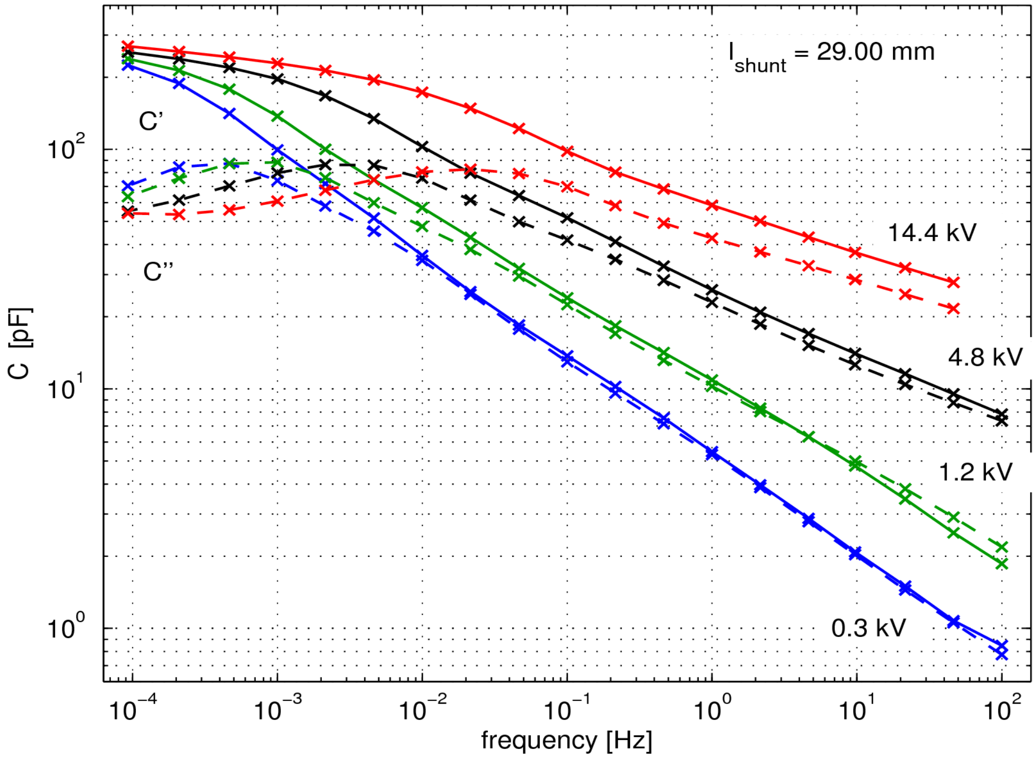
Only the nonlinear distributed is worth considering over the full range of |V| and f.

Several simplifications in the literature, e.g. $i(t) = t^{-n}$, or `perfect' nonlinearity.

Modelling most common for potentials at HF, not current at LF.

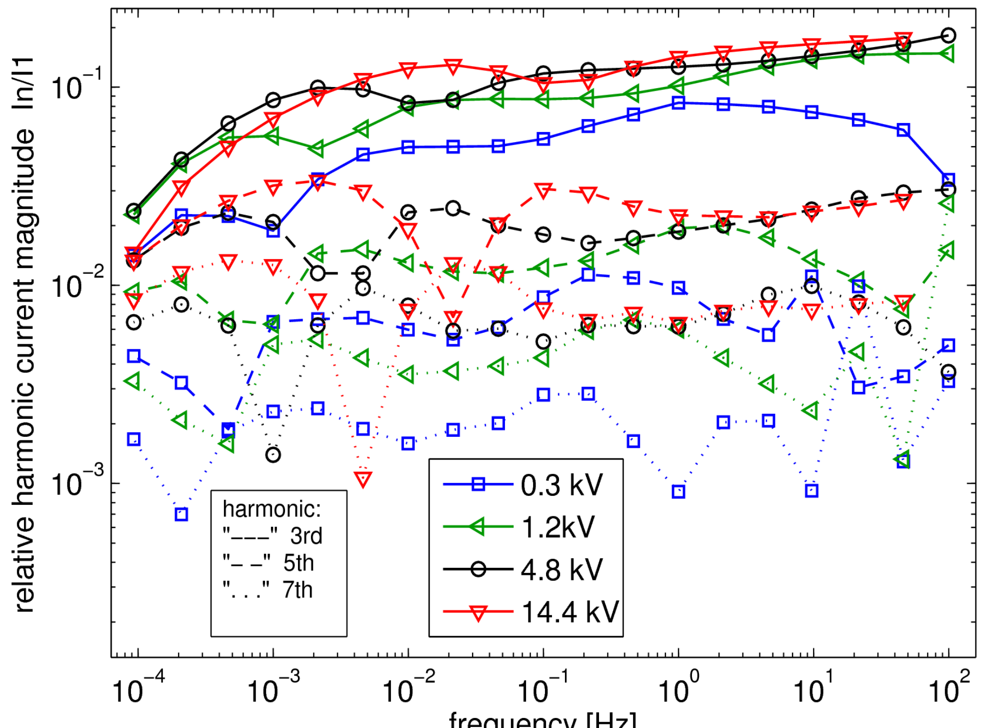


Currents due to stress-grading in real bars



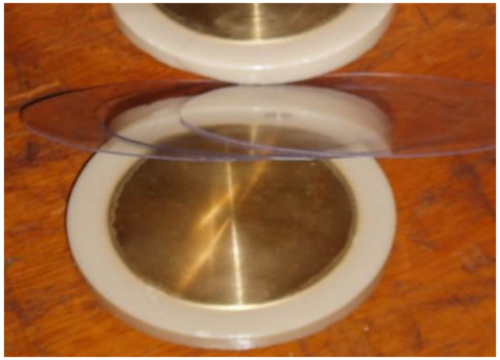
Currents are measured in the grading-region beyond the guard-gap. The complex capacitance from the guarded slot-part is used, scaled by length, to estimate the current in the active region of grading alone.

Note how the loss peak occurs even for the real bars, at reasonable |V| and f. From earlier experiences (licentiate) it was thought that this would be only at very low frequency.



Simple laboratory PD-objects

simple cavity

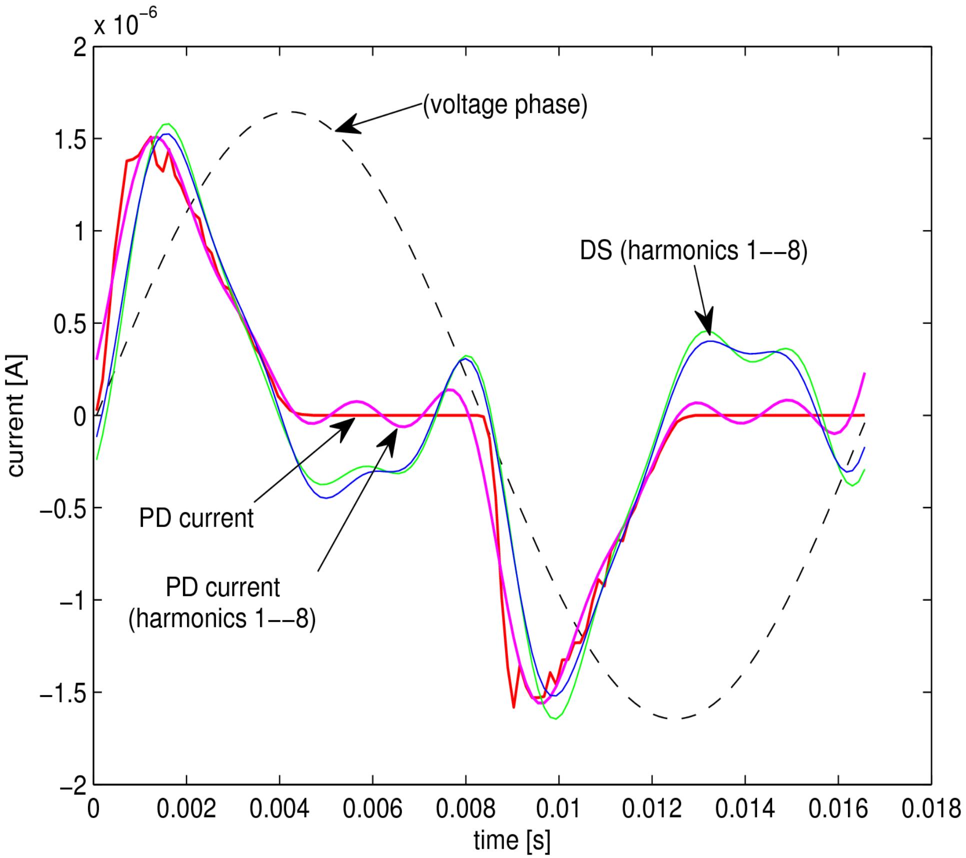


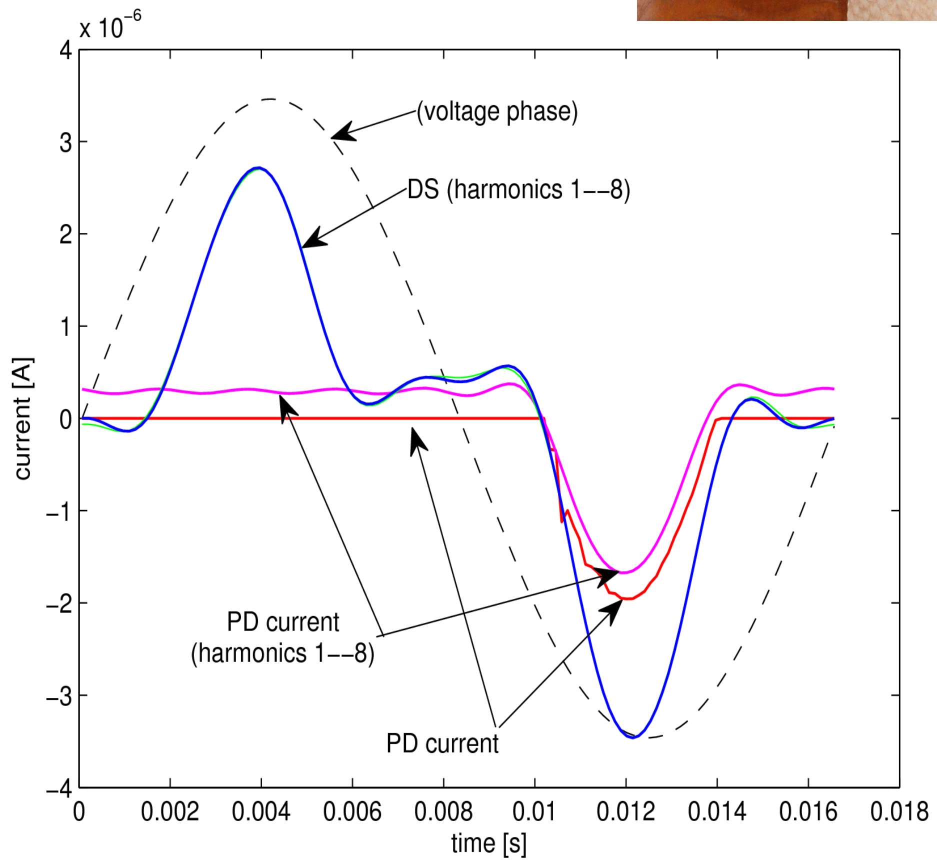
Comparison of PD current by DS and PD-pulse methods.

PD pulse method: current represented by PDP

DS method: estimate and subtract non-PD current
(based on scaling the current measured at low-voltage)

point-hemisphere

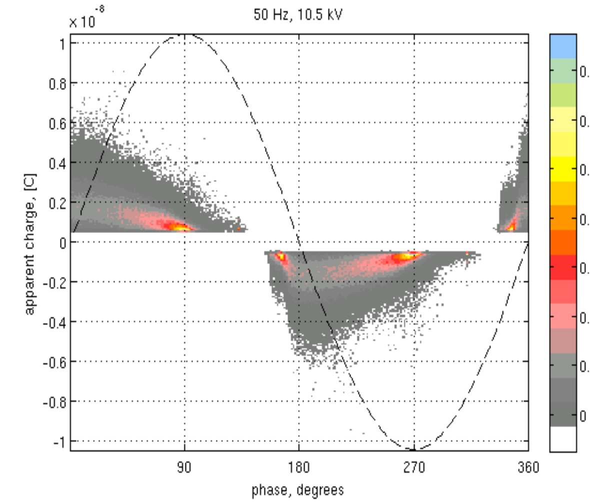




Larger PD-objects

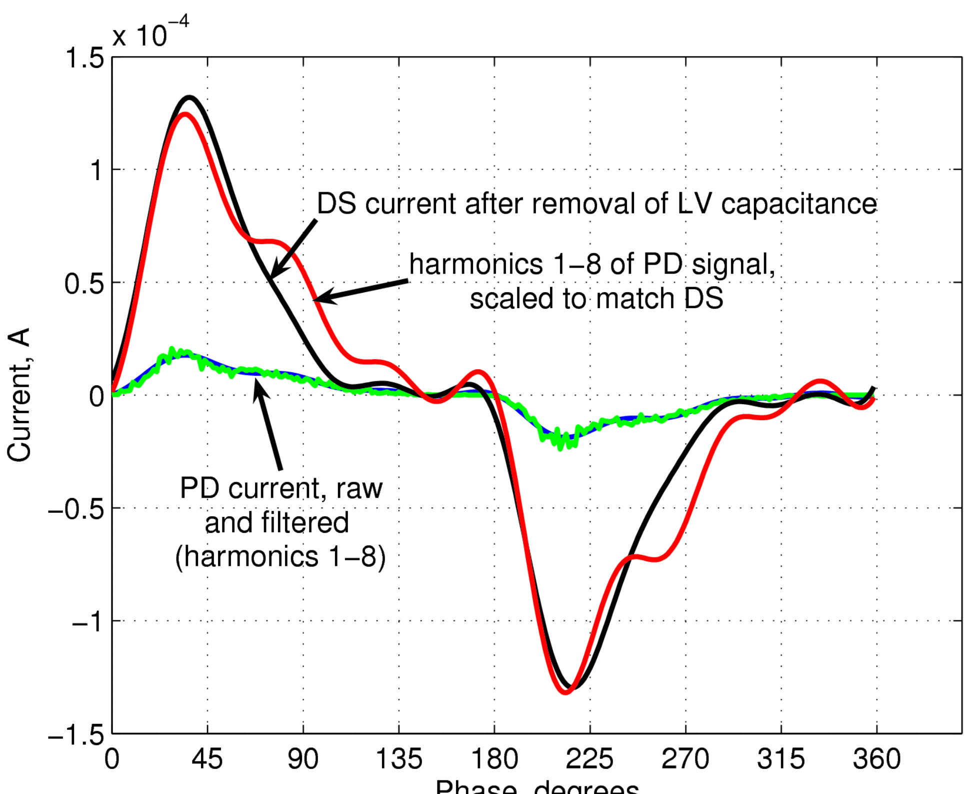
Measured total PD current much less according to PD-pulse system than according to DS.

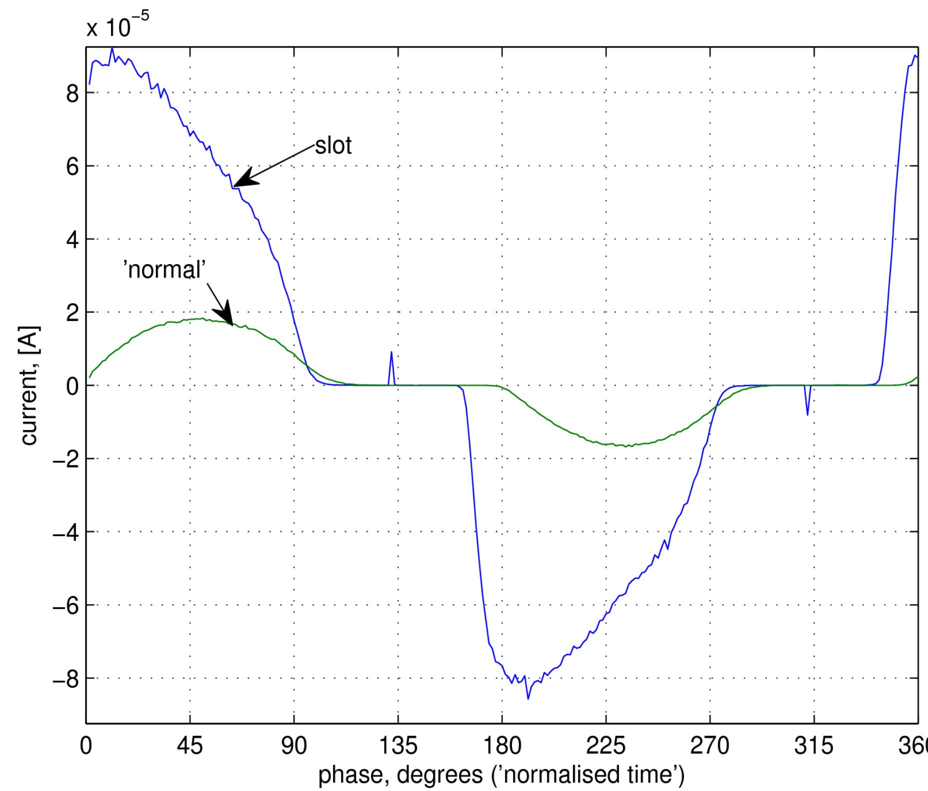
- Deadtime
- Dynamic range, and noise
- Calibration problem: reflection, attenuation
- PD 'form': pulsed, glow, ...



Single (guarded) coil in laboratory

Industrial measurement
[Note: PD only: estimate DS from C-tan(delta)]





Summary of a few points

PD charge is seen very differently between PD-pulse and DS measurement.
    Current-practice of PD-pulse & C - tan(delta) already does both, at 50|60 Hz.
    Inclusion of some low harmonics reveals the current waveform.

Nonlinear stress-grading strongly disturbs nonlinear and frequency-dependent currents.
    Poorly-known parameters: modelling this current away will be very approximate...

PD frequency-dependence is itself an interesting matter.

Sticking to frequency-dependence in LV measurements perhaps of some interest?

Further interest

More work on simultaneous DS+PD: noise, earthing, further trouble of field-measurements?

Practicality of LF measurements (time, minimum number of cycles for good PD pattern).

Relations between measurable quantities by the new methods, and condition of insulation
    service-aged bars [+ destructive test?]
    lab-aged bars [+ destructive test?]

Thesis Map

The Object

Stator Insulation 2
- Materials
- Construction
- Faults

Aging of Insulation 3
- Service aging
- Accelerated aging

Diagnostics & Prognostics 4
- Aims, online/offline,
- trending, comparison,
- methods for stator insulation

DS

Dielectric Response 5
- polarisation and conduction
- terminology
- DR of whole insulation systems
- sources of DR current in stators

DR measurement 6
- time/frequency
- electrometer & feedback
- DFT and disturbances
- nonlinearity
- methods for stator insulation

The DS instrument (IDAX) 9
- components/specification
- control

PD

Partial Discharge 7
- gas discharges
- partial discharges
- stator PD sources

PD measurement 8
- apparent charge
- other forms of measurement
- pulse propagation in stators
- PD methods for stator insulation

The PD instrument (ICM) 10
- components/specification
- control

"Conjectured Advantages" 11
reasons, aims, early ideas, changes, suggestions, subjects for study

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DS instrument tests 12
- consistency, varied feedback
- synchronisation of ICM

PD instrument tests 13
- synchronisation, data–transfer
- linearity

Simultaneous DS+PD x
- noise (HV and LV)
- PD sensitivity to noise
- DS sensitivity to phase–shift
- earthing

Pulses into DS instrument 14
- correct result?
- EM overload?

PD seen as pulses or in DS 17
- simple or complex object
- similar or complementary result

Principles ('of investigation') A
- presentation
- experiments and analysis
- laboratory notes, automation
- computers, simulation

Displaying results 15
- many points
- reduction to indices
- 'harmonic capacitance'

Previous Excitation 16
- statefulness
- aim of measurement
- recommendations

End–grading currents 19
- physical models
- numerical models
- real bars

End–grading materials 20
- description
- sensitivity

End–grading parameter estimation x
- from LV nonlinearity?
- assume a long grading?
- assume fixed parameter?