Diagnostics of Stator Insulation by Dielectric Response and Variable Frequency Partial Discharge Measurements

A study of varied low frequencies in stator insulation, with particular attention to end-winding stress-grading



Licentiate presentation by

KTH Electrical Engineering

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- 1. Stator insulation
- Machine construction
- Stator insulation construction
- Stator insulation defects
- Current diagnostic practices

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- 2. (HV) Dielectric spectroscopy
- 3. (VF) Partial discharge measurement
- 4. End-winding stress-grading
- 5. Examples on real stator insulation
- 6. Conclusions

MACHINE CONSTRUCTION



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Stator insulation slot end

Rotor insulation Mechanical (bearings)

STATOR INSULATION

 $U_{\rm n} \gtrsim 1 \, {\rm kV} \implies {\rm form}{-}{\rm wound}$ $U_{\rm n} \gtrsim 5 \, {\rm kV} \implies {\rm `corona \ prevention' (grading)}$ $U_{\rm n} \lesssim 30 \, {\rm kV} \quad {\rm in \ spite \ of \ ratings} \approx 1{-}1500 \, {\rm MW!}$



Relevant Constructional Variations

Insulation binding material

(between the mica pieces):

- *bitumen* high loss, migrates
- polyester resin
- epoxy resin

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Hydro- or turbo-generator: diameter/length, affects which ratio of endlength/slot-length and propagation of PD signals.

Cooling and coolant:

— *indirect:* heat comes out of windings through the insulation - direct: a coolant (typ. water) is used within the windings — *air/hydrogen:* air has lower $E_{\rm BD}$ and heat capacity, allows O_3 generation by PD, and assists oxidation of organic insulation

'Corona-prevention' (semiconductor layers) or not?

STATOR INSULATION DEFECTS



Stress: Thermal, Electrical 'Ambient', Mechanical

Cause: primary, secondary?

Manifestation:

Delamination, cavities

Electrical Treeing

Worn slot semiconductor

Worn end semiconductor

Contamination on end-windings

DIAGNOSTIC METHODS IN COMMON USE

Many methods *don't* depend on electrical connection to the windings, e.g. detect PD by measuring RF emissions, chemicals, sound, light, or use mechanical measurements and visual inspection, PD measurement by couplers.



Others more relevant to this work: off-line, with galvanic connection. Note that off-line usually implies significant differences from normal stresses.

On-line—Off-line: expenses, realistic versus controlled conditions.

Measurement \longrightarrow (Physical State) \longrightarrow P(failure) Complex system. Different phenomena can look similar in a particular measurement. Cannot expect any method to give no false positives or negatives.

Electrical Diagnostics in Common Use

Insulation 'Resistance' (IR): 'DC' with quite HV, i.e. a form of time-domain spectroscopy with stepped voltage). This is also known as 'megging', and the derived quantity 'Polarisation Index' (PI) is popular.



Capacitance and Loss, possibly including 'Tip-Up': generally power frequency (≈ 50 Hz), with several voltage steps typically up to the rated *line* voltage per phase, i.e. overvoltage factor of $\sqrt{3}$

Partial Discharge (PD) measurement: again, generally power frequency, often as 'phase resolved' pattern.

- 1. Stator Insulation
- 2. (HV) Dielectric Spectroscopy
- Dielectric Materials and their Response
- Dielectric Spectroscopy (DS)
- Material Measurements and Disturbances
- Non-linearity

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- High-Voltage (HV) DS, and Applications
- HV DS on Stator Insulation
- 3. (VF) Partial Discharge measurement
- 4. End-Winding Stress-Grading
- 5. Examples on Real Stator Insulation
- 6. Conclusions

DIELECTRIC MATERIALS

Polarisation:

— bounded movement of charge, changing charge-distribution

- increases supplied charge to electrodes (if fixed V)
- many mechanisms (e⁻, natural dipole, ionic ...)
- some mechanisms very fast, lumped as ε_{∞} , an increased ε_0
- other mechanisms have considerable dynamics: represent as such with polarisation function f(t) or susceptibility $\chi(\omega)$:

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$$P(t) = \varepsilon_0 \int_0^\infty f(\tau) E(t-\tau) d\tau$$

$$P(\omega) = \varepsilon_0 \chi(\omega) E(\omega)$$

$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega) \dots$$

$$= \mathscr{F} \{f(t)\}$$

DIELECTRIC RESPONSE: EXPONENTIAL MODEL

Time

Frequency

$$f(t) \propto e^{-t/\tau}$$
 $\chi'(\omega) - i\chi''(\omega) \propto \frac{1}{\left(1 + (i\omega\tau)^{k_1}\right)^{k_2}}$

 $k_1 = k_2 = 1$ in pure exponential case





DIELECTRIC RESPONSE: POWER-LAW MODEL

Time

Frequency



POWER-LAW MODEL WITH TWO PARTS



DIELECTRIC SPECTROSCOPY

Dielectric Spectroscopy \implies Dielectric Response at varied t or ω .

Time-Domain (TD) measure f(t), (plus conduction and possibly prompt response): e.g.

- Step-Response, e.g. Polarisation-Depolarisation Currents (PDC)
- Ramp-Response
- Return Voltage Measurement

Many frequencies are measured at once, but noise rejection is low.

Frequency-Domain (FD) measure $\chi(\omega)$ (plus conduction and prompt response), usually by applying a sinusoidal driving voltage $V(\omega)$ and measuring the resultant current $I(\omega)$ for various ω .

$$C'(\omega) - iC''(\omega) = \frac{I(\omega)}{i\omega V(\omega)} = \frac{C_0}{\varepsilon_0} \left(\varepsilon'(\omega) - i\varepsilon''(\omega) \right)$$
$$\varepsilon'(\omega) - i\varepsilon''(\omega) = \left[\varepsilon_0 \chi'(\omega) + (\varepsilon_\infty - \varepsilon_0) + \varepsilon_0 \right] - i \left[\varepsilon_0 \chi''(\omega) + \frac{\sigma}{\omega} \right]$$

We favour FD: ease of PD measurement, form of non-linearity.



PRACTICAL DS MEASUREMENTS

Basic Measurement sees:

- Free-space capacitance
- Polarisation current
- Bulk conduction
- Surface conduction
- (Fringing, material case)



Guarding: remove surface conduction and fringing.

Removal of conduction current is harder: PDC time-domain methods, or analysis of frequencydomain results within assumptions of linearity.

On actual equipment, one might be less interested in the material properties than in the total current.

Non-linearity measured with $\ensuremath{\mathrm{FD-DS}}$

Non-linearity: $\frac{\text{out}}{\text{in}}$ relation is dependent on amplitude.

Currents at frequencies other than the fundamental iff non-linear or supply voltage not sinusoidal.

Frequency-representation allows even small non-linearity to be seen.



Frequency-representation still allows a lot of directly interpretable information about the form of the time-domain distortion (odd/even, sine/cosine).

C' and C'' are values calculated on the fundamental components: C'' maintains its significance of power loss.

$$\bar{s}(t) = \operatorname{Re}\left[\sum_{n=0}^{K} |S_n| \mathrm{e}^{\mathrm{i}(n\omega t + \angle S_n)}\right] = \sum_{n=0}^{K} (A_n \cos(n\omega t) + B_n \sin(n\omega t))$$

HV-(FD)DS System







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Applications of HV-DS

- Why HV?
- Non-linearity
- Higher current (SNR)



Development of HV-FDDS field-test system Water-trees in XLPE cables (picture \longrightarrow)



ETK Aesthetic Obligation

Machines: usually in time (TD)
Megging? (Qualifies? Inverse Step Response!)
Ramp test
A little recent research interest, TD & FD
End-windings often guarded! (lab, not field)

- 1. Stator insulation
- 2. (HV) Dielectric spectroscopy
- 3. (VF) Partial discharge measurement
- Partial discharges (PDs)
- PD detection and analysis
- Effect of frequency on PDs
 - PDs and PD measurement in stator insulation
 - 4. End-winding stress-grading
 - 5. Examples on real stator insulation
 - 6. Conclusions



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PARTIAL DISCHARGES (PDS)

A discharge that fails to bridge the space between the electrodes that are applying the field; it therefore cannot develop into a disruptive discharge. For example:





Presence of PD can suggest a problem in an insulation system; detection methods may allow a distinction to be seen between different sources of PD activity.

PD may cause insulation degradation by thermal, chemical, electrical and radiation effects.

PD DETECTION

Many detectable consequences, for example ...

- released chemicals, e.g. Ozone (O_3)
- remnant chemical effects, e.g. powder on surfaces
- sound, ultrasound
- visible light, UV light
- RF emission
- HF and total (integrated) currents in supply \iff

Some give an averaged idea of PD activity, some give information about each PD event (pulse).

Some localise the PD sources.



PD CHARGE & CALIBRATION

PD charge > measured charge



Simplistic relation of actual and measured PD charge, assuming cavity voltage not changed. $Q_{\rm apparent} < Q_{\rm actual}$

 $Q_{\text{apparent}} \propto \text{energy in PD}$ (fixed V)

Calibration: relate measured Q_{apparent} to a known injection at the terminals.

Frequency-response (spectrum of pulse) can affect measured charge. DS methods *can* (but needn't) capture the whole measured charge.

VF-PRPD System



Measuring impedance is typically in test-object earth for lab, or in coupling capacitor earth for field tests of earthed objects.

Here, all but the PR-PD system is 'home-brew'.

Phase-resolved PD: Simple Example



For each cycle, for each phase-channel (x), any measured PD charge, Q(y) increments the count in that phase-amplitude (x-y) point.

Phase-resolved PD: Typical Plot





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Intense cluster at bottom is typical for cavities; here there are also many, widely distributed, large charges — delamination?

Phase-resolved PD: View as Current





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PD with Variable Frequency Excitation

Sources of frequencydependence



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 τ_{cavity} — relaxation of voltage across the cavity due to conduction of current through σ_{surface} on the cavity's walls. τ_{material} — relaxation of (space-charge) field in material, due to $\varepsilon_{\text{bulk}}$ and σ_{bulk} . $\tau_{\text{statistical}}$ — delay due to the (random) occurrence of a suitable initiating ionisation in the cavity volume v.

Consider e.g. large and small σ_{material} and σ_{surface} , or both = 0.

EXAMPLE: PD FREQUENCY-DEPENDENCE

Number of PD pulses from a single cylindrical cavity. Note the greater distinction between different cavities when at low frequency.



PD MEASUREMENT ON STATOR INSULATION



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Several very different sources: different magnitude to fit between detection threshold and full-scale

Large size: many 'simultaneous' PDs: some lost in dead-time?

PD propagation: stator is large, contains magnetic material but also the unshielded end-windings; measuring system frequency-response important.

Frequency-Dependence of Stator PD

All 3 general-case effects τ_{material} , τ_{cavity} , $\tau_{\text{statistical}}$ may be involved in the many sizes and shapes of cavity and delamination that can all be present together within the insulation.



Around the end-windings: PD on the surface, damaged stress-grading, conductive contamination; PD between end-windings.

Spreading of earth potential increases the stress in the insulation material under the stress-grading — more PD, from this part of insulation too?

At extreme low frequency, end-winding stress-grading may have earth potential up to its end — surface PD?



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(end of SI, DS, PD overview)

Advantages: \mathbf{HV} -FDDS or \mathbf{VF} -PRPDA

FD-DS is here extended with the independent (controlled) variable of voltage amplitude, V, and with the independent (measured) variable of the low harmonic spectrum.



- excite non-linearities in the test-object
- distinguish non-linear components in the current

PRPDA is here extended with the independent variable frequency, f. — get a better idea of location and type of PD sources — reduce driving voltage source if able to stay $\ll f_{\rm n}$

SIMULTANEOUS VF-PRPDA AND HV-FDDS

Both methods require a quite expensive HV amplifier, driven by the controlling computer.

Both methods may take a *long* time, when doing LF sweeps at several voltages!



Both methods give complementary information, and it may even be good to compare measurements from the same measurement time if PD currents measured by the two systems are to be compared.

 \Rightarrow combined system, measuring simultaneously, gets more information, more directly comparable information, takes no more time than using just one of the methods, and costs less than the sum of the separate systems.

SIMULTANEOUS MEASUREMENT: USEFULNESS

Simultaneous Measurement even without a strong link between DS and PD measurements may be useful in itself: more clues to the state of the insulation, without extra measurement time.



If PD current seen by integrating charges measured by PD system is very similar to the PD current measured in the DS system, the PD part of the DS measurement could be removed. If not, then there are two measures of PD, which may be a useful complement.

- 1. Stator insulation
- 2. (HV) Dielectric spectroscopy
- 3. (VF) Partial discharge measurement
- 4. End-winding stress-grading
- Purpose and methods
- Significance to HV-DS and VF-PD measurements
- Material properties, SiC paint and tape
- Physical test objects
- Numerical modelling
- 5. Examples on real stator insulation
- 6. Conclusions



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END-WINDING STRESS-GRADING

High surface field if slot semiconductor just ends.(Why not continue the slot semi-

conductor at the ends?)



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Must reduce the field to prevent surface discharge.

'Grading' around the end:

- geometric, refractive, capacitive: nice frequency-response, too much space!

resistive: frequency-dependence,
so only useful for a narrow frequency band

- non-linear resistive: small space, wide frequency range; but, wreaks havoc on measurement of small V and f dependencies in diagnostic measurements!

Effect of Stress-Grading on DS & PD

\mathbf{PD}

Very low frequency spreading of earth potential: surface PD? Variable stress in insulation under the stress-grading: varied PD?

\mathbf{DS}



Considerable (some %) increase in C', much more in C''Large *change* with V ('tip-up') in C' and C'' ($\Delta C' \approx \Delta C''$) Large change in C' and C'' with frequency Non-linearity: harmonic currents from a source other than PD

Need to determine current into grading, in order to remove it from DS measurement, if any more 'material' property is to be seen or if PD current is to be seen from harmonics. This modelling is described here ...

Possibilities of Use of Model



Get some manufacturer data or do a brief measurement to determine parameters. Then calculate and subtract the stress-grading current! *FAIL:* hopelessly poorly defined parameters: material *and* geometry.

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Measure DS, use V, f dependence to determine parameters. Problem of PD currents having also a non-linear source. Is DS of stress-grading *below* the PD inception level sufficient?

Physical test-objects





PTFE tube (inner 20 mm, outer 31 mm), tightly around a metal tube, with central external metallic electrode and stress-grading material on either side. Low loss/dispersion apart from grading.

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SiC-based grading materials



SiC material around a 30 mm diameter insulating tube. The resistivity spans several decades even just up to 300 V/mm. The measured results are well fitted (the black circles) by:

$$I_{\text{axial}} = E_{\text{axial}} G_0 \exp\left(n|E_{\text{axial}}|^{2/3}\right)$$

Note the huge variation with the paint — a matter of thickness.

SiC-based Grading Materials

$$I_{\text{axial}} = E_{\text{axial}} G_0 \exp\left(n|E_{\text{axial}}|^{2/3}\right)$$

This equation is numerically friendly, e.g. the case E = 0. With I_{axial} in A, E_{axial} in V/m, the parameters are:

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Material	$G_0 (\mathrm{Sm})$	n	$ \rho(0)_{\text{surface}} = \frac{2\pi r}{G_0} (\Omega) $
Paint(thin)	2.5×10^{-16}	0.00114	3.9×10^{14}
Paint(medium)	1.8×10^{-15}	0.00115	5.4×10^{13}
Paint(thick)	1.0×10^{-13}	0.00110	$9.7 imes 10^{11}$
Tape	5.5×10^{-13}	0.00115	1.7×10^{11}

The "non-linearity" coefficient, n, is very similar in all cases. It is small as E is in V/m.

TAPED BAR: PURE GRADING RESPONSE

 $C_{\text{plotted}} = C_{\text{measured}} - C_{\text{LV,nograding}}$



Nearly a plain f shift in loss-peak with V

Low V case nearly linear: $C' \approx C''$ at HF

'Full' (whole grading length) C' at LF

C'' at LF and HV (high stress at grading end) rises: surface leakage?

A GENERAL 1D GRADING MODEL



 $R_{\rm s}$ surely non-linear. End-leakage? $C_{\rm s}$ needed? $C_{\rm s}$ constant? Assumes symmetry around axis. $R_{\rm s}, C_{\rm p}$ alone popular even at HF.

WHY CONSIDER SIMPLE CASES (LINEAR, DISCRETE)?

The real case and the realistic 1D models have parts that resemble simpler models, e.g. with low frequency or low voltage-amplitude.
People often simplify the real case to a very primitive model for quick qualitative discussion: how wrong is this?



Vsupply Vsupply Usupply Usuppl





In the plot here (left), three values of R are used, as a crude approximation of voltage-dependent grading.

This is the Debye response, seen earlier. Slopes (log-log) of ± 1 for C'' away from loss peak, and -2 for C' at frequencies above loss-peak.

$$C' - iC'' = \frac{C_{\rm s}}{1 + \omega^2 R_{\rm s}^2 C_{\rm s}^2} - i\frac{\omega R_{\rm s} C_{\rm s}^2}{1 + \omega^2 R_{\rm s}^2 C_{\rm s}^2}$$

LINEAR, DISTRIBUTED: A DIFFUSIVE TL

The FD Transmission Line equations are not LC[RG] specific. Using per-unit-length values of R_s and C_p , with l as TL length,

(characteristic impedance)
$$Z_0 = \sqrt{\frac{Z_{\text{series}}}{Y_{\text{shunt}}}} = \sqrt{\frac{R_{\text{s}}}{\mathrm{i}\omega C_{\text{p}}}}$$

(propagation constant) $\gamma = \sqrt{Z_{\text{series}}Y_{\text{shunt}}} = \sqrt{\mathrm{i}\omega C_{\text{p}}R_{\text{s}}}$
 $Z_{\text{in}} = \frac{Z_0}{\tanh(\gamma l)}$ (when $Z_{\text{end}} = \infty$)
 $Z_{\text{in}} = Z_0 \frac{Z_{\text{end}} + Z_0 \tanh(\gamma l)}{Z_0 + Z_{\text{end}} \tanh(\gamma l)}$ (else)



$$C' - iC'' = \frac{1}{i\omega Z_{\rm in}} = \left\{ \frac{1 - i}{\sqrt{2}} \sqrt{\frac{C_{\rm p}}{\omega R_{\rm s}}} \tanh\left(l\sqrt{i\omega R_{\rm s}C_{\rm p}}\right) \right\}_{\rm if \ Z_{\rm end} = \infty}$$



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The Linear Models Compared



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- At high frequency, distributed case end is not 'seen', $\therefore l = \infty$ and C' = C'' because $C' - iC'' = \frac{1}{i\omega Z_0} = \sqrt{\frac{1}{i}}\sqrt{\frac{C}{\omega R}} = (1 - i)\sqrt{\frac{C}{2\omega R}}$. - At low frequency, the discrete and distributed cases are very similar; the effective length is short. - The loss peak, $\widehat{C''}$, is independent of resistance: this is seen for the

discrete case from $\hat{\omega} = \frac{1}{RC}$, and $C'' = \frac{C(\omega RC)}{1+(\omega RC)^2}$.

NON-LINEAR, DISCRETE



- Even C'' is similar for all V at LF (low stress, so small effect of non-linearity)

- Effect of V on loss peaks almost as effect of scaling $R_{\rm s}$

- Very fast HF fall-off of C' & C'', at different rates

$$V_{\rm NL} = V_{\rm supply} - V_{\rm capacitor}$$
$$C \frac{\mathrm{d}V_{\rm capacitor}}{\mathrm{d}t} = V_{\rm NL} G_0 \exp\left(n |V_{\rm NL}|^{2/3}\right)$$

NON-LINEAR, DISTRIBUTED



Comparison: Models of Varied Degree



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COMPARISON: MODEL AND MEASUREMENT



Correct Parameters? $R_{\rm s}$ $(G_0), n, C_{\rm p}$

Sufficient Model? Any need for C_s , G_{end} , etc.?

The Physical Measurement: correct subtraction of bulk current?

HARMONIC CONTENT IN GRADING CURRENT



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Solid lines: physical Dashed lines: simulation

Quite good correspondence (but this was close to the loss peak, where the model fitted well).

POTENTIAL-DISTRIBUTIONS IN THE GRADING



Improvement of Modelling

Extra components in model not very helpful. Variation of R_s (G_0) allows much improved fitting. n (non-linearity) is largely constant between the materials used. C_p maybe not so easy in real, aged insulation.



Suggestion: assume SG and PD is the only non-linearity; get SG parameters from sub-PD-inception voltages.

DIFFERENCES BETWEEN PHYSICAL MODELS AND REAL STATOR INSULATION

Geometry: not circular.

Isolation: surrounded by others, not in open space.



 C_0 typically larger (thinner insulation) in the real case. Permittivity is greater for stator insulation than for PTFE. So, C_p is larger in real case, and loss-peak at much lower frequency. — unfounded worries about PD at end at practical LF — HF part of model $(l \to \infty)$ is of most interest

- 1. Stator Insulation
- 2. (HV) Dielectric spectroscopy
- 3. (VF) Partial discharge measurement
- 4. End-winding stress-grading



- 5. Examples on real stator insulation
- Measurements on a coil, new and aged

Accelerated thermal aging, Practical stress-grading parameters, PD current by

PD and DS methods, Frequency-dependence of PD

— Field measurement on whole windings

Constraints on frequency, Variability of different measurement methods

6. Conclusions

REAL STATOR COILS: A1 & A2

Newly made stator coils. Accelerated thermal aging.



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Slot length between guards $l_{\rm s} = 1553$ mm External slot cross-section $w_1 \times w_2 = 11.5 \text{ mm} \times 33.0 \text{ mm}.$ Insulation thickness ≈ 1.9 mm. Rated r.m.s. line voltage, $U_{\rm n} = 7.2$ kV.

SLOT SEMICONDUCTOR RESISTIVITY



- Surface resistivity $\approx 5k\Omega(/sq)$ before, $\approx 2k\Omega(/sq)$ after aging. - With Al foil taped around slot-section, very small loss tip-up. - Slight voltage-dependence - blame this on the very low voltages (contact?), not important for our usual voltage levels.



Largely linear. $\approx 10\%$ increase in C', 50 Hz $\rightarrow 0.0001$ Hz $\approx 5\times$ increase in C'' in same range.

UNGUARDED DS ON NEW COIL (A1)



Not linear. Extra $\approx 10\%$ increase in C', 50 Hz $\rightarrow 0.0001$ Hz Now $\approx 10\times$ (previously 5×) increase in C'' in same range.

Guarded DS on Aged Coil (A1)



— Amplitude-dependent increase in C' and C'' is very similar, reflecting the $\approx 45^{\circ}$ phase of the non-linearity (PD).

— Amplitude-dependent increase is greater at lower frequency, suggesting greater PD charge, implying (on average) long τ_{cavity} or some external PD.

DS AND PD MEASUREMENT OF PD CURRENT

Accelerated thermally aged stator coil. PD and guarded DS.



Waveform fits well between DS and PD measurements.

Magnitude doesn't! See scaling factors for PD.

Very heavy PD: — dead-time — attenutation — spectrum



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New and Aged Coils: Lessons

Much lower frequency of the loss-peak of stress-grading than in the laboratory models.

Obvious large influence of stress-grading on insulation and PD currents.



The thermal aging at 180°C for about 1 week left a large number of PD sources throughout the previously PD-free (as much as detectable) insulation.

Even without very long windings and ferrous surroundings, DS apparently measures much higher total PD current than is seen from the calibrated PD pulse measurement.

FIELD-TEST: DS ON WHOLE WINDINGS

Large-diameter hydro-generator.

 $S_{\rm n} = 10 \text{ MVA}, \ U_{\rm n} = 6.3 \text{ kV}$

About 30 years old.

Diagnostic testing before and after some maintenance work.





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WHOLE WINDING: INSULATION 'RESISTANCE'

IR ('megging') at 5 kV.3 occasions. Measure u, v, w, uvw.

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Expect $\approx 5000 \,\mathrm{M}\Omega$ at 600 s

Large difference between phases

uvw value tracks worst of u, v, w

Large difference between the three measurement occasions 1a,1b,2!

WHOLE WINDINGS: DS WITH LV & LF



WHOLE WINDINGS: DS WITH HV





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(*Note:* a different occasion (2) from the LV&LF measurement (1b)). Too little time or current to go much lower or higher in f. A large difference in loss is seen in u, with HV.

WHOLE WINDINGS: LESSONS

Time is very limited during outage: cannot do large number of V values or very low f. Need a well-planned V, f sequence. Particular advantage of simultaneous measurements if doing DS & PD.



Winding capacitance is of the order of 1 μ F (at 50 Hz). Maximum frequency is therefore around 1–2 Hz for 5 kV test with our amplifier.

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The above points restrict the usable range of frequencies! One consequence is a reduced bandwidth requirement for the stress-grading model.

Varied V and f may have a large effect on the measurement in the presence of insulation problems.

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CONCLUSIONS

- Stress-grading model presented seems good for fundamental and harmonic components away from the extremes of frequency; components other than $R_{\rm s}_{\rm (NONLINEAR)}$ and $C_{\rm p}$
- Stress-grading model needs good parameters: the most variable is G_0 , within the expression for R_s . Infeasible in real machines to calculate parameters *a priori*; try fitting from sub-PD measurements?
- Stress-grading C' and C'' strongly disturb insulation DR and PD harmonics.
 Different V dependence: insulation DR generally quite linear, PD doesn't occur below some inception voltage.
- PD measurement with varied V and f is distinctly interesting!
- Whole PD current may be measured with (suitable) DS system; this may be a lot more than measured with a PD pulse detector (is this useful?).
 Consequently, removal of PD from DS given a PR-PDP is *not* feasible.
- Use of harmonic spectrum in DS is a good way to consider just the phenomena beyond the (largely linear) bulk material.



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CONTINUATION

- Equipment for simultaneous measurement
- More comparison of DS and PD measurement of PD current
- Approximate removal of SG harmonics to leave PD harmonics, using sub-inception sweep to determine parameters of SG
- Further investigation of frequency-dependence of PD in stator insulation
- What is a good 'index' for PD and non-linear DS measurements? For example, C'&C'' ignores substantial and interesting currents.
- Some more thorough field tests on various machines.

