

A Literature Review:  
PD Signal Propagation in Stator Windings,  
and its effect on PD Calibration.

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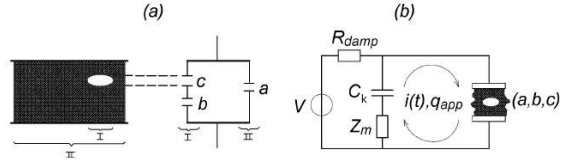
# 1 Background Details

## 1.1 Background to PD measurement

Partial Discharges (PD) are electrical discharges that “do not fully bridge the gap between the electrodes that are causing the electric field”. An example of such a situation is a gas discharge in a highly divergent field, where beyond some distance from an electrode the field is too weak for propagation of streamers. Another example is a discharge within a cavity in solid insulation, a very common situation in the insulation of high-voltage stator windings. The insulation of high-voltage stator windings consists of flakes of mica, impregnated with bitumen or resin. Some cavities are expected, due to thermal and mechanical wear and imperfect impregnation; PDs at modest levels can be tolerated due to the high withstand of mica against thermal and chemical attack. Measurement of the currents due to PDs is a common diagnostic method for high-voltage stator insulation, checking whether particularly many or particularly large PD sources have appeared.

Each PD in a HV insulation system causes a movement of charge, tending to reduce the potential between the electrodes until more charge arrives from the supply. The classic ‘abc’ model of this is shown in figure 1a. In this way, PD pulses may be seen as similar to dielectric polarisation, but in a quite large discrete pulse. Due to the generally very high propagation speeds involved in gas breakdown processes, and the small size of typical cavities, the time-scale of PDs is very short. Typically, PD pulses at the PD site are of the order of nanoseconds [Sto98], generating therefore a very wide-bandwidth disturbance in the potentials of supply wires and other nearby conductors, as currents flow to reach equilibrium potentials for the new charge-distribution.

Measurement of PD pulses is often performed by the ‘apparent charge’ method (e.g. the well-known IEC 60-270). A real PD pulse inside the test object will cause an effective charge injection to the test-object’s electrodes that is proportional to the actual PD charge and to the change in voltage across the PD site, i.e. to the energy of the PD, as can be seen by consideration of figure 1a; this injection is called the apparent charge, and is the measurable quantity. For research, high-frequency oscilloscope measurement of individual pulses’ shape may be required rather than apparent charge measurement. For industrial use in insulation diagnostics, the apparent charge is of

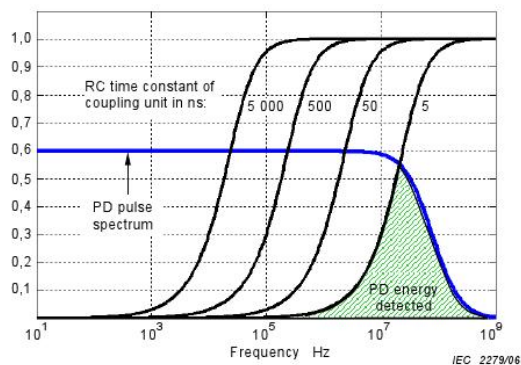


**Figure 1:** The classic ‘a,b,c’ PD model (a) for an electrically small capacitive object, together with a typical PD measurement circuit (b). From [Pem06].

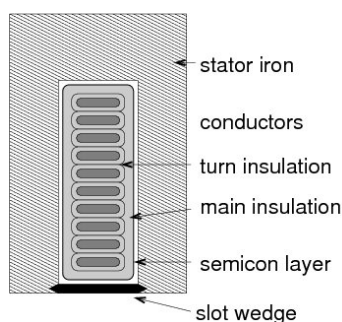
the main interest, and restriction of the measurement bandwidth is used to limit disturbances and simplify the equipment.

The test object  $C_a$  is in parallel with a ‘coupling capacitor’  $C_k$  that acts as a high-frequency source, as shown in figure 1b. This combination is connected across a supply that provides the AC excitation voltage but doesn’t supply the high-frequencies of the PD. A PD in the test object causes a high-frequency current in the loop of  $C_a - C_k$ , and into this loop is inserted a detection impedance  $Z_m$  (also known as ‘coupling device’ or ‘quadrupole’), which should have a linear relation of charge in the input pulse to peak voltage of the output pulse, given the assumed flat spectrum in the measurement frequency band. Figure 2 shows the interaction of the spectrum of the pulse in the  $C_a - C_k$  loop and the measurement frequency band. The measurement frequency band is often around 100–500 kHz for a ‘wideband’ measurement system; ours can be set from 40–800 kHz. Narrowband systems have around 30 kHz bandwidth also around frequencies in the tens and hundreds of kilohertz. Other systems extend much further up in frequency, e.g. ‘UHF’ systems employed for gas insulated switchgear can measure up to some gigahertz; these are not considered here.

For a particular test object, a calibration pulse of known charge and of rise-time less than 60 ns, is applied across the unexcited test object. The measurement system’s response is then calibrated to this charge, and the assumption of direct proportionality of detected peaks to apparent charges is used to calibrate the whole scale up to the quantiser’s maximum value. For a small test object, similar PD energies in different parts of the object can be expected to give similar apparent charges, and these will correspond well to the calibration pulses in how the system measures them; the results for apparent charge therefore have some meaning for comparisons with other equipment or other discharge locations.



**Figure 2:** Example of PD and measurement system bandwidths, from [IT06], assuming simple resistive coupling device.

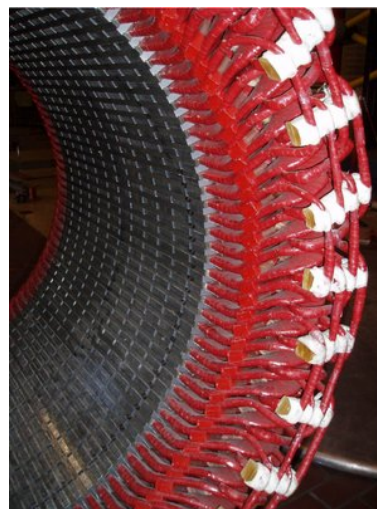


**Figure 3:** Cross-section of a simple stator coil within its slot.

## 1.2 Stator windings and insulation

The stator *core* of any a.c. rotating machine (motor, generator) is a set of thin steel laminations piled together and insulated from each other to form: a central bore in which the rotor is placed; a set of *slots* into which the windings are placed; *teeth* between the slots to carry the magnetic flux around the windings and into the rotor; a *back* (or ‘yoke’) that links the teeth together to carry the magnetic flux from groups of slots whose currents sum together.

A stator of about 1kV and higher rating has a well-defined insulation geometry, usually with rounded rectangular conductors placed together with thin insulation then all wrapped in an outer insulation in a coil or bar that is placed into a slot. An example is given in figure 3. High-current conductors often have separate parallel conductors called *strands* for flexibility, that need to be slightly insulated because of small voltage differences that are evened out over whole windings by transposition but that do exist at intermediate positions. Multiple *turns* of the



**Figure 4:** Part of a 10 MW motor’s stator core and winding, with the rotor removed. The complex-looking end-windings are in the foreground, together with the bracing required to prevent excessive movement in the event of a short-circuit.

stator coils may be contained within a single one of the prefabricated winding units, requiring modest insulation for the few hundred volts that may be developed between turns. In modern stator insulation the strand and turn insulation may be the same. The whole set of conductors is then surrounded by the *main* (or ‘*ground-wall*’) insulation to insulate the conductors from the earthed metal core. The windings stick out beyond the core, in the *end-winding* (or *overhang*) region, in which conductors pass round to return through other slots, sometimes passing a long way around the circumference of the core. Figure 4 shows the whole assembly of an example machine.

Medium-rated machines, generally up to tens of megawatts and some ten kilovolts, have *coil*-type windings, in which an insulated coil of two slot-parts and their end-winding connections is prefabricated, then the slot-parts are inserted into their slots and the conductors (both electrical ends of the coil emerge at one geometrical end) are joined to those of the adjacent coils in the winding. An advantage with this method is that several turns of a continuous conductor can be included in the pre-fabricated unit, without requiring connections to be made between the turns after insertion in the core. The disadvantage is that in large sizes the coils would be too stiff for non-damaging insertion. Large ratings of machine use *bar*-type windings, in which single slot-parts are formed (generally with continuous transposition of the sub-conductors, known as a Roebels bar) then all the connections between them at both ends are

made after insertion in the core.

A mildly conductive coating called the *slot semiconductor* or slot corona-protection is applied around the main insulation. This prevents PD in the inevitable small gaps between the bar and the stator core, but does not conduct enough to cause considerable loss by shorting-out the laminations. Values of surface resistivity range from a few hundred to some ten thousand ‘ohms per square’ (surface resistivity means a resistance between opposite edges of any square of the material, the thickness being whatever the natural thickness is for that type of surface layer), typically about  $4\text{ k}\Omega/\text{sq}$ . This slot semiconductor is quite linear, i.e. it has a near constant resistivity with applied electric field.

At the start of the end-winding region, windings rated above about  $5\text{ kV}$  have a further, nonlinear semiconductive coating over some ten centimetres or so, to limit the surface electric field where the slot-semiconductor finishes. The end-winding region has no surrounding conductor or semi-conductor, so capacitive coupling exists between the end-windings. The end-winding stress grading material is usually based on silicon carbide particles in a paint or a resinous tape; its conductivity changes by several orders of magnitude from zero field up to the few hundred volts per millimetre that are the maximum normal stress.

There are two main families of large generators. Turbo-generators are designed for high-speed (gas or steam turbine) operation, and have usually one or two pairs of poles. They have a relatively small diameter and long length of the core. The ratio of slot-part to end-windings of the winding is therefore quite high. Hydro-generators are lower-speed machines, sometimes with tens of pairs of poles. The diameters can be very large. The winding connections vary between types and ages of machines in how the electrical connections and physical placement of coils are related (lap-wound, wave-wound) and in how many parallel and series sub-units make up the whole winding. Larger machines generally have two coil-parts or bars in each slot, stacked radially; these pairs are often parts of different phase-windings.

### 1.3 Inidealities of measurement

Practical HV equipment has large enough dimensions that significant attenuation and reflection occur between a PD source and the terminals where measurement and calibration are performed). This upsets the assumption of proportionality of measured apparent charges at the terminals and the

values near the site of the PD. Rotating machines’ stator windings are especially badly behaved in this way, since they consist of inductive loops capacitively coupled to each other and to ground, passing through slots in laminated magnetic material and looping around each other at the end-winding ‘overhang’ beyond the stator core. In fact, for inductive equipment, the standards for PD measurement, e.g. [Std00] [IT06], warn against use of ‘apparent charge’ terminology, pointing out that the results cannot be compared to those from other objects or measurement systems.

The following are some effects that one might reasonably think should be considered if interested in the relation between local and measured PD pulses at various point in a stator winding: capacitive and inductive coupling between adjacent unshielded connections in the end-winding region; inductive coupling between the weakly (semi-conductor) screened coils or bars in the slot-part; capacitive and inductive coupling between turns within a single bar or coil; attenuation of propagating waves due to the semi-conducting screen; enhanced inductive coupling in the slot-part due to the presence of iron; frequency-dependence of the effective permeability of the iron, due mainly to skin-depth or perhaps partly hysteresis; resonances and general frequency-dependent behaviour due to the combination of inductances and capacitances; reflection of waves as the winding enters and exits the earthed and high-permeability core; the effect of a non-linear semi-conducting layer extending around the slot to end-winding transition; escape of HF signals by coupling to other phases or by radiation from long connectors especially in the end-windings. It is also interesting to have an idea about how widely applicable any models and measurement data are to the many various forms of stator winding.

Just to limit the scope a little, it can be pointed out that all our work is on ‘off-line’ measurements, in which a whole winding is isolated then driven at a high voltage, with the entire length of the phase, from neutral to line terminals, at this same voltage. This has the simplifying effect that turn-insulation is not stressed, so only turn-to-ground PDs need be considered. ‘On-line’ measurements are made with the normal operating distribution of potential in the windings. We also use PD equipment that can only measure frequencies between  $40\text{ kHz}$  and  $800\text{ kHz}$ , but information about frequencies beyond this range has nevertheless been included out of interest in gaining some understanding.

## 1.4 Relevance to the project

The project in which this review has been made is called ‘*Combined HV-DS and VF-PRPDA for diagnostic measurements on insulation of HV rotating machines*’. It investigates the use of the PD apparent charge method as described above, together with the dielectric spectroscopy (DS) method, as diagnostic measurements on stator insulation. HV-DS is ‘high-voltage dielectric spectroscopy’, in which the fundamental and low-harmonic components of the current into the insulation system are measured, for sinusoidal applied voltage at varied frequency. VF-PRPDA is ‘variable-frequency phase-resolved partial discharge analysis’, in which PD pulses are registered by magnitude (supposedly of apparent charge) and the phase of a.c. voltage at which each PD occurred, with varied frequency. There are several novel possibilities being investigated. The excitation of the insulation for PD measurement with *varied, low frequency* from the usual 50 Hz down even to as low as 1 mHz, may help in extracting more useful detail about the likely sources of the PD. Use of DS measurements on stator insulation is very limited so far, largely because of the effect of the end-windings transition’s non-linear semiconductor coating which interferes with other voltage-dependent and frequency-dependent effects. Use of the DS measurement to measure integrated PD charge may be of interest either as an alternative or a complement to PD pulse measurements.

DS ultimately does measure the PD currents, in their integrated form, as the supply recharges the  $C_a||C_k$  combination, provided that the HF filters don’t allow PD pulses’ charge to bypass the DS electrometer. This gives rise to the possibility of measuring phase-resolved PD current with the DS system (but without any resolution of individual pulses), or of using the PD measurements to determine what current can be subtracted from the DS current to see the PD-free behaviour of the insulation. The close relation of PD and DS has been observed and analysed already in previous projects, with simple, compact test objects. The trouble here is that for stator coils the PD system measures charges that depend strongly on the position within the coil, while the DS system measures (we expect) the whole current due to PD as well as other sources. Further effects such as multiple PDs within one measurement time-window, or PDs following previous ones before the measurement system is ready to detect them, can worsen the gap between actual PD charge and PD charge measured on a (apparent charge) calibrated PD system.

So — to the purpose of this review! Is there any hope at all of using measured PD apparent charges to compensate the component of DS current due to PD? If not, that is at least good for the potential use of DS as a less position-dependent PD measurement. To give a better idea of good settings for the PD system, such as detection passband settings, what sort of spectrum is expected from the terminals of a full machine stator or single coil in air, when excited by an impulse within the winding?

## 2 Summary of Literature

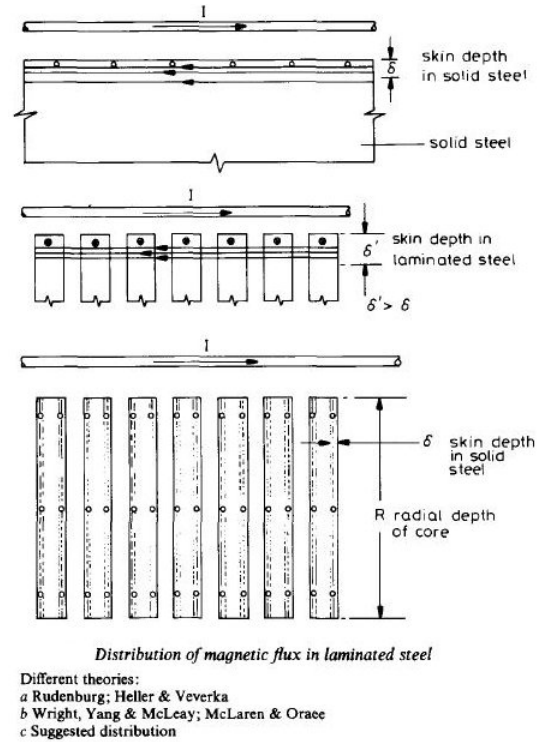
Relevant literature was found by a search according to keywords<sup>1</sup> (see appendix) and from the extensive section A.2 in the bibliography of the IEEE Standard [Std00]; some further works were then found from the bibliographies of those already acquired. The most important points from each paper are summarised here, sorted by year of publication. The division of each summary is into four sections: *Purpose* describes any claimed point of the work; *Claims* quotes any interesting claims made, other than results from the authors' own experiments; *Method* has salient points about test-objects and apparatus; *Results* is usually the major section, of the authors' own results and their apparent usefulness. Apart from parenthesised comments about the importance, unclarity or apparent absurdity of claims or results, the aim is to give only the authors' claims, leaving analysis for the later section that gives a summary of all the literature.

[Tav88] **Coupling of discharge currents between conductors of electrical machines owing to laminated steel core.** P.J. TAVNER AND R.J. JACKSON, 1988

**Purpose:** Describe the inductive component of coupling between conductors of a winding, through the laminated steel core. The work has been done to increase understanding of the modification of PD pulses between source and measurement. Questions to be answered are: what is the flux distribution due to a current in the slot at frequencies greater than power frequency; how does the effective permeability of a laminated core vary with frequency; how does the coupling coefficient between conductors vary with frequency; at what frequency does the laminated core become an 'impenetrable flux screen'. (This is a very well-written and thorough work, from an olden-days-utility research laboratory.)

**Claims:** Previous work has assumed that the pulses of interest have such high frequencies that no penetration of the steel by magnetic field will occur, and therefore the permeability of the steel can be ignored. This was asserted by Rudenburg, Veverka and Wright, and used as an assumption for a model. Wright is quoted as claiming that 'The behaviour of the core iron under these circumstances [1 MHz] is like that of an impenetrable earthed sheath', to

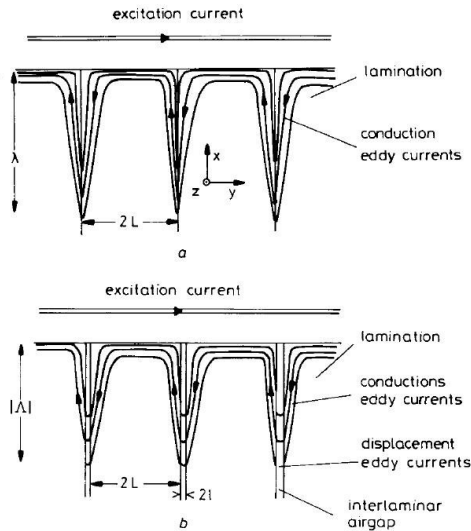
<sup>1</sup>The main source is the IEEE Xplore website, since brief searches elsewhere showed very little material of direct relevance. It is understandable that the rather practical IEEE would have more relevant material in this subject than, say, Elsevier, Physics journals, etc.



**Figure 5:** The claims of previous groups (top, middle) and the proposal of [Tav88]

which the retort is given that 'These conclusions were drawn in these three references despite the fact that the core is laminated at right angles to the flow of any eddy currents which would act to screen the core'. McLaren later justified the claims of an impenetrable sheath by pointing out that the thin insulating layers would be low-impedance capacitors at the frequencies of interest. This paper proposes looking at the skin-depth around each lamination piece, as in the final part of figure 5, as being more appropriate than the simple 'impenetrable sheath' or the modest skin-depth approaches. The path then taken by the flux is as shown in figure 6. Other work on pulse propagation speed is cited as showing propagation speeds that indicate a significant effect of the iron core even at the frequencies at which the core has been claimed by others as impenetrable by magnetic flux.

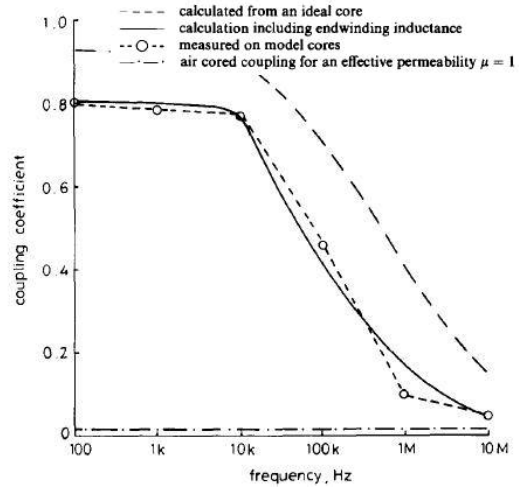
**Results:** There is a lot of work using some existing literature and analytical derivation of models, in the early sections and in the appendices. A model is derived, and is tested against a simple toroidal core arrangement, with much better agreement than is obtained by the other more simple models; see figure 7. For practical materials and lamination of a large generator, displacement currents between laminations will not significantly reduce the effective permeability up to 20 MHz. Both types of core



**Penetration of high frequency magnetic flux into laminated core**  
*a* The effect of neglecting displacement currents when the penetration is equal to the pitch of the excitation winding  
*b* The effect of interlaminar displacement currents at high frequencies when the penetration depth is less than the pitch of the winding

**Figure 6:** Currents between and through the laminations. The magnetic flux (not shown, but normal to this plane) can only occupy the space between the excitation current and the point in the iron in which the opposing current has integrated to the same value. When the currents in the iron do not lie on the surface, the iron is permeable to the magnetic flux. From [Tav88].

used for measurements had greater than unity effective permeability up to 1 MHz. Measured permeability at high frequency is generally lower than predicted, perhaps due to hysteresis. Coupling is measured as the ratio of mutual inductances between bars to the self-inductance of one of the bars. Values from 3–10% were found here, and 25–65% is ‘expected’ for a large turbo-generator core. The finite permeability is therefore expected to influence propagation of PD pulses in stators. ‘The laminated steel cores of generators and large motors, made up of laminations of 0.35 mm or 0.5 mm thickness, make a significant contribution to the coupling between the conductors embedded in them at frequencies up to 20 MHz.’ This decreases the propagation speed of series mode propagation, and increases the coupling of parallel mode currents. Penetration of magnetic flux into the core depends not only on the frequencies involved but also on the radial depth of the core, and on the stacking factor.



**Figure 7:** Comparison of the proposed and earlier models with measurements, for the coupling coefficient (ratio of mutual inductance to self-inductances between slots). From [Tav88]

**[Gea90] Towards improved calibration in the measurement of partial discharges in rotating machinery.** R. GEARY, I.J. KEMP, A. WILSON, J.W. WOOD, 1990

**Purpose:** Improve calibration of stator PD measurement by using DSP methods to determine the most likely source of a measured PD signal, based on the mixture of high and low frequencies and their spread in time, then from this to be able to estimate the form of the PD at its source. The paper is mainly a review and suggestion, rather than a concluded project.

**Methods:** One of the authors had results from pulse injection at various points in the winding of small (6.6 kV motor) and large (500 MW generator) windings, with wideband (0–17 MHz) detection. By another of the authors, variable rise-time pulse injection around the ‘parallels’<sup>2</sup> of three motors were measured with 30 kHz and 70 kHz narrow-band, and 20–200 kHz and 30 kHz–100 MHz wide-band PD systems as well as with a 10 Hz–500 MHz spectrum analyser. Further measurements were made on a 6.6 kV motor stator with 5–300 ns pulses injected and detected at phase terminals and inter-coil links, using a 400 MHz oscilloscope.

**Results:** There were similar qualitative properties for all machines studied: a high-frequency fast pulse with transit time of <50 ns, followed by lower frequencies delayed by times dependent on winding lengths. The high frequencies are thought to couple

<sup>2</sup>The parallels are the conductors in the end-windings that link together the coils from different poles that are on the same phase; i.e. they are ‘bus-bars’ in substation terminology.

capacitively between end-windings, and the lower frequencies to travel through the windings. An injected pulse gave a flat spectrum from 10–400 kHz when injected at the measurement terminals: but, with injections within the winding only, narrow-band peaks were measured, of up to ten times the flat spectrum’s level. The further measurements showed no dependence on which way round the injection and measurement were made. The fast component was not significantly affected by positions of injection and measurement, but the slow component was attenuated and broadened. The ratio of the components depends also (expectedly) on the pulse rise-time.

**Theory:** The ‘Analytical Models’ section cites some interesting-looking work from the 1980s, mainly in IEE proceedings not available online from that period. Narang’s model is for predicting interturn voltages<sup>3</sup> at the ‘line-end’. It determines a wave speed and characteristic impedance within the slot-part of the winding by simple use of  $\epsilon_r$  of the insulation, neglecting the iron. Reflections at the ends are then calculated using a discontinuity impedance at the end. The initial voltages for all the turns are set by capacitive division. A lattice diagram is used to calculate the potentials over time. McLaren and Oraee use 2-port network matrices for each slot or end-winding part of the coil, cascading these to give the whole model. It is assumed that the laminated iron core around the slot-part of the coil is a barrier to magnetic flux. Jackson and Tavner have shown that flux penetration is significant below about 1 MHz (actually, that was for their model; 20 MHz was claimed for large machines), and that it permits some coupling between slots. It is finally claimed that a useful model must consider lumped end-winding and distributed slot elements, mutual inductances and radiative effects.

**[Zhu92] Pulse propagation in rotating machines and its relationship to partial discharge measurements** H. ZHU, I.J. KEMP, 1992

**Purpose:** Increase the worth of PD measurements as a measure of actual PD-site events.

**Methods:** This is a continuation in the same style as [Gea90] (probably the same ‘6.6 kV motor’). Varied rise-time pulses were injected at a phase terminal and detected at various inter-coil links.

<sup>3</sup> External impulses such as lightning or inverter drives may cause high voltages between the first few turns from the line-terminal side of a winding. Off-line measurements with floating windings, as is the main interest for us, make all parts of a winding have the same potential.

**Results:** Rise-times over 100 ns don’t really show the high-frequency component. The time between high-frequency and low-frequency components is proportional to electrical distance between injection and measurement. The low-frequency component has two parts, of which the second seems to be a reflection; its transit time decreases with increased electrical distance. The low-frequency propagation speed is about 125 m/ $\mu$ s. The high-frequency component was not as high a proportion of the low as it was in the previous investigation, [Gea90]. The high-frequency coupling is suggested as likely to be more inductive than capacitive, but this is argued little and poorly. It is pointed out (not clear in previous descriptions and [Gea90]) that the measurements on the 6.6 kV machine were made *with the rotor removed*. It is claimed that the presence of the rotor would block much of the HF coupling, leaving mainly the much less rapidly attenuated propagation along the winding. The lowest measurement frequency band, 20–100 kHz, is therefore recommended as giving the least position-dependence in measured discharge magnitude, leading to variations of ‘just’ 2.5 times in the ratio of injected and measured pulses.

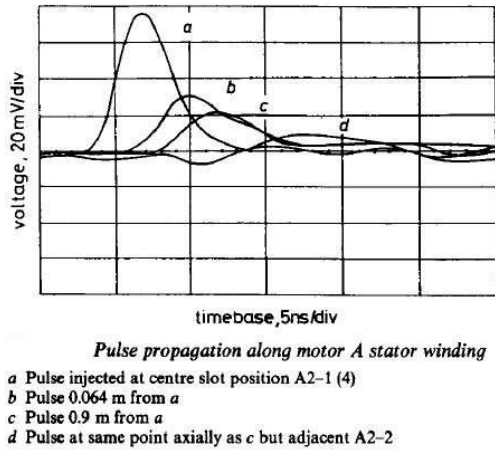
**[Woo93] Partial discharges in HV machines; initial considerations for a PD specification.** J.W. WOOD, H.G. SEDDING, W.K. HOGG, I.J. KEMP, H. ZHU, 1993

**Purpose:** There is an interest in defining PD-test criteria for rotating machines. Is any meaningful such criterion feasible? Is there a good frequency range to use to avoid resonances and attenuation? What are the discharge signal transfer mechanisms?

**Methods:** More measurements were made, on cables, several-bar physical models, and small machines.

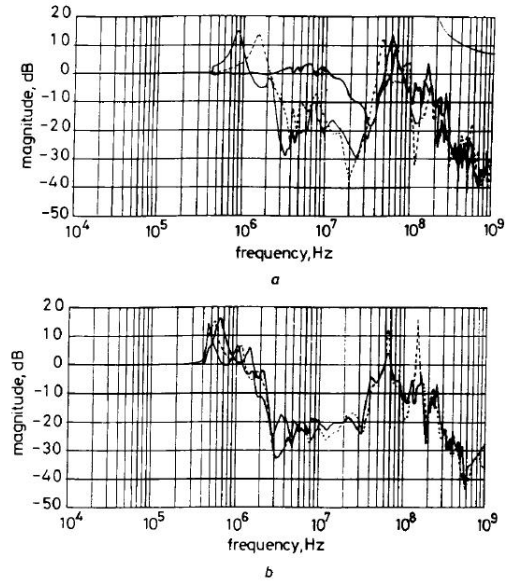
**Results:** A cable (100 m with two intermediate points) was used as a low-loss model of a winding, to see if the presence of a measuring impedance is a substantial impedance mismatch when teed off the cable; significant reflections were not seen. The small (lab) section of 500 MW stator has three slots, each with two bars stacked radially. The bars sound like real ones with epoxy-mica insulation and ‘low conductivity coating’ around them (the slot ‘semicon’). Different forms of coupling were investigated, with 5 ns risetime pulses into a bar being measured in that bar and another on a 300 MHz passband oscilloscope and (in some cases) a 35–250 kHz discharge detector. ‘Radiative coupling’ (?) between the bars was reduced by five layers of aluminium foil. Direct coupling (capacitive?) between end-windings was reduced by a factor of about 10 for





**Figure 8:** The (slow) travelling wave, attenuated and distorted along the stator winding, from [Woo93]

about 1.5 mm more separation. The description of the work with this stator model is not very clear about the test object and the purpose. For the real-machine measurements, two 6.9 kV motors were used, with different winding configurations. Measurement and injection points were added (destructively – the motors were at end of life) to give good HF connections. Time-domain measurements were made with down to 1 ns risetime of injected pulses. Figure 8 shows the delay and changed form of the travelling wave component. For frequency-domain measurements, a 10 kHz–1.8 GHz spectrum analyser with internal tracking generator was chosen over FFT or sine-sweep methods. A FET probe ‘with flat amplitude response up to 1 GHz’ was used as the sensor in all cases. Pulse injection within a slot gave no fast high-frequency component but just a travelling wave through the winding. Direct injection into the end-winding gave only about 15% of the measured signal being the fast high-frequency component. Figure 9 shows frequency-domain results, making clear the flat response up to the hundreds of kilohertz. The discussion and conclusions state that the 500 MW model showed that capacitive and inductive coupling in the end-winding is weak, and that a travelling wave is the main mechanism of transit. High frequencies, of hundreds of megahertz and above, are strongly attenuated. Lower frequencies still greater than some hundred kilohertz have peaks and troughs of reflections and resonances. Below some hundred kilohertz there is a very flat response. A terminal-to-terminal calibration in this flat region should be enough for good PD calibration; that is, inject the calibration pulse at one end of the winding, and measure at the other end. Aspirations are mentioned of modelling



**Figure 9:** Spectrum analyser measurement of winding frequency response, from [Woo93]. All have the same detection point, at the end of the winding. a) shows results for injection points within the slot in the nearest three turns, then b) shows results for the next three turns (connected by a longer end-winding section).

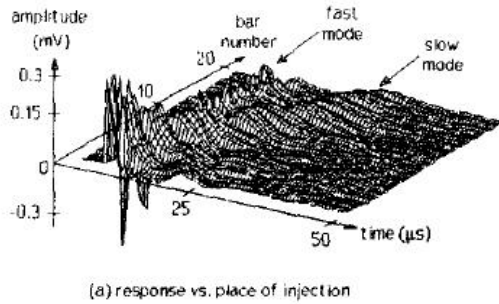
sections of the winding by cascaded transfer functions, to relate measured to actual PD waveforms.

[Pem94] **Partial discharge monitoring of turbine generators; laboratory and live measurements.** A.J.M. PEMEN, P.C.T. VAN DER LAAN, P.T.M. VAESSEN, 1994

**Purpose:** Localisation of PD. There is also some interest in estimating the local apparent charge.

**Method:** Measurements were made on a rotorless 35 MW generator in a lab, and some verification of inter-phase end-winding crosstalk on a 125 MW generator in service, using capacitive coupling and rogowski coils. The 35 MW stator had pulses of <1 ns rise-time and 50 ns duration injected, by a coaxial cable’s inner conductor going through a drill-hole in the insulation and the outer shield being well connected to the iron core, with a 50 Ω resistor included (presumably as shown later in figure 19) in an attempt at matching. ‘Adequate EMC-measures were taken’ (against interference), citing a 1990 PhD [Hou90]. All six winding terminals could be accessed for measurement. The digitizer used had a bandwidth of 1 GHz.

**Results:** The propagation speed in the slot-part of the winding was 80 m/μs. The slow (travelling wave) and fast (end-winding coupling) components were seen. These are shown in 10. Other results



**Figure 10:** Presentation of response *vs.* position of injection, for the 35 MW stator in [Pem94]

and conclusions are more related to on-line measurements, e.g. using simultaneous measurement of all phases to see which phase had the discharge even in the presence of cross-talk.

[Zho95] **The PD pulse behaviour in rotating machine stator windings.** C. ZHOU, I.J. KEMP, M. ALLAA, 1995

**Purpose:** Usual justification: aiming at better relation of measurement to the actual PD event.

**Method:** Usual method: the 6.6 kV rotorless motor. It's well described here, as is the measurement equipment of a 1 GHz BW FET probe and oscilloscope.

**Claims:** Simulation of a 'practical PD pulse' should have rise-time between 350 ps and 3 ns, and a duration of 1–5 ns. From this, one expects almost linear increase in measured energy with increased bandwidth up to about 200 MHz, in absence of noise or modification of the pulse. Earthing is mentioned, in its importance in HF measurements. (It is not very clear exactly what is claimed as the origin and extent of the troubles from not earthing well.) The travelling wave has a component in the core and frame, and with improper earthing this may distort the measured pulse waveform; also, at HF, improperly earthed core and frame increase the coupling between coils. All earths [presumably the injection and measurement?] should be commoned to a single point. (Sounds odd – doesn't this demand rather large loops?)

**Results:** Using 100 ns, 50 ns and 5 ns rise-times, the same basic results are obtained as in the earlier publications by Kemp's group, with some fast high-frequency coupling for short rise-times. (The analysis states the fast coupling is 'radiative' coupling 'through displacement current' which sounds as though the use of 'radiative' in other publications also referred to near-field displacement cur-

rent. Note the contrast with the inductive coupling suggested in [Zhu92].) For the machine tested here, about 10 MHz was a break-even point between the magnitudes of the slow travelling wave and fast capacitive coupling components of the measurement. The travelling wave component became a smaller proportion of the total measured signal when the stator was poorly or not at all earthed. The resonances noted in [Woo93] when above the flat low-frequency (up to hundreds of kilohertz) band are not significant in the measurements here, i.e. there is just a general attenuation. This is attributed to differences between multi-turn coils (more lossy) and large stator bars (why?).

[Hud96] **Investigation of partial discharge signal propagation, attenuation and pattern recognition in a stator winding.** C. HUDON, P. GUINIC, A. AUDOLI, 1996

**Purpose:** Not clear. Claims the patterns (PRPD) can distinguish slot or end PD (as is well known) and there is significant signal attenuation even below 1 MHz (also well known).

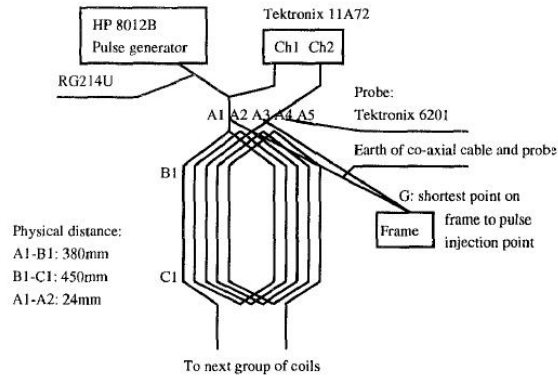
**Results:** Measurements have been made on a small, 3.5 MW, machine. The most interesting figure is number 7 within [Hud96]. It shows a full PRPD pattern for three placements of the PD source. There is not enough difference between the patterns that one can feel confident the variation is mainly due to the controlled parameter rather than to chance!

[Kem96] **Measurement strategies for PD testing and pulse propagation in stator windings.** I.J. KEMP, C. ZHOU, 1996

**Purpose:** Recent work on modification of PD pulses within stator windings has 'poor comparison' between results (i.e. it seems to be saying that different groups have inconsistent results). An experimentally based investigation of the importance of experimental techniques is therefore attempted here. Actually, the content is very little, and no real analysis is made, notably about the important matter of earthing.

**Claims:** The usual things about 350 ps–1 ns rise-times of PD, poor emulation of this by calibrators, and position-dependent modification of pulses in the winding.

**Method:** Again, a rotor-less 6.6 kV motor stator (star-connected, diamond-wound) was used. This paper gives further details about the stator and the measurement equipment – far more than in the previous papers from this group. The pulse generator had a minimum rise-time of 5 ns. The os-



**Figure 11:** ‘Basic configuration’ from [Kem96], included partly out of EMC interest in earthing.

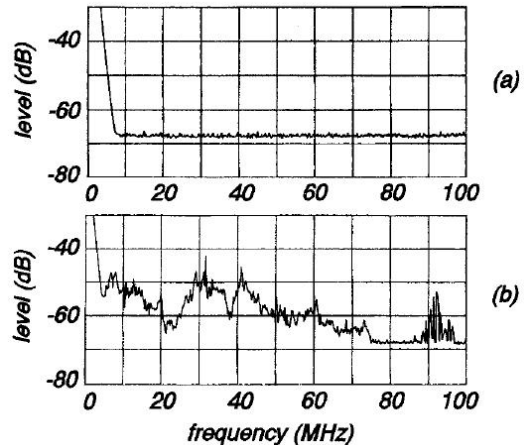
cilloscope, FET probe and RG214/U cable all had 1 GHz bandwidth. A lower-bandwidth (200 MHz) probe and ‘normal’ cable were ‘found to distort the PD pulses significantly’.

**Results:** Pulse amplitude is decreased by reflection at the injection point. No mention is made of using a matching resistor. Earthing: figures show an applied 5 ns or 50 ns pulse, together with the signal at some other points (A1,A2,A3 of figure 11) with good earthing or no earthing of the stator. ‘Earth’ is presumably the signal earth for their instruments. Without earthing, the coupling (fast) components are stronger and the travelling (slow) components are weaker. The explanation at the end of the section is rather shaky. Pulse width is important in determining proportions of travelling and coupling components; the need for similar spectra of PD and calibration is again stated.

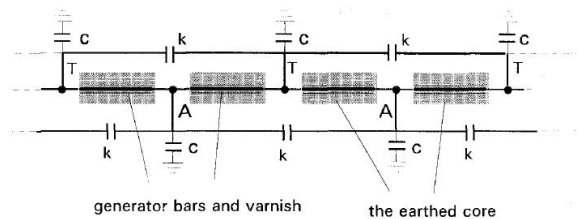
**[Pem01] Pitfalls of partial discharge measurements on stator windings of turbine generators.** A.J.M. PEMEN, P.C.T. VAN DER LAAN, 1996

This isn’t really about propagation within the windings, beyond cross-talk in the end-windings. It is mainly oriented to on-line measurement, and choosing a narrow (but high – tens of megahertz) frequency band in which only the PD signals are dominant.

What is interesting is the initial EMC emphasis! The importance even of the connectors in reducing noise is shown (see figure 12 here), and the measuring equipment is said to need to be in an EMC cabinet. (For our much lower normal frequency range of interest, this is presumably not as important).



**Figure 12:** Effect of ‘good’ N-connectors (a) versus ‘bad’ BNC-connectors (b) when short-circuiting the sensor side of a spectrum analyser’s cable; from [Pem01]

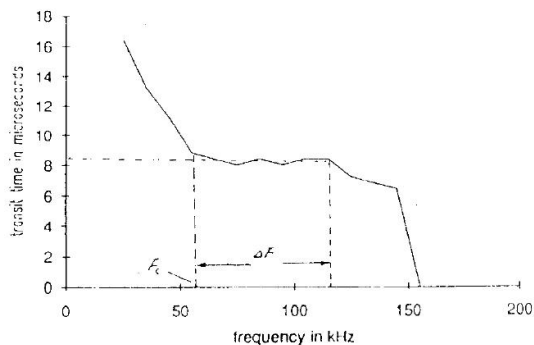


**Figure 13:** Transmission line with end-winding capacitances (to ground, C, between windings, k), from [Su97]

**[Su97] Travelling wave propagation of partial discharges along generator stator windings.** Q. SU, C. CHANG, R.C. TYCHSEN, 1997

**Purpose:** Improve accuracy of apparent-charge PD measurements, using a travelling-wave model and a suitably low frequency-range of detection; this has been part of the authors’ work for a decade. The aim is of course very similar to that of many the previous papers. The modelling focus here is on the travelling wave rather than on the fast coupling.

**Claims:** Stator windings can ‘significantly attenuate and distort’ signals at higher frequency than 10–50 MHz. In the lower range 100–300 kHz the effect is small. From ‘theoretical analysis and test results’, a stator winding can ‘always be approximately represented by a transmission line’ within ‘a certain frequency range’. Travelling wave speed in this frequency range increases with frequency. Newer stators with wave-type windings and multiple parallels in each phase have a stronger mutual coupling that makes the travelling wave mode less obvious. The iron core around the slot-part of the winding has a high permeability at low frequency, leading to high inductive reactance. It’s not clear



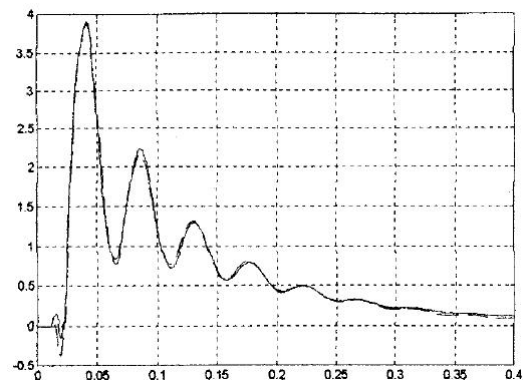
**Figure 14:** Transit time,  $\mu\text{s}$ , between ends of a phase of a 350 MW turbo-generator, from 10 kHz to 200 kHz. From [Su97].

which of the claims about speeds and frequencies. in the ‘PD Transmission Modes’ section, are from the model and which are from measurements. Nor are results from the model compared to those from measurement. Four modes are proposed. *Low-frequency travelling waves*, from about 10 kHz up to 100–300 kHz, presumably dependent on the stator’s construction. The attenuation is very small. Travelling wave speed is 20–100 m/ $\mu\text{s}$ . *Travelling waves along the slot-parts*, normally above 200–500 MHz. There are high losses, and distortion. Travelling wave speed is 150–250 m/ $\mu\text{s}$ . *Travelling waves along end-windings*, mainly of interest with hydro-generators due to their large diameter and consequent long paths in the end-windings. Losses are low, and speed is up to 250 m/ $\mu\text{s}$ . *Capacitive coupling between end-windings*, especially important for turbo-generators (compact windings in a small radius).

**Results:** Spectrum analysis was used on measurements of pulses injected at the remote end of the winding. A derived transit time, i.e. a measure of mean propagation speed, is shown in figure 14. The final section describes a system using HF current measurement on the neutral to compare coupled and travelling wave arrival times for estimation of position of PDs.

[Maj98] **A high frequency model for the analysis of partial discharge propagation along generator stator windings.** S. MAJOR, Q. SU, 1998

**Purpose:** To provide a model that is sufficient for estimation of travelling waves, so that generators’ properties needn’t be measured in each case when PD signals are to be interpreted. The most interesting point is (the claim) that a fully lumped model is sufficient, when including couplings and frequency-dependence, for the frequency range up



**Figure 15:** Apparently very impressive (if only we knew how it was done) comparison of simulation (dashed) and measurement (solid) data, with no axis labelling... assume signal against time? From [Maj98].

to hundreds of kilohertz.

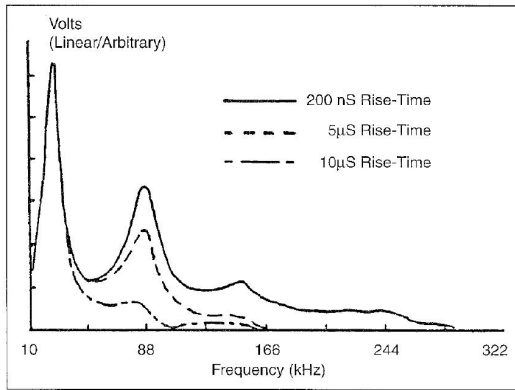
**Claims:** There are only a few dominant resonances. A lumped-element model can be made sufficient by use of sufficiently many more elements than the number of dominant resonances. Earlier models (from other groups) have neglected mutual coupling between adjacent turns and coils in the same slot, and the frequency dependence of couplings, and have assumed uniform voltage distribution between turns of a multi-turn coil. Inductance is especially frequency-dependent, due to penetration of magnetic field into the iron core: higher frequencies decrease the external inductance (due to the iron core) and the internal inductance (due to skin effect on the conductor) and increase resistance (skin effect again).

**Method and results:** A fully lumped model is shown, very hard to read. It includes inductances and capacitances along the slot-part and in the end-windings. There are connections between phases. Parameters were estimated by measurements on the whole winding. Figure 15 shows (incomprehensibly but temptingly) some results from this model. The model is stated to contain just 20 sections per phase and therefore to be unsuitable over about 200 kHz.

[Sto98] **Calibration of PD measurements for motor and generator windings – why it can’t be done.** G.C. STONE, 1998

**Purpose:** Part of an IEEE society’s magazine’s series about PD measurement, explaining the problem of PD apparent charge concepts in a complex system such as a stator winding.

**Claims:** Unlike other apparatus, stators have no established acceptance test based on PD pulse measurement, although the  $\tan \delta$  tip-up is an indirect



**Figure 16:** Transmission of various pulses from neutral to phase end of a motor winding. Note the resonances even within the 30–300 kHz band that is often mentioned as very flat. Originally in Kemp *et al.* 1987. Shown in [Sto98]

PD measurement. pC measurement, by calibration with a pulse of known charge, avoids the problem that the measured voltage depends on the object’s capacitance as well as on the discharge magnitude. The distributed and inductive nature of windings is one problem with pC measurement. Another problem is the distinction between PD as a cause or a symptom of insulation problems (as opposed to the case in e.g. polymeric cables in which any PD can be seen as damaging), which means that the size of the PD isn’t a good indicator of the current rate of damage. PD by the HV conductors, leading to turn-insulation failure, and PD tracking along end-windings, are the two main forms of PD that may actually cause damage. Figure 16 shows some evidence that, depending on a particular stator’s resonances, even a quite narrow band in the supposedly quite flat range around 100 kHz, could have calibration troubles, due to resonances. A 1987 reference is cited as giving ‘calibrated’ pC figures ranging from 60 pC to 1000 pC depending on the system used; the lowest measured values came from much higher bandwidth systems, so this should be expected from all the results of earlier papers. Ultimately, avoiding pC and using just dB or mV, then considering only trending of a particular machine, is recommended.

**[Su00] Analysis of partial discharge pulse propagation along generator stator windings.** Q. SU, 2000

**Purpose:** This promises an ‘explanation of PD pulse propagation phenomena’ by theoretical examination of models and by measurements on ‘a number of generators’.

**Claims:** Corona (air) discharges can have rise

times as low as 100 ps, and length 1 ns. Even in oil, the values are usually less than 5 ns and 20 ns. These give wide spectra, up to gigahertz, but the part that’s not strongly attenuated or resonant under 100–300 kHz. Some results from the earlier work [Maj98] are mentioned. Early developments (Wagner 1915, Bewley 1951, Heller and Veverka 1968) are mentioned, on the theory of modelling coils as lumped elements. At low frequencies, the end-winding capacitances can be neglected, to give a model with homogeneously distributed coils. The maximum frequency for which this is valid is given as about 500 kHz for continuous lap-windings, and 100 kHz for bar wave-windings. The main difference between a stator coil and a (generalised) transmission line are the capacitive couplings in the end-windings and the inductive couplings between bars or coils. There are frequencies high enough that the iron largely excludes magnetic flux (so, quite low and constant inductances) but low enough that the end-winding capacitance can be neglected, giving a band of quite flat response, as shown in figure 14. Turbo-generators generally have larger end-winding coupling capacitances, and therefore lower critical frequencies. Measurements above 20 MHz are regarded as being obviously unable to be translated into pC, but those below 1 MHz are suggested as being manageable to reasonable resolution (nothing quantitative is said). It is noted that modern epoxy-based stator insulation can be expected to have sufficiently low rate of PD events that the resolution time of the measurement system no longer requires a frequency band beyond the low-attenuation region.

**Method and results:** The results presented, of transit time against frequency, are as already seen in [Maj98].

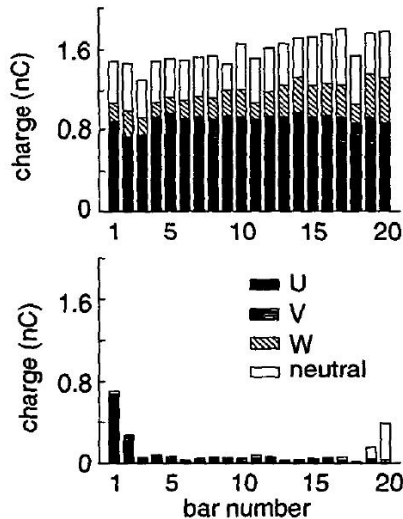
**[Pem01] Analysis and localization of spurious partial discharge activity in generator units.** A.J.M. PEMEN, P.C.T. VAN DER LAAN, W. DE LEEUW, 2001

**Purpose:** More information about the type and origin of PDs, by use of waveshape data, as well as PD patterns.

**Method:** Injection of pulses into parts of a 35 MW stator, and measurement of response at the terminals.

**Claims:** ‘Standard’ PD detectors only integrate frequencies ‘above 100 kHz to 500 kHz’ and ones for field measurements only work above 1 MHz to avoid interference. The speed of the slow mode is typically about 9 m/μs (*very slow...*).

**Results:** Above 400 kHz the fast part of the response starts to be seen. A figure is shown of



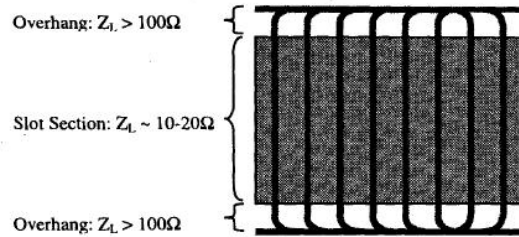
**Figure 17:** Measured charges at terminals, for different injection points. (a) is the ‘complete’ responses, (b) is the ‘fast modes’. From [Pem01]

the measured response split into the two components by filtering, as also in [Pem06]: see figure 20. The measured apparent charge as a function of the number of slots away from the injection point, figure 17 shows very little difference when the whole charge (wide frequency range) is used, but large variation when using just the high-frequency components. The winding behaves like a transmission line, with electrical-distance-dependent delay. Higher frequencies can also couple through the end-windings by ‘electromagnetic couplings’ without appreciable delay. The electromagnetic couplings also cause cross-talk between phases. The two modes’ amplitudes depend on the origin of the PD, and decrease rapidly when the PD is further into the winding. The total charge measured at the terminals is only weakly dependent on the origin. The remainder is about cross-talk, and the need for measuring on all phases to be able to tell which one really has the PD. This is not important for our use, as the off-line measurements will have only one energised phase at a time.

**[Gro02] Partial discharge measurement and monitoring on rotating machines.**  
D.W. GROSS, 2002

**Purpose:** None. But there are some interesting claims about parameters.

**Claims:** Typical stator bars have a characteristic impedance around 10–20  $\Omega$ , the smaller values tending to be true for lower voltage machines. The conductor design determines the attenuation at higher frequencies; insulated strands increase high-



**Figure 18:** Slot and end-winding (overhang) characteristic impedances from the model in [Gro02]. (Note that the frequency at which the slot values are valid is not stated here.)

frequency attenuation, and semi-conducting layers at the electrodes cause high-frequency attenuation with strong dispersion, at frequencies over a few megahertz. Outside the stator slot the characteristic impedance is over 100  $\Omega$ , so reflections are to be expected on entry and exit. Figure 18. The wave-model (‘cable-section’ model) becomes relevant when dealing with values of permittivity, slot length and frequency that a wavelength is of the order of the slot length. Increased characteristic impedance causes a positive reflection at the slot exit. The reflection is typically 80%, trapped in the slot section. Tests on various stators have shown them to be ‘relatively transparent’ at 40 kHz and below. Problems with the low-frequency band then come from the characteristics of the actual PD signals from stator windings. The band-pass filtering limits rise-time with its upper cut-off frequency, and limits ringing of the pulse tail with its lower cut-off frequency. The lower frequency therefore limits the maximum pulse-repetition rate. A thermally aged epoxy-mica stator insulation system has repetition rates of some 20 000 to 100 000 per second and needs therefore a lower cut-off not less than about 100 kHz. The rest of the paper is about the importance of high-resolution PRPD patterns, and about commercial on-line PD-measurement systems.

**[Gro03] Signal transmission and calibration of on-line partial discharge measurements.**  
D.W. GROSS, 2003

**Purpose:** A little information on validity of calibration, and signal propagation. Much the same as last year’s [Gro02].

**Claims:** The slot semi-conductor layer causes dispersion and therefore varied group-delay, depending on the thickness of the layer, the material and the frequency. The ‘corner-frequency’ for the semi-conductor layer having significant attenuation is up to 20 MHz (in contrast to the situation with cable systems, having the corner usually around 5–10 MHz). Above about 100 MHz

the semi-conducting layer is the dominant cause of attenuation. The section on reflection is largely the same as in [Gro02]. Cross-coupling and resonance are mentioned in a non-quantitative way. About ‘charge-referred partial discharge measurements’, IEC60270 recommends corner frequencies as a lower value  $30\text{ kHz} \leq f_1 \leq 100\text{ kHz}$  and upper value  $f_2 \leq 500\text{ kHz}$ , for a ‘wideband’ system. This range can be extended widely if  $f_2$  is considerably less than the corner frequency of the PD spectrum (see figure 2). The calibrator needs also to have a spectrum extending beyond that of the measurement system. Heterodyne techniques allow further broadening of the frequency range. The resolution bandwidth needs to be wide enough to separate individual pulses. Typical epoxy-mica coils have high-rate PD activity, requiring large bandwidth. ‘If an adequate low-pass filter follows the detector circuit, charge-referred calibration is possible.’ The acquisition of an integrated pulse rather than a voltage peak makes the measurement less susceptible to effects of reflection and cross-coupling. (Note: IEC60270 points out that the detector [quadrupole] should give an output whose peak is proportional to the charge in the pulse in the input circuit). After all this, the section on calibration says that for all but small simple capacitive objects the term ‘calibration’ is confusing, and the calibrator (pulse simulator) should be regarded as being used just to get an idea of the sensitivity of the measurement. Measurement of a ‘calibration’ (or ‘cross-coupling’) matrix by measurement and pulse-injection at various points is recommended as instructive for stators and transformer windings. As the structure of the PRPD pattern isn’t changed by the calibration value (even though it is changed by propagation effects from how it would seem with the same PD events right at the terminals) the pattern is still useful. To remove external noise from the typical IEC60270 frequency range (exciter switching pulses are used in the example) gating can be used to block measurement during short periods of noise. Another method is to find a (possibly narrow) frequency range at which the noise is weak. The exciter-pulse example had noise only up to 3 MHz, and a measurement at 9.4 MHz using a spectrum analyser as a front-end was able to detect a very similar pattern to the normal 100–800 kHz measurement, but without the regular exciter pulses. In summary, the message of the body and of ‘Conclusions’ seems contradictory or at least unclear. Quasi-integration (charge measurement) over a wide frequency range is touted as a way to avoid effects of cross-coupling and reflection. But a warning is given about needing to consider ‘limitations introduced by the high-frequency behaviour

of real high-voltage equipment’.

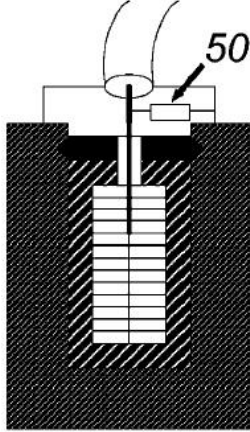
**[Pem06] Propagation of partial discharge signals in stator windings of turbine generators.** A.J.M. PEMEN, P.C.T. VAN DER LAAN, WOUT DE LEEUW, 2006

**Purpose:** A more thorough write-up of much of the work from previous papers by this group, as well as some new checks (such as the extent of coupling outside the end-windings). No aim is given, apart from summarising knowledge about HF propagation in stator windings.

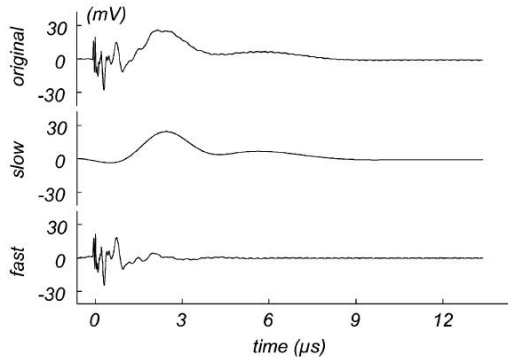
**Claims:** The classic abc PD model (see figure 1) is shown and explained. Important exceptions are GIS and HV cables: treatment as a lumped capacitance is not valid. Wave-propagation, damping and dispersion make calibration problematic in such equipment. In transformers, three main modes are found: higher frequencies, 100 kHz–10 MHz through a capacitive ladder network; travelling waves guided by the windings, up to 10 kHz; an oscillating from internal resonant frequencies from 10–100 kHz. For rotating machine stators, the literature is cited as a PD pulse ‘essentially propagating as a travelling wave and that the stator winding can be regarded as a transmission line’; the higher frequency components are capacitively coupled and are heavily attenuated; according to a 1986 reference there is cross-talk. The stator used here was 35 MW-rated, with bar lengths of about 3 m, one bar per slot. Larger rated generators have bar lengths from 5–7 m and two bars per slot. One should therefore be cautious about the relevance of results from here to other machines, but some other authors have obtained similar (regarding slow mode propagation speed and the fast/slow attenuation) results on quite different machines including hydro-generators. An attempt to measure PD apparent charge, taking into account the modification of the pulse over the distance from the source as estimated by fast-to-slow time-delays, should examine the charge of the pulse, not the peak voltage, to reduce sensitivity to frequency-dependent attenuations and distortions.

**Method:** Pulses were injected into various points on a 35 MW stator winding (presumably the same as in earlier work by this group) with the rotor removed. It is noted that this has the unusual feature, for its size, of only one bar per slot. (This might have some cross-talk relevance?) A fast pulse of 1 V, 50 ns, risetime 1 ns, was injected into several points of each coil of a phase. The response at the high-voltage terminal was measured.

**Results:** The separation of fast and slow parts of the response is shown, figure 20, as in [Pem01].

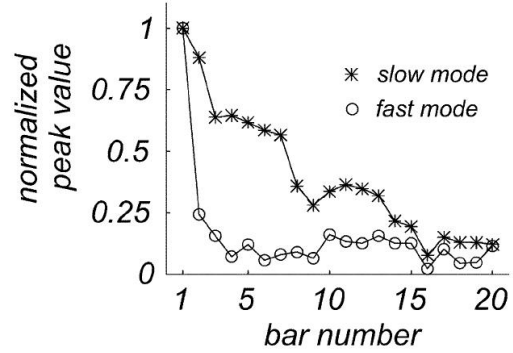


**Figure 19:** Connection of a  $50\ \Omega$  co-axial cable into the low characteristic-impedance slot-section of stator winding. From [Pem06].



**Figure 20:** Total signal, with separated slow and fast components; slow is obtained by filtering, fast by subtraction of slow. From [Pem06].

Time delays for reaching phase and neutral sides of the winding are shown, giving nearly linear plots of opposite sign, when plotted against the position of the injection point in the winding. Lack of pure linearity is confidently blamed on variation in length of end-winding links between coils (even though the propagation speed in the end-windings is very high). The transit time for a total winding-length of  $89\text{ m}$  was  $8.9\ \mu\text{s}$ , i.e. the slow mode has a mean propagation speed of about  $9.1\text{ m}/\mu\text{s}$  ( $0.03c$ ). The fast mode arrives with a delay varying from  $59\text{--}86\text{ ns}$ . This is partly the time of the coupled wave in the end-windings and partly the transit time along any proportion of the stator slot from the injection point to the end-windings. Since injections are made at several points along the slots, the propagation speed of the high frequencies in the slot can be calculated, giving  $87\text{ m}/\mu\text{s}$  ( $0.27c$ ). If all magnetic field is assumed as restricted to the



**Figure 21:** Normalised (i.e. all relative to the largest) peaks of detected fast (HF) and slow (LF) components of a PD-simulating pulse injected at increasing winding-distance from the measurement terminals. From [Pem06].

dielectric, due to exclusion of the HF field from the iron, the propagation speed using  $\epsilon_r \approx 4$  would be higher than the measured value; this suggests that the iron cannot be ignored, and [Tav88] is cited as an explanation (displacement current between laminations). A plot (figure 21) is shown, of the fast and slow modes in their peak magnitude for different points in the winding. The slow modes are visible at greater than 50% of the highest value over some 35% of the winding, but the fast modes are rapidly attenuated. This can be compared to figure 17 for charge, shown in [Pem01] as well as in [Pem06], which gives much less variation. Cross-talk between the phases is seen to be able to have a greater than unity value, i.e. the measured signal can be larger in a phase other than the one in which the discharge occurred. One obvious reason is that the windings sharing a slot or close to each other in the end-windings may have very different electrical lengths back to the measurement terminals, so the one without the PD may be a much less attenuated route. The inductive or capacitive coupling between phases was investigated by replacing the end-windings with short and well-separated copper strips. The measured response matched a high-frequency travelling wave, with the speed that already has been determined from the fast-mode measurements on injections from different parts of the slots. This suggests the high-frequency coupling occurs in the end-windings (but remember this is only a one-bar-per-slot stator). The remainder of the paper is relevant to on-line work, considering the effect of external connections and measurement points.



### 3 Summary and Conclusions

There are sufficient differences between the reviewed papers that one gets conflicting ideas about the feasibility of measuring a good approximation of the local apparent charge of PDs within a stator winding. There is clear consensus that around 100 kHz is the best band for low attenuation of signals from all points on the winding, but just how broad this region, and how flat its response, is not so clear. Some possible factors accounting for the differences are machine size, hydro or turbo design, winding connection, insulation material, coil-type or bar-type winding construction, different measurement quantities such as charge or peak voltage, different applied and measured frequency bands, and presence of the rotor during measurements.

#### 3.1 PD pulses

PD pulses in machine insulation may be expected to have a rise time of some 0.3–3 ns and a duration of a few nanoseconds. This is much quicker (higher frequency) than typical injected pulses for calibration. But, for our usual measurements in the low-frequency band from some 30–800 kHz, it can be expected that the calibration source and real PD pulses can both provide a flat spectrum within and beyond this measurement band.

#### 3.2 Fast and slow components

There is a strong distinction between a ‘fast’ component of high-frequencies that travel to the terminals by shorter routes than propagation along the conductor path, and a ‘slow’ component of lower frequencies whose transit time is proportional to the length of conductor between the PD site and the measurement. The boundary between the frequencies of these fast and slow components is in the region of 1 MHz, but is seen differently by different groups, and in some cases only the slow component is observed.

The fast coupling is of little interest to us, because it is dominant at frequencies above the range of our present pulse measurements, and because the resonances and attenuations in this range make it very unsuitable for consistent measurements with PDs in different parts of the winding. The nature of the fast coupling is contested anyway: it is shown experimentally in [Pem06] that the absence of end-windings prevents the fast coupling, but in [Tav88] inductive coupling between slots is expected, for frequencies even up to 20 MHz in for large machines; in [Gea90] the fast coupling

is thought to be capacitive, but in [Zhu92] it is wondered whether it is in fact more inductive; in [Zho95] the fast coupling is said to be due to displacement current; in [Woo93] an injection into the slot-part rather than the end-windings gave no fast component, but in [Pem06] the fast-component’s propagation speed in the slot was calculated by the measured fast component at the terminals due to injection in the slot-part; [Su97] defines one of the four signal transmission modes as capacitive coupling between the end-windings; with a rotor present the fast coupling is claimed by [Zhu92] as being reduced, which suggests capacitive rather than inductive coupling. Injected pulses of insufficiently short rise-time, e.g. 100 ns rather than 5 ns, will reduce the size of the high-frequency stimulus, changing the relative magnitudes of the incident high and low frequencies. When the fast mode propagates through the slot-part, due to injection within the slot, this is at higher speed than the slow-mode; about 90 m/μs was found in [Pem06] in contrast to 9 m/μs for the slow mode. This is due to more screening of the higher-frequency magnetic field by the stator core, and therefore a lower effective relative permeability of the core, as described in [Tav88]. The fast mode is highly attenuated within the windings, by reflections at the ends of the slot-part when the wavelength is small enough for treatment as wave propagation, and by transmission-line attenuation due to the the semiconducting layers as the frequency increases[Gro02].

The slow, low-frequency, ‘travelling wave’ mode propagates along the conductors of the winding, possibly with inductive coupling to other bars. The attenuation of this slow mode is very low, and its propagation speed is given from about 10–100 m/μs by different sources.

#### 3.3 Propagation and reflection

According to several sources cited in [Rob04], the relative permittivity of mica<sup>4</sup> is around  $\epsilon_r \approx 6$  at 1 MHz and even at ‘radio frequencies’. Typically, epoxy-mica insulation consists of more than 90% mica, so except for low frequencies where a model must take into account the field distribution due to conduction currents and mica barriers, it seems reasonable to assume that the dielectric’s permittivity is largely dispersion free (frequency-independent). Dielectric dispersion is therefore unable to account for the large differences between measured propagation speeds of low and

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<sup>4</sup> Biotite and Phlogopite forms of mica, not Muscovite; but these two had very similar properties.

high frequencies in the slot-part, and division of the free-space propagation speed  $c$  by  $\sqrt{6}$  does not come as low as the measured speeds. The permeability of the surrounding iron core must therefore be considered, even though some early sources and models ignore this completely on the grounds of the small skin depth that would be valid for a homogeneous rather than a laminated core. Due to the lamination of the stator core, the induced currents that would make solid iron exclude strongly any high-frequency magnetic field are unable to travel just on the surface, but spread deeper down and travel by displacement across lamination insulation [Tav88]. This causes the iron to carry significant flux, increasing self-inductances and inductive coupling up into the megahertz range, contrary to expectations based on the simplistic treatment.

The characteristic impedances of stator windings are given in [Gro02] as 10–20  $\Omega$  for the slot-part, with lower values corresponding to lower-voltage machines, and as  $>100 \Omega$  for the end-windings with their floating outer potential surrounded by air (and other winding-ends). Reflection of a wave travelling out of the stator core is therefore high, around 80%.

### 3.4 Measurement technique

EMC aspects of measurement, particularly when including the high frequencies of many megahertz, are important. In [Pem96] the use of an earthed EMC cabinet for the measurement equipment is recommended, and it is claimed that BNC connectors have unacceptable transfer impedance compared to N-type connectors. In [Kem96] a 1GHz cable and FET-probe was claimed to have been needed in order to avoid distortions that were found with ones rated up to 200MHz. In [Zho95] the importance is stressed of good earth connections of the injection and measuring leads on the stator core. Single-point earthing is recommended, which seems rather strange, unless only intended for the low frequencies where the required earth-tails would be much shorter than a wavelength; the paper lacked justification of this point. Bad earthing is claimed to have been experimentally seen as giving higher fast-mode coupling. This is unsurprising if the core was not tied to the measurement systems's earth and therefore could form a floating middle electrode of a capacitor between coils.

Modern epoxy-mica insulation systems have, according to [Su00], a low PD rate such that there

is no need to take the measurement systems's frequency band beyond the flat response region of up to about 100kHz; but, according to [Gro02], *thermally aged* epoxy-mica insulation has so high a repetition rate that a lower cut-off of  $>100$ kHz is needed. We have, indeed, observed that thermally aged epoxy-mica insulation can have a fantastically large amount of PD, and we intend to continue with more thermal aging. Laboratory measurements without an iron core can be expected to have different signal propagation properties, which should be considered and measured further. However, if the final aim is to make statements about how well a certain condition could have been seen in a real machine by the DS and PD methods of interest to us, then we must consider what the measurements would have been had the same aged coil been part of a winding in a complete machine.

### 3.5 Consistent measurement of PDs

The frequency range of a few tens to a few hundreds of kilohertz gives the lowest variation in measured apparent charge. According to [Sto98] this range may still not be very flat, but others show quite a flat response, such as the spectrum-analyser results in [Woo93] (which don't show *charge*), and [Pem06] which shows very little position-dependence in charge but a few times variation in voltage peaks. Measurement even with a high-frequency wideband system (up into tens of megahertz) of PD charge, rather than peak voltage, is able to give a value that is not very much (percent, ten percent) affected by position of the PD source within the winding. Good calibration requires that the calibrator and PD both have similar spectra beyond the measurement system's upper cut-off. Use of the lower frequencies avoids the large variation in HF components. Use may instead be made of a narrow band to avoid external interference or internal resonances, which is often implemented with a spectrum-analyser as a front-end to a PD system.

### 3.6 Omissions: still unclear

Most important to our later interest in propagation in stator coils and windings are these two distinctions.

Should a coil be regarded as a single loop, since the strong internal capacitive and inductive coupling would strongly couple signals in one conductor to the others, or should it be treated as several loops with moderate coupling?

How different are our coils in air in the lab, from the case of a surrounding laminated iron core? This is important for how much relevance the

results of this review have for our main form of measurement (laboratory, single coil), and for how much relevance the results we get in the lab have to the case of a complete machine.

The strangest point about all the mention of ‘travelling waves’ in many of the reviewed papers, is that the concept was often applied to signals at up to a few hundred kilohertz. The speeds given for a wave propagating along a stator slot (at these frequencies where the iron core had significant permeability) ranged from about 125 m/μs [Zhu92], through 80 m/μs [Pem94], to 9 m/μs [Pem06]. The wavelengths would be  $\lambda = v/f$ , which is smallest for large  $f$  and small  $v$ ; taking therefore 400 kHz as the upper frequency normally mentioned in this ‘slow’ low-frequency band, and 9 m/μs as the lowest propagation speed claimed in any of the papers,  $\lambda = 9 \times 10^6 \text{ m s}^{-1} / 4 \times 10^5 \text{ Hz} = 22.5 \text{ m}$ , which is several times the length even of a large turbo-generator’s stator. This high frequency would probably be associated with higher propagation speeds than was used here, since the iron’s effective permeability increases to low frequencies: the estimated wavelength is conservative! What, then, is meant by a travelling wave in a 1 m stator with a propagation speed of 80 m/μs and a frequency of 80 kHz, where the wavelength is 1000 times the slot length? This seems like a validly quasi-static situation.

SiC-based non-linear semi-conducting composites have very fast response to changed fields; grading the surface field even when subject to lightning impulses is one of their major purposes in cable accessories. Materials of this sort are applied to some 10 cm or so of the end-windings beyond the end of the (more conductive, approximately linear) slot semi-conductor layer. The transition at the slot-end is therefore not a hard transition from one sort of transmission line with a quite well conducting sheath and laminated high-permeability material around that, into an insulated but unshielded conductor in air. Rather, it is a transition of a disappearing magnetic core, then a few centimetres later a transition from a quite high-conductivity sheath to a non-linear low-conductivity one, and finally from this to no sheath (in fact, the effect of the non-linear part disappears before its end for the high frequencies). The validity of the simple impedance transition of [Gro02] is not obvious. This matter seems most relevant to high-frequencies, i.e. megahertz, where the slot length is significant compared to a wavelength; in this case it is not of great importance for us.

### 3.7 Relevance to combined DS/PD

The PD pulses themselves are very short: the resolution required for the present 256-channel PD detector with excitation of the test object at  $\leq 100 \text{ Hz}$ , is much less strict. Therefore, accurate recording of the precise time of arrival or pulse shape is not necessary, and the DS measurements of a PD pulse should match in phase those recorded with a PD system even if there is modification of the pulse by attenuation, distortion and resonances. The results of the reviewed papers suggest that there is a good chance, particularly on the large machines rather than few-megawatt motors, of being able to measure within a flat-response frequency band, from 40 kHz up to 100 kHz or 300 kHz. Troublesome resonances in this band were found in one case, in a small machine, but measurement over the whole band of 100 kHz or more would average these out a lot. It is our current practice to measure over the systems’s full range, up to 800 kHz; the higher end of this range seems from most of the results to be a trouble if well-calibrated charge measurement of pulses is desired. The familiar problem of high pulse repetition rate may also place bounds on reasonable frequency ranges, and in a large or highly aged winding may make the whole charge unmeasurable by the PD pulse-detection method rather than the DS method.

### 3.8 Future Work

A good deal of work has already been done on this subject, as shown in the references. There have been models of the laminated iron, models of waves guided between turn-conductors, and measurements using various instruments to measure real PD, other pulses, or swept frequencies, on a range of actual stators. There seems no point in trying to add to this type of work in the very small time available away from the main parts of this project. It might be of some value to make specific measurements of frequency response on test-objects in the lab, in order to get more detailed values for the propagation in the actual test-objects in use. This is not a practical way to treat whole-machine test-objects as there wouldn’t be time to mess about with such preliminary measurements in the field. The comments in [Pem94] on EMC, and the example with very different results depending on screening, will be important if trying to reach realistic frequencies of PD pulses.

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# A Search-terms and results

A search on IEEE-Explore, on 2007-05-02:

```
(
(
(generator<or>machine<or>motor)
<and>
(stator<or>winding)
<and>
(partial discharge<or>pd<or>high frequency<or>hf)
<and>
(signal<or>impulse)
<and>
(propagation<or>attenuation<or>transmission)
) <in> metadata
)
```

“Your search matched 27 of 1558879 documents.”

Of these 27, several had no relevance. All are shown in the following list, each followed by the notes originally made when selecting the useful ones.

1. Partial discharges in HV machines; initial considerations for a PD specification  
Science, Measurement and Technology, IEE Proceedings A  
\* Looks good: plenty of (Canadian) practical experience and measurement; claims that low frequencies, below slot cut-off of ~1\,MHz, are little attenuated.
2. Propagation of partial discharge signals in stator windings of turbine generators  
Pemen, A.J.M.; van der Laan, P.C.T.; Wout de Leeuw;  
Energy Conversion, IEEE Transactions on  
Digital Object Identifier 10.1109/TEC.2005.847949  
\* Includes whole-machine measurement with injected charge. Considers wide range of frequencies, and considers relation of apparent charge at site and at terminals. Claims “field” equipment generally measures only over 1\,MHz.
3. Objective methods to interpret partial-discharge data on rotating-machine stator windings  
Stone, G.C.; Warren, V.;  
Industry Applications, IEEE Transactions on  
Digital Object Identifier 10.1109/TIA.2005.861273  
\* Already got this paper, for other reasons. Not of high relevance. Mainly about mining a huge database of measurement results.
4. Travelling wave propagation of partial discharges along generator stator windings  
Properties and Applications of Dielectric Materials, 1997., Proceedings of the 5th International Conference on  
Digital Object Identifier 10.1109/ICPADM.1997.616648  
\* Worth pursuing; now claims 100-300\,kHz as low-attenuation band; travelling-wave treatment of these frequencies is claimed as the right way, and charge measurement is reasonable.
5. Advances in online monitoring and localization of partial discharges in large rotating machines  
Energy Conversion, IEEE Transactions on  
Digital Object Identifier 10.1109/TEC.2003.819103  
\* From our Chalmers & ABB friends. Not much use here as it’s mainly a brute-force attack using billions of sensors.
6. Measurement of large AC electrical machine stator windings parameters at high frequency  
Electric Machines and Drives Conference, 2003. IEMDC’03. IEEE International  
\* Not available to our subscription (damn the IEEE). Aimed at inverter-drive effects. Foil-wrapped bars measured. Two modes found. Not worth pursuing.
7. Analysis of partial discharge pulse propagation along generator stator windings  
Power Engineering Society Winter Meeting, 2000. IEEE  
Digital Object Identifier 10.1109/PESW.2000.849969  
\* Shows voltage injection and out. Claims epoxy insulation typically would have so low repetition rate as to make lower frequencies (some 100\,s of kHz) acceptable for space resolution. Some good references to follow.
8. Analysis and localization of spurious partial discharge activity in generator units  
Solid Dielectrics, 2001. ICSD ’01. Proceedings of the 2001 IEEE 7th International Conference on  
Digital Object Identifier 10.1109/ICSD.2001.955703  
\* Looks quite similar to their later paper; gives list of salient points. Again claims little dependence of measured charge upon location of source.
9. Partial discharge and dissipation factor behavior of model insulating systems\  
for high voltage rotating machines under different stresses  
Electrical Insulation Magazine, IEEE  
Volume 21, Issue 5, Sept.-Oct. 2005 Page(s):5 - 19  
Digital Object Identifier 10.1109/MEI.2005.1513425  
\* Already got, for its description of various classic PD patterns. Only mentions path-dependence as a limitation on the work.
10. New practices for partial discharge detection and localization in

large rotating machines  
Dielectrics and Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on]  
Digital Object Identifier 10.1109/TDEI.2003.1255782  
\* Again, mainly about zillions of sensors all over the place.

11. A high frequency model for the analysis of partial discharge propagation along generator stator windings  
Electrical Insulation, 1998. Conference Record of the 1998 IEEE International Symposium on  
Digital Object Identifier 10.1109/ELINSL.1998.704722  
\* few-section pi model with f-dependent parameters; intended up to ~200\,kHz, else add more sections; try reading briefly in case any real use to us.
12. The PD pulse behaviour in rotating machine stator windings  
Electrical Insulation and Dielectric Phenomena, 1995. Annual Report., Conference on  
22-25 Oct. 1995 Page(s):372 - 375  
Digital Object Identifier 10.1109/CEIDP.1995.483740  
\* nothing very special, but get and read anyway
13. Measurement strategies for PD testing and pulse propagation in stator windings  
Electrical Insulation, 1996., Conference Record of the 1996 IEEE International Symposium on  
Digital Object Identifier 10.1109/ELINSL.1996.549320  
\*
14. Investigation of partial discharge signal propagation, attenuation and pattern recognition in a stator winding  
Electrical Insulation, 1996., Conference Record of the 1996 IEEE International Symposium on  
Digital Object Identifier 10.1109/ELINSL.1996.549317  
\* Measurements on injections in real offline small hydro-generator; significant attenuation of signal even below 1\,MHz
15. Partial Discharge cross-talk recognition in rotating machines by pulse-shape analysis: preliminary results  
Cavallini, A.; Conti, M.; Montanari, G.C.; Contin, A.; Puletti, F.;  
Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference, 2003. Proceedings  
23-25 Sept. 2003 Page(s):33 - 37  
Digital Object Identifier 10.1109/EICENC.2003.1247849  
\* Mainly on the coupling, but this itself could be of vague use, as a source of distortion.
16. Towards improved calibration in the measurement of partial discharges in rotating machinery  
Electrical Insulation, 1990., Conference Record of the 1990 IEEE International Symposium on  
Digital Object Identifier 10.1109/ELINSL.1990.109726  
\* Goes over basic models and signal processing methods; has results from injections between ends and terminals.
17. Extraction of PD Signals from an Electro-optic Modulator Based PD Measurement System  
Electrical Insulation and Dielectric Phenomena, 2006 IEEE Conference on Oct. 2006 Page(s):623 - 626  
Digital Object Identifier 10.1109/CEIDP.2006.312009  
\* Lewin (Soton) &co. Appears to be tformer based.
18. Signal transmission and calibration of on-line partial discharge measurements  
Properties and Applications of Dielectric Materials, 2003. Proceedings of the 7th International Conference on  
\* From our PD supplier (Detlev). A bit of an idea about impedances and pulse risetimes. Not very helpful to the main aim here of verified models and parameters.
19. Acquisition of rotor anisotropy signals in sensorless position control systems  
Holtz, J.; Hangwen Pan;  
Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the  
Volume 2, 12-16 Oct. 2003 Page(s):1165 - 1172 vol.2  
\* No!
20. Acquisition of rotor anisotropy signals in sensorless position control systems  
Holtz, J.; Hangwen Pan;  
Industry Applications, IEEE Transactions on  
Volume 40, Issue 5, Sept.-Oct. 2004 Page(s):1379 - 1387  
Digital Object Identifier 10.1109/TIA.2004.834053  
\* No!
21. Development of an On Line Monitoring System for Partial Discharges on Hydrogenerators  
W. J. Trinitario; R. O. Febres;  
Transmission & Distribution Conference and Exposition: Latin America, 2006. TDC ’06. IEEE/PES  
Digital Object Identifier 10.1109/TDCLA.2006.311406  
\* Capacitive sensors on ends. Interest in f>1\,MHz may be interesting -- many others focused on the travelling waves below this.
22. Feature extraction and pattern recognition of multi-source PD signals  
Electrical Insulating Materials, 2001. (ISEIM 2001).  
Digital Object Identifier 10.1109/ISEIM.2001.973580  
\* The ‘back-propagation’ apparently refers to some neural-net sort of thing...
23. Slot discharge signal patterns in high voltage machines  
Electrical Machines and Drives, 1995. Seventh International Conference on (Conf. Publ. No. 412)  
\* Looks rather interesting: relevance of slot semicon to propagation, FEM model of this effect.
24. New diagnostic techniques for large utility generators  
Fernandez, J.; Mandl, W.; Slomovitz, D.; Trigo, L.;  
IEEE International Symposium on Electrical Insulation, 1998.

Digital Object Identifier 10.1109/ELINSL.1998.704721  
\* About use of general-purpose 'scope, plus processing software, to replace PD systems; only mentions propagation as a limitation.

25. Pitfalls of partial discharge measurements on stator windings of turbine generators  
Dielectric Materials, Measurements and Applications, Seventh International Conference on (Conf. Publ. No. 430)  
23-26 Sept. 1996 Page(s):394 - 397  
\* Doesn't seem to help much for current interest, BUT worth trying for its consideration of noise-rejection in PD measurements.

26. Partial discharge monitoring of turbine generators; laboratory and live measurements  
Electrical Insulation and Dielectric Phenomena, 1994. IEEE 1994 Annual Report., Conference on  
23-26 Oct. 1994 Page(s):118 - 124  
Digital Object Identifier 10.1109/CEIDP.1994.591724  
\* Looks rather familiar, but get anyway; injection measurement on 35\MW stator.

27. Modeling and analysis of IPT system used for PRT  
Electrical Machines and Systems, 2005. ICENS 2005. Proceedings of the Eighth International Conference on  
Volume 1, 27-29 Sept. 2005 Page(s):839 - 842 Vol. 1  
\* Nothing to do with it: variable-speed drives again.