# A literature review: The nature of partial discharges in stator insulation

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# 1 Introduction

This is a literature review that was done to try to get an idea about what details are known of the small, transient and hidden phenomenon of partial discharge (PD) in and around the stator insulation systems of high-voltage rotating machines.

From searches made on electronic sources (mainly Google Scholar, IEEExplore), then short-listing of results, some twenty papers were found, and some more were found from the citations within these. An example of search terms used, in IEEExplore format, is:

For each paper that had some relevant information, a summary is made here of the main claims of interest. Any very important or confusing points are pointed out at the end; images are sometimes included.

At the end of all the descriptions of the literature, a general summary is given, with consideration of the gas-discharge aspects of PD in relation to standard gas-discharge theories.

A modified 'alpha' citation format is used, with the first three letters of the first author's name followed by the two-digit year of publication; I find this a good clear way to recognise the citation without having to keep thumbing to the back of the document, and it has a further advantage that the citation is consistent between different works that I or others might write (multiple publications in one year are the exception ...).

# 2 Summary

Here, the real 'review' is given, over all references together. The relevance of the references to the desired subject of the nature of PD in real stator insulation is first considered, then the references' results are compared.

As a brief introduction to the terminology: bars and coils are the insulated conductors of the stator, with bars being single straight parts joined at the ends after assembly, and coils being two straight parts including their connections, joined to other coils after assembly; the slot is the space within the iron core of the stator, where the insulated stator windings fit; the end-winding or 'overhang' is the part of the windings where the bars or coils are outside the slots, going back into other slots.

# Relation of experimental work to real stator PD

# Gases used as the atmosphere

Many stator windings operate in atmospheric air, making relevant the literature on experiments in air, or on effects of humidity. Most of the stator-specific references reviewed here have been in air at approximately atmospheric pressure.

Some large machines have windings operating in pressurised hydrogen, which explains the choice of this atmosphere in [Woo73, Kim97]. This has good thermal conductivity for cooling the rotor windings, but it also has dielectric benefits for the stator from its higher inception voltage and lack of aging reaction with epoxy, compared to atmospheric air.

Use of plain nitrogen in machine-oriented studies, as in [Woo73], is not so easy to understand, unless purely as a comparison with air to reveal the effects of oxygen. The electronegativity of oxygen is recognised by [Hud93, Flo95b] as strongly influencing the PD, so industrial nitrogen cannot be seen as electrically similar to dry air. Nitrogen may, though, be a reasonable approximation to the air in a cavity after the oxygen has reacted to solids.

Just [Woo73] makes use of a further gas, helium, giving a more gentle surface PD than with nitrogen, even under very high stresses; the helium atmosphere is not found in practical stator insulation.

# Solid insulation choices

So far, the literature studied has been specific to PD in modern high-voltage stator insulation, which uses mica flakes bonded with an epoxy resin. Older insulation systems have used other binding materials such as bitumen, but epoxies are much the most common now. The proportion by volume of mica is given in [Wic77] as around 70 %, but a manufacturer has mentioned 'less than 10 % epoxy' to me, for recent constructions; some of the discrepency may be due to the presence of backing tape for the mica flakes. At any rate, the proportion of epoxy is much less, by volume, than that of mica.

Some references, [Hud90, Hol91, Hud93, Hud94], have looked at plain epoxy, with its advantages of optical transparency and material homogeneity. This has some justification

when the results of interest are the properties of the cavity surface or the PD, with fresh or mildly aged cavity surfaces, where the epoxy binder might still be expected to cover the mica filler. The long-term wear and breakdown mechanisms of the insulation cannot be expected to be well represented with just the epoxy; mica is the main part of the real insulation, and is much the more PD-resistant of the materials.

# Geometries

Most of the references used either real stator bars or coils, or models of approximately similar dimensions. In [Fen03], measurement of the on-line PD of a real machine was presented, besides laboratory work on the quite different insulation EPR (a polymeric insulation material used in some cables). In [Dym02] and [Wal91], end-winding surface discharges were the focus, and only real machines were mentioned. In the references using plain epoxy, the test objects were laboratory ones, either a small block with a single cavity [Hol91], or thin layers on plane electrodes, as in [Hud90] and later papers by the same author.

# Applied stress

The actual electrical operating conditions of modern stator insulation are typically about  $3 \,\mathrm{kV/mm}$  (rms) at 50 Hz. Higher stresses are essential for any study of long-term aging and lifetime of practical insulation materials, whose working life at normal stresses is a matter of decades.

By the well-known method of increased voltage amplitude, and increased frequency to give an approximately proportionately large number of PD events per unit time, the time to failure or to some aging level can be shortened. The realism of the 'acceleration' depends on the factor being not so high as to modify the dominant aging mechanism; for example, values that cause much higher temperatures than normal or that cause discharges where there never would be discharges in normal operation.

Extremes of 15 kV/mm were used in [Wei06], at 50 Hz. In [Kim97] a more modest 5.5 kV/mm was used, on the grounds that changes in deterioration mechanism occurred beyond 6 kV/mm; the frequency here was 420 Hz, which is within the range generally thought to be a valid acceleration. The surface discharges in [Woo73] were done at stresses of up to 12 kV/mm at high frequencies of  $\sim 1 \text{ kHz}$  (where it's not clear whether the electric field is defined in the solid or the gas, but presumably the gas), which gave extreme heating in the N<sub>2</sub> atmosphere. Other references stayed closer to practical values of stress. Certainly, [Woo73] and [Wei06] cannot be regarded as having measured 'normal' PD.

In some references the PD inception voltage (PDIV) is used to express the applied voltage, e.g. 'up to three times the inception voltage', paraphrased from [Flo95b]. It should be noted that PDIV is often defined as the level at which regular PD is detected when raising the amplitude of a periodic excitation; variation in the detection sensitivity or the significance of statistical time-lag can alter this value.

# Results

The overall picture of PD within stator insulation, given by the references that have been studied, is the following.

# Possibility of PD inception

The operating peak electrical field in the solid insulation is about 3 kV/mm, which is about the classic Townsend breakdown value for non-tiny gaps in atmospheric air. The epoxy-mica insulation material has a permittivity of about  $\varepsilon_{\rm r} \approx 4$ ; the gas in a void in the insulation therefore experiences a similar or enhanced field, compared to the field in the solid, depending on the shape of the void.

Voids can be small 'bubble-like' cavities where the epoxy binder has not reached during manufacture, or larger 'delaminations' between the layers of mica-bearing tapes sometimes due to thermal cycling and mechanical or thermal stress. A small cavity in the insulation generally has so little volume that the statistical time-lag can delay PD until a strong excess field exists. A delamination, a void of modest height in the field direction but large dimension in the plane normal to the field, will have strongly enhanced field compared to the case if the space were filled with insulation material.

# Surface discharges

Surface PD, although particularly important in the end-winding region where there is no low-resistivity coating around the insulation surface, is not well covered by the references. Their interest in the subject lay mainly in breakdown mechanisms [Woo73] or analysis of occurred breakdowns [Wal91, Dym02], and there is not much about the discharges themselves, in real stator insulation, e.g. pulse sizes, waveforms, inception criteria. In [Fen03] the PDIV is shown as a function of humidity, measured between EPR-coated electrodes, as part of an investigation of the effects of humidity on stator insulation, presumably aimed at the insulation surface rather than at the moisture-shielded cavities within the insulation. This reference goes on to show measurements on a real stator, in varying humidity, with discharge rate increasing with *decreased* humidity within the <50 % range of relative humidity; this was attributed to the electronegativity of water molecules, absorbing electrons.

# **Cavity discharges**

**Hudon** In all of [Hud90, Hud93, Hud94] the test object was an epoxy-bounded 0.5 mm gap between edge-contoured plane electrodes, in which air was sealed and a modest 3.2 kV at 60 Hz was applied for over a thousand hours. This is thus a classic dielectric barrier discharge situation. The results, e.g. figures 12 to 14, show that at some time between tens and hundreds of hours of aging, a gradual but clear transition occurred from strong, spark-like discharges (mentioned in [Hud93] as being suggestive of the 'streamer-like' form in [Dev84]) to smaller, slower Townsend-like discharges, and ultimately to pulseless glow discharge. It should be noted in advance of the results that the rise-times

given, mainly in [Hud93], are very long, compared to [Hol91] and to general views about PD! The measurement system, a 200 MHz oscilloscope measuring the voltage across an unspecified RC detection impedance, may be part of the explanation; the oscilloscope would not be able to resolve sub-nanosecond and few-nanosecond events.

The spark-like discharges involved apparent charge,<sup>1</sup> of some hundreds of picocoulombs, with the peak current seen after about 50 ns. The Townsend-like discharges involved much lower apparent charges, of the order of tens or units of picocoulombs, with about twice the rise time and a low plateau of continued current seen for some 200 ns after the peak; this shape is explained as a Townsend electron avalanche followed by slower ion removal. In some specimens, all detectable pulses disappeared after some hundreds of hours of aging, but emission of light still occurred even when no pulses were detected, and the applied voltage was high enough that there must be some sort of discharge in the cavity in order to prevent the cavity voltage rising enough to make noticeable pulsed discharges; this was called the glow regime.

The surface conductivity of the epoxy was seen to increase by some six orders of magnitude during the first hundred hours or so of the aging, due apparently to the deposition of simple acids on the cavity surfaces. The increased conductivity means that large areas of the cavity can be discharged. The crystal form of some of the acids on the epoxy surface was hypothesised as helping to initiate discharges from the sharp edges. The bound oxygen in degradation products increased even long after all but the weakest PD pulses had stopped; the continuing glow discharge has a considerable aging effect.

In the later stages of discharge — Townsend-like pulses, and glow — the cavity voltage is held close to the inception voltage; new (pulse) or increased (glow) discharges occur easily when the voltage across the cavity rises, until the extra charge on the dielectric barriers has compensated the change in voltage. In the earlier stages — spark-like pulses — the cavity voltage can often rise to much greater values than the inception voltage, due possibly to lack of initial electrons or electronegativity of oxygen in the gas; when a discharge does start, the strong local electric field can cause a strongly ionising discharge that reduces the local electric field to much less than the inception value; the electric field in different parts of a cavity can vary, due to low surface conductivity. Figure 15 gives a diagrammatic view of this distinction.

The transition of PD mechanism has received earlier attention, as is mentioned in the reference lists of Hudon's papers. The contemporaneous thesis by Morshuis [Mor93] makes similar findings on homogeneous polymeric cable insulation. Relevance to stator insulation is marred somewhat by the lack of mica filler in the solid epoxy insulation; [Woo73] shows small (few micrometre) formations on an epoxy-mica insulation surface, that turned out to be chemically similar to mica — how would these combine with the acids from epoxy and oxygen, in terms of surface conductivity and emissions?

**Holbøll** In [Hol91] a different approach was taken, with fast photography of the spatial development of discharges from two angles, or of their time development. There was

 $<sup>^1\</sup>mathrm{Apparent}$  Charge: the charge that gets transferred by the supply to balance the charge transfer in the cavity

also oscilloscope measurement of the current in a  $50 \Omega$  series resistance, using a 1 GHz oscilloscope. This again is in epoxy, and the main results can be seen in figures 8 to 10.

Again, there are two distinct types of discharge seen; a fast one, described as 'streamer', and a slow one, described as 'diffuse'. There is not, however, a mention of a clear transition in time from a predominance of one to the other; the measurements appear to have been made on quite new cavities without a long time of aging as in the [Hud93] series. The camera images shown, with channels for the fast discharges, and diffuse less-intense light from the whole cavity for the slow discharges, provide a welcome verification of the hypotheses of [Hud90]. Later work in [Hol94] used another form of high-bandwidth measurement of PD currents in cavities in epoxy-mica insulation in a model of a stator bar in its slot; fast and slow discharges were again seen.

It is interesting to note that although the cavities have diameters from twice to ten times the air-gap in the [Hud93] case, the oscilloscope traces and time-development photographs of [Hol91] show much shorter times of the pulses. The more credible is [Hol91]: its figure of around 1 ns tallies with many other sources in the literature about cavity PD, its oscilloscope had a greater bandwidth, and the camera images provide further verification.

**Other** The size of cavity PD pulses under reasonable voltages was given by several references as having apparent charges in the order of hundreds of picocoulombs up to a few nanocoulombs.

# Availability of electrons

The significance of metal-bounded cavities, as good sinks and sources of electrons, is discussed in [Flo95a], with reference to the work function and to the large field-enhancement, of some hundred times, around microscopic roughness in the metal surface, which makes field emission possible even at the normal working fields. In [Wic77] some metal-bounded cavities are compared with purely dielectric-bounded ones.

Again from [Flo95a], the significance of surface charge and trapped charge on dielectric bounds is discussed, as being a source of rapidly available electrons that prevent the large overvoltages that can arise when the statistical time-lag is affecting the discharges.

# **3** Separate summaries of the papers

# [Woo73] J. WOOD, D. RYDER, W. HOGG, 1973

Discharge studies of epoxy/mica turbine generator insulation

The authors are from a machine manufacturer and a university. The aim is a general improvement in understanding of the breakdown mechanisms of stator insulation due to electrical stress.

The PD system used has resolution of  $0.5 \,\mu$ s and sensitivity of  $0.05 \,p$ C[sic] (this seems incredible; how about  $0.05 \,n$ C, which fits better with the 70 pC mentioned by table III) for a 10 pF sample, calibrated by known-charge injection. Five materials were used, in nominal thicknesses of 0.18 mm built up into five-layer objects. The materials used are: objects A&C, phlogopite mica in 0.1 mm to 1.0 mm flakelets, bonded with respectively novobond or a cyclo-aliphatic resin; objects B&D, the same but in a 25 mm wide tape; object E is novobond bonded muscovite mica flakes about 40 mm across faces and 25  $\mu$ m thick.

Frequencies from 800 Hz to 1200 Hz were used, This 'factor of 24' of aging rate, on the classic assumption of number of cycles being dominant, is claimed to be 'not expected to change the mechanism of damage and progression to breakdown at service stress' (based on experience, not further justified) and the dielectric loss is quite constant over this range. Initial work was done with plain epoxy in N<sub>2</sub> at 800 Hz to 1200 Hz, from 4 kV/mm to 12 kV/mm, to confirm for example that the stress/lifetime relation was as expected from previous work (the purpose is not very clear).

Removal of a faulted test object from the supply is noted as being very important, to allow its condition at failure to be preserved and to allow other objects to continue aging; HV fuses and special air-blast breakers were used here. It is claimed that a binocular optical microscope is no good for more than  $20 \times$  magnification with the required depth of focus; electron microscopy was used for study of surfaces.

Surface discharges were made across a 0.2 mm gap from a profiled electrode, at 800 Hz.

In an atmosphere of  $\geq 99\%$  N<sub>2</sub> at normal temperature and pressure (NTP), 'multisamples' (multiple samples, for repeated tests?) of objects type A,B,C,D,E were tested with 12 kV/mm, six times the inception level, a very severe stress. Some discharges were tangential, across the insulator surface, as evidenced by tracks. Maximum discharges were as high as 40 nC. The thermal effect of this severe stress was considered to be the main cause of breakdown, whose progression was described as 'removal of the bonding material, delamination, internal void formation, puncture of laminations or tracking between flakes and butt-joints'; in this case the high stress clearly made the acceleration by frequency be invalid, due to the high temperature.

In an atmosphere of He at NTP (presumably the same high stress as with  $N_2$ ?), which is pointed as as having a discharge inception stress 'considerably lower than that of  $N_2$ '. Maximum discharges were from 5 nC to 11 nC, with no breakdown up to the stop at 'equivalent' five years of aging; careful inspection of the degradation suggested a process of 'removal of bonding material, delamination and void formation, erosion of

		Maximum Discharge Magnitude pC							
Material	Discharge Inception Voltage,Vi, kV	Actual t=0		t=2400 h		t=4800 h			
		Pos.	Neg.	Pos.	Neg.	Pos.	Neg.		
А	1.3	2280	1620	400	460	250	340		
B	1.3	4150	1900	900	480	420	290		
С	1.2	4500	4200	180	250	230	270		
D	1.1	3300	5500	140	120	200	100		

Figure 1: PD magnitudes and inception voltages with air at NTP in cavities in different types of epoxy-mica insulation. From [Woo73] (table III).

mica flakes, puncture of mica flakes between cavities or tracking between mica flakes'. Delamination happened more in objects of type E, with the larger flakes, and damage near joints was visible in the taped form of mica.

Internal discharges (cavity PD) were made by omission of part of one  $\sim 0.2 \text{ mm}$  layer of a multi-layer sample. The applied stress was 4 kV/mm, at a frequency of 1200 Hz, the 'equivalent' of twenty-five 50 Hz years. Three samples of each of A,B,C,D were tested, in two different atmospheres, with 15 minutes of gas circulation before testing.

In an atmosphere of dry air at NTP, the maximum PD values fall by a factor between about 2 and 30 between 0 and 1200 hour values, then more modestly to the final times; the number of discharges increased while the maximum size decreased, which is described as usual behaviour for internal voids in air. Table III of this reference (figure 1 here) shows PD + and - maximum magnitudes at 0, 2400 and 4800 hours from the start of aging. PD maximum values are from about 2 nC to 5 nC and the 4800 hour values are from 100 pC to 500 pC. Inception voltage is about  $1.3 \,\text{kV}$ . There was just one failure in air, at 21 equivalent years, of a type B sample; it failed in the same way as the wear in the He surface discharge case. (Claim: the small mica flakelets are less likely to delaminate, so less susceptible to PD attack, than the flakes of type E).

In an atmosphere of  $H_2$  at 3 bar and  $65 \,^{\circ}$ C, the same tests were done as for air. The PD charges are large and less varied, from about  $12 \,\text{nC}$  to  $20 \,\text{nC}$  at all times, with inception at  $2.6 \,\text{kV}$ , (Most  $H_2$  data is missing, along with many of the references; IEEExplore has been informed.)

Dendritic deposits (figure 2) from the PD were analysed: regardless of whether muscovite or phlogopite mica was used, the deposits from surface discharge were seen to be silica, and those from the cavities were seen to be the same composition as the mica (containing Al or Mg as well as Si). It seems therefore that both sorts of deposit come from mica, not from the epoxy.

The paper's final section points out the apparent similarity in wear, in the surface and cavity cases (ignoring the excessively hot case of surface in  $N_2$ ), the importance of tape joints, and the difficulty of going as far as failure when dealing with lifetimes greater than 25 years. The large magnitudes in  $H_2$  cavity PD are attributed mainly to increased pressure and therefore increased inception voltage, but mention is made that PD charges



Figure 2: Electron micrographs of PD-induced changes on micaceous insulation. At the left, deposits on external surfaces; in the centre, deposits on internal surfaces, including a close-up; at the right, a puncture through a mica flake. All main pictures are to approximately the same scale, the height of the image being  $\sim 150 \,\mu\text{m}$ . From [Woo73], combining several images.

can increase with temperature in epoxy systems even without change in partial discharge inception voltage (PDIV), but the relevant references are missing in the electronic copy.

An external discussion of the paper states that the per-cycle pulse size distribution should be shown to be the same at different frequencies used, in order to verify the 'same mechanism' with frequency-accelerated aging, and that stress at the corners is typically twice as great as on the flat sections of a stator bar. The authors response is that they only claimed to have used a number of cycles the same as that of 25 years at 50 Hz, that similar pulse sizes do not either imply valid extrapolation, and that preliminary measurements with filler (mica), binder (epoxy) or a mixture, had shown little dependence on frequency up to  $1.2 \,\text{kHz}$  for ventilated PD, or up to  $0.5 \,\text{kHz}$  for PD in sealed cavities.

Summary: This is well executed and described; it gives a convincing description of epoxy-mica breakdown mechanisms, and gives PD maximum + and - magnitudes for different aging state and atmosphere/temperature.

# [Wic77] A. WICHMANN, P. GRUENEWALD, 1977

Influence of dielectric stress concentration on voltage endurance of epoxy-mica generator insulation

The authors are from a machine manufacturer, an AEG/Siemens branch. The main aim is a better cross-section of the HV conductors and insulation of large turbogenerators, to reduce wear.

PD was studied on surfaces and artificial voids of mica splittings and papers, with various epoxy resin binders. Insulation thickness was 3 mm, around a stator-like conductor with edge-radius 1 mm, cross section  $10 \text{ mm} \times 50 \text{ mm}$  and length 1 m. The breakdown strength of the complete insulation was tested at increased voltage and frequency. A relation log  $t = k - \alpha E$  was a 'good' approximation (actually, it looks rather concave in



Figure 3: times to 50% failure for varied voltage at 1.2 kHz; 'from figure 1' is similar objects without the added PD source of the cavity shown above. From [Wic77].

all cases) of the time t to breakdown at field E, with k being between 25 kV/mm and 30 kV/mm and  $\alpha$  being about 3 to 4 kV/mm per decade of t.

Cavity PD was formed in holes of 3 mm diameter, drilled about 1 mm into the flat part of the insulation, with the surface outside the hole covered in conductive paint and an earth electrode. Breakdown occurred one in three times at the edge of the bar, not at the artificial weakness, so the change in lifetime with seven such holes in parallel was not very different from the pristine case.

Another case of cavity PD used holes of about 2 mm depth, with an inserted electrode of 1 mm, i.e. just 1 mm height in the cavity. The breakdown in this case was shifted some two decades of time shorter than the pristine case.

In all the above cases, results for two insulating materials are given: 'mica paper folium' and an apparent VPI epoxy-mica (called by slightly different names in each case); breakdown at high voltages happens sooner for the epoxy-mica, but at low voltages it happens sooner for the mica paper folium.

PDIV was 8 kV for the pristine case, and 2 kV for the case with inserted electrodes. Partial discharge magnitudes around PDIV measured in the artificial voids were around 0.5 nC to 0.6 nC with the short hole, but 1.0 nC to 1.6 nC with the longer hole and inserted electrode, and at 30 kV the respective magnitudes were 2.5 nC and 5.0 nC. Similar tests were then made with small samples of various materials, still 3 mm thick. Nine specimens of each were used. The life expectancy (definition, with range of voltages?) of the impregnated mica paper, around 60% mica, was about half-way between the shorter time of the pure resin and the longer time of the mica splittings.

*Summary:* Some PD charge magnitudes are given for well defined cavities, and different proportions of binder and filler are compared for breakdown time.

# [Reh88] R.H. REHDER, V.R. MULHALL, V.A. MOORE, D.G. MCLAREN, 1988 All stator windings are not created equal

The authors are from a machine manufacturer. There is no own experimental work; this is just a quick summary of insulation-system evolution and the present direction.

Higher frequencies for acceleration are claimed to be 'proven by an international interlaboratory test program' to be not valid as a linear scaling, though useful in some slot and end-winding cases.

Long-term voltage degradation is by PD, energy and chemicals, changing the insulating material. Attention was previously on the slot section, packing the surrounding of the bars or coils and ensuring well-compacted and impregnated insulation. Now, with these parts improved and stresses increasing, attention is moving to other places, e.g. the gas around end-winding bars or coils; Paschen's law is mentioned as the way to decide whether end-winding PD will occur.

#### [Hud90] C. Hudon, R. Bartnikas, M. Wertheimer, 1990

Surface conductivity of epoxy specimens subjected to partial discharges

The authors are at a university and a machine user. The aim is a description of the PD-induced change in epoxy surfaces, of relevance to PD characteristics in epoxy-bound insulation.

Two 50 mm diameter electrodes were coated with 1 mm and 0.5 mm thicknesses of epoxy, with the faces separated by 0.5 mm in a sealed test cell. An applied voltage of 3.2 kV 60 Hz was used, with PD measurements made on an RLC detection impedance in series with a coupling capacitor, averaging results from 100 cycles every hour or ten minutes.

Conductivity was measured between evapourated gold electrodes of  $4 \text{ mm} \times 20 \text{ mm}$  at a separation of 1 mm, that were deposited after the aging; the applied voltage for these measurements was 200 V for 120 s. Specimens were stored in dry atmosphere and measured in a vacuum, to avoid humidity effects (known to have enormous influence on surface conductivity).

The results of conductivity measurements are given in  $(\Omega \text{ cm})^{-1}$ , which is strange since this is a material value rather than a surface value, so it implies that the thickness of the measured layer is known; in the later work [Hud93], siemens are used, with similar numbers, so it can be assumed that the current paper has wrongly described its units.

For a few minutes of 'de-gassing' (removal from test-cell, or after the gold-deposition?) the conductivity changed rapidly, but it became quite steady after a while; measurements were made after 1 hour.



**Figure 4:** 'Surface conductivity' (meaning?) of epoxy specimens, dependent on time of exposure to PD in a sealed cell. From [Hud90].



Figure 5: Time-development of normalised discharge amplitude, for a specimen which took only a few hours to reach a steady low value. From [Hud90].

Unaged specimens had lower than  $10^{-16}$  S surface conductivity (the detection limit); specimens aged for 500 hours had about  $10^{-10}$  S; specimens aged for at least 100 hours had a similarly high surface conductivity regardless of whether they were removed from the aging while showing a large or small discharge intensity, the small intensity being generally the final state; a sample that had attained a low intensity after only 5 hours (figure 5) was measured at 20 hours and found to have still a low conductivity of  $10^{-14}$  S/cm. The (mean) surface conductivity and measured average amplitude are not strongly related!

In discussion it is mentioned that increased surface conductivity would be expected to



Figure 6: Time-development of normalised discharge amplitude, for a specimen which took hundreds of hours to reach a steady low value; note that this value is rather lower than that in figure 5. From [Hud90].



Figure 7: Microscope images, approximately 70 times larger than life (see the scale, bottom right), of the epoxy surface after exposure to PD. On the left, 'drops' after short exposure (hours, tens of hours?); on the right, 'crystals' after long exposure (hundreds of hours?). From [Hud90].

increase pulse sizes, but that the *average* discharge magnitude doesn't confirm this, from which the conclusion drawn is that another type of discharge occurs due to the changes in the surface: glow (pulseless) or pseudo-glow (small pulses). A glow was seen during the aging (but was not recorded so as to allow comparison of its development with the conductivity and PD size), and the occurrence of glow discharges in voids is backed up with two references.

The interaction of glow discharges with polymer surfaces causes chemical changes, as reported in other works about PD effects mainly on XLPE. Work on XLPE has shown similar looking drops and crystals, which turned out to be drops of simple organic acids (formic, acetic, carboxylic), and crystals of oxalic acid,<sup>2</sup> formed from volatile polymer

 $<sup>^{2}\</sup>mathrm{IUPAC}:$  'ethanedioic acid',  $\mathrm{H}_{2}\mathrm{C}_{2}\mathrm{O}_{4},$  melts at 101 °C

oxidation products ( $H_20$ , CO,  $CO_2$ ) in the plasma; it is therefore suspected that the same is true for the epoxy, as it would have similar oxidation products.

Summary: for three pages this paper has a lot of interesting information; the measures of PD are not clear to me (e.g. intensity, amplitude, when applied to an ensemble rather than a particular pulse) and it seems that mean charge has been used in much of the discussion, hiding changes in the peak values; main points to note are the order of change of conductivity, the localisation of high conductivity parts, and the variability of times of changes in PD behaviour.

#### [Wal91] P. WALKER, J.N. CHAMPION, 1991

Experience with turn insulation failures in large 13.2 kV synchronous motors

The authors are machine users, who have had a 'very high rate of failures' in a population of large (21000 hp) motors; the results of investigation provide a theory of end-winding PD.

Early failures occurred in the end of the first or second coil groups in several machines. A (commendable) lot of investigation was done, including analysis of surges arriving at the machine due to switching.

It was noted that the windings had no separate turn insulation, but just strand insulation. In the end-windings, with twisting of the coils, there was chance of delamination of the ground-wall, and any ensuing PDs would be in the space between this ground-wall and the thin, mica-based, conductor (strand) insulation (this is described as 'the arc of a partial discharge ... play directly ... thin conductor insulation'). Quite high-conductivity contamination, e.g.  $3 M\Omega$  between points separated by about a fifth of the overhang length, was found on the end-winding surface, with strong dependence on humidity. High surface conductivity tends the stress on the ground-wall insulation to approach half of the applied value, rather than being much lower as for a floating insulation surface. For various sizes of such voids, the Paschen voltage of the void was calculated, along with the (rms) applied voltage needed to achieve this; one assumes this applied voltage is the value between phase conductors, i.e. line voltage or applied test voltage when one is excited and the others earthed.

d = 25\*[0.005, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07]; % mm void size v\_ins = [0.725, 1.15, 1.85, 2.50, 3.08, 3.60, 4.30, 4.80]; % kV in cavity v\_app = [5.75, 5.14, 5.06, 5.39, 5.75, 6.10, 6.78, 7.18]; % rms kV applied, eps\_r=4.5

Conclusions are that the new, thin, strand insulation adjacent to voids is part of the problem; surface contamination is a problem, and there should be periodic cleaning; common test methods can fail to detect this end-winding PD source, so it is important to measure PD on each phase while the others are earthed.

There was discussion of the paper by two others (users/consultants). Both suggested that half-lapped mica tape as conductor/turn insulation is inadequate, at least for critical machines. A relation of PD-based prognoses to later failures was asked after; it turns out that of four new motors, the one with significantly higher PD was the first to fail, after just 3000 hours. The authors dispute that the weak conductor insulation is responsible for undue susceptibility to impulses; the wear to this by PD takes thousands of hours, and



Figure 8: 'Fast and slow' pulse currents. The extra curves are supposed to be sines starting at the phase of the applied voltage at which the pulse occurred (clearly not in the same timescale). From [Hol91]

is on the ground-wall parts, not the part between conductors where transient voltages appear.

*Summary:* the only point directly about gas discharges is the simple calculation of Paschen voltages for voids.

# [Hol91] J. Holbøll, J. Braun, N. Fujimoto, G. Stone, 1991

Temporal and spatial development of partial discharges in spherical voids in epoxy related to the detected electrical signal.

The authors are from a university and a generator user. The aim is a general one of relating PD measurements on apparatus to the physical mechanisms of the source.

The test objects are clear bisphenol-A epoxy containing in each case a single spherical void, of diameter from 1 mm to 5 mm, formed by injecting dry air; the gas in the final void is thought to be vaguely air-like — 'mainly nitrogen'... Optical measurements were by a camera/lens/mirror/prism system, able to take two images from different angles or to take a streak image showing time-development; only cavities of at least 3.5 mm had detectably large discharges for the camera. A 1 MHz to 750 MHz oscilloscope measured the voltage across a  $50 \Omega$  resistor in the earth wire of the sample.

Two clearly distinguished classes of discharge pulse were seen: 'fast' ('A') pulses had a rise-time of less than 500 ps and width of 700 ps, and nearly constant maximum pulse size; 'slow' ('B') pulses had a rise-time of more than 1 ns, width of 2 ns to 10 ns, and magnitude variable but always about 5 to 100 times smaller than that of the fast pulses (assuming the quoted dB values were in amplitude, not power). Figure 8 shows the time-domain currents for examples of the two types.

The optical measurements showed streamer-like and diffuse discharges, corresponding to the fast and slow measured pulses, as shown in space and time in figures 9 and 10. These are at 19 kV applied voltage, but under X-ray irradiation to provide start-electrons the inception was at 6 kV; this means there is a large over-voltage available, which may



Figure 9: Spatial resolution (two angles each) of different discharges in a 3.5 mm diameter spherical cavity in epoxy. From [Hol91]

account for the high speed of the streamers when they do happen. [The relevant page here is clipped off on ieeexplore, and should be put right in a week or two, as of 2008-10-02.] [There's not a clear mention of the other dimensions of the test object: how much epoxy is in series with the cavity?]

That familiar friend, the phase-resolved partial discharge pattern, is shown in figure 11, in slightly different form from the usual KTH one. It doesn't add to the previous information, but it's a nice summary.

The voids that were big enough for optical measurements, i.e. whose PDs had strong enough light above the  $\sim 430$  nm absorption boundary of the epoxy, are bigger than typical voids in HV insulation, but had similar patterns of measured pulse current to those that were visible; it is therefore expected that the optical results are relevant even to practical cases. It is noted that integrated-charge methods don't resolve the two types of PD clearly.

*Summary:* streamer or diffuse PDs occur in a single cavity, the streamer being faster and of higher charge.

[Hud93] C. Hudon, R. Bartnikas, M. Wertheimer, 1993

Spark-to-glow discharge transition due to increased surface conductivity on epoxy resin specimens

The authors are from a university and a machine user. The aim is a description



Figure 10: Time-developmet of two discharges in a 3.5 mm diameter spherical cavity in epoxy. From [Hol91]



**Figure 11:** Phase-resolved PD pattern, including the slow and fast pulses. (Note how + and – parts have the same orientation, upside-down.) The streamers have much larger pulse size. From [Hol91]

of the gas-discharge effects of PD-induced changes to an epoxy dielectric surface, and investigation of whether large PD pulses necessarily are more harmful to insulation than are more glow-like discharges.

The description of the test system is as in [Hud90], contradicting [Hud94] in the double thickness of the epoxy on the contoured electrode (1 mm, but 0.5 mm in [Hud94]), and contradicting my guess of the chosen test voltage of [Hud94] by stating explicitly 4 kV. An addition compared to [Hud90] is a photomultiplier tube. The oscilloscope measuring PD pulses could detect automatically down to 10 pC reliably (compared to as low as 0.5 pC with human interpretation). PD was recorded for 120 s with 100 pC threshold then with 10 pC threshold, every hour.



**Figure 12:** Time development of (mean) PD amplitudes, considering charges above 100 pC (left) and above 20 pC (right). From [Hud93].

In contrast to [Hud90], the surface conductivity is given in siemens, which makes sense, being the reciprocal of 'ohms per square'. Electrode arrangements for measurement of conductivity are as in [Hud90]. It is noted that the use of vacuum, to avoid humidity, may have caused some volatile compounds to evapourate.

Large (hundreds of pC) PD pulses stopped being regular beyond about 180 hours, and stopped altogether after about 300 hours; some smaller pulses started during this interval, and beyond 320 hours there was no pulse large enough for automatic detection; beyond 800 hours there was not even any discernible (>0.5 pC) pulse until conclusion of the measurement at 1150 hours; the automated measurements are shown in figure 12.

The current of the pulses, shown in figure 13, has quicker rises and falls for the larger early PDs, and a plateau of over 100 ns. The same time-development of discharge was seen in many specimens, but with varied spark–Townsend transition times ranging between 20 and 300 hours. The slower, Townsend-like waveform is explained as an initial peak due to electron transfer, then a slower tail due to current transfer from ions.

Photomultiplier current, at the right of figure 14, is much higher initially, in the presence of some large spark discharges, but definitely continues at a very constant level, not changing significantly at the times at which the >20 pC then >0.5 pC PDs were seen in figure 12 to cease; this points to a glow or very small-pulse pseudo-glow discharge. The conductivity, at the left of figure 14, rises sharply at the very beginning, in some ten or so hours, and thenafter increases quite gradually; this suggests that the glow is not much less effective than the pulsed PD at causing changes on the surface. (But, how were conductivity points obtained, and how many are there; they were presumably from different specimens, and specimens are acknowledged as having very different times to particular states of PD; there are also not many points shown — about seven are visible in this plot.)

In an attempt at explanation of the change in PD properties with aging, the twin



Figure 13: PD pulse waveforms for the early-stage large spark-type discharge and the later-stage smaller, slower discharge. From [Hud93].



Figure 14: Surface conductivity and photomultiplier current due to emissions from the PD (note that the  $\sim 0.4$  nA final value is some 100 times the dark value). From [Hud93].

mechanism is considered, of increase in surface conductivity and decrease in free oxygen concentration. It is known that high overvoltages before a PD event, i.e. something preventing PD from happening as soon as it could do, lead to larger, more spark-like PD pulses. Oxygen is electronegative, so tends to capture free electrons; it has been seen that oxygen compounds form on the dielectric surfaces, so the oxygen in the trapped air is presumably dimishing with aging, leading to easier PD inception with little effect of time-lag (why not try the measurements in an open atmosphere to test this?). The 1971 reference (#18) 'Some Observation on the Character of Corona Discharges in Short Gaps' looks interesting, having a discussion of spark and glow discharges, but it's not electronically available (yet).



Figure 15: Cavity electric field after the two types of discharge. (Not at all to scale, even in vertical direction alone.) From [Hud93].

Figure 15 shows the suggested influence of surface conductivity on discharge development: the point from that 1971 reference is shown here, that in a glow discharge the 'remnant' voltage across the cavity stays close to the breakdown value, while with the spark discharge the remnant voltage (in a more confined area) collapses to a lower value than the breakdown voltage.

*Summary:* beyond the results of [Hud90], this shows waveforms of PD pulses in the spark and Townsend regimes, hypothesises about reasons for the transition, and clarifies the definition of surface conductivity.

# [Hud94] C. Hudon, R. Bartnikas, M. Wertheimer, 1994

Chemical and physical degradation effects on epoxy surfaces exposed to partial discharges The authors are from a university and a machine user. The aim is a description of chemicals on surfaces after PD activity. This is an extension of the analysis of work reported in [Hud90].

Measurements are made using 0.5 mm epoxy coatings on plane (one of them contoured at edges) electrodes, with a 0.5 mm gap of sealed air between the coatings; twice the PD inception voltage was used. The description of the construction is mainly referred to previous publications, but from [Hud90] a different geometry with one coating being 1 mm was stated. It is not clear from the writing here what the applied voltage actually was: a figure of 4 kV is given, which may have been PDIV or the used 2×PDIV, peak or rms; since the Paschen minimum for a 5 mm gap in air at 1 bar is about 2.3 kV, and the air gap would get about  $\frac{2}{3}$  of the total voltage if  $\varepsilon_{\rm r_{epoxy}} \approx 4$ , it seems that a test voltage of 8 kV peak value is meant, but [Hud93] explicitly mentions 4 kV.

PD charge measurements were made with detection thresholds of 100 pC and 1 pC, to allow for the large change in pulse magnitude during aging. A photomultiplier tube (PMT) was used to record the light emission from the gap. Chemical analysis of the surfaces, and microscopy of a cross-section of the insulation, were performed after aging.

All fresh specimens had a regime of pulses up to several hundred picocoulombs in the first 100 hours to 300 hours; next was a period of 'Townsend-like' (because of the size, or was waveform measured?) pulses of  $\sim 1 \text{ pC}$ , superimposed on a steady glow, for hundreds to thousands of hours; in some specimens this pseudo-glow eventually turned, after about 1000 hours, to a pulseless glow, at least down to the 0.5 pC detection threshold.

Binding energy (eV)	285.0	286.5	287.8	289.0
Assignment	С-Н, <b>С-С</b>	С-О-R, С-ОН	C=0, 0-C-0	COOH, COOR
P.D.Duration (hours)				
(a) 0 (control)	61.0	28.0	0	10.0
(b) 240	45.0	34.0	3.0	18.0
(c) 1000	32.0	34.0	5.0	29.0

Figure 16: Surface concentrations of chemical groups, by X-ray photoelectron spectroscopy, at varied aging times. From [Hud94].

The photomultiplier current (mean or peak over some interval?) decayed in a way very similar to the mean pulse amplitude, but then settled to a steady value some 100 times more than the PMT dark current, even in the cases where no more PD pulses were detected. No significant change in gas pressure was observed, so other factors such as gas and surface composition have to be found to account for the transition of discharge mechanism.

The chemical composition of the surface was analysed in several ways; figure 16 shows the considerable increase in some oxygen-containing bonds during aging, even during the pseudo-glow regime. Elemental ratios O/C rose from about 0.4 to over 1.0 during aging.

The droplets and crystals formed during early and later stages of degradation have already been physically described in [Hud90], and were assumed to be chemically similar to those found in XLPE. Here, they were analysed, showing the crystals to be of hydrated oxalic acid and the drops to contain formic, glycolic, glyoxalic[*sic*] and nitric acids.<sup>3</sup> A suggested mechanism for accelerated failure due to the presence of such crystals is a local stress enhancement leading to inception of electrical trees; a case was found of a tree-like structure coming from a crystal *across* the insulator surface. Analysis of the epoxy beyond the the surface layer was done by cleaving the surface at normal and at cryogenic temperatures, and taking microscope images, of which typical examples are shown in figure 17.

It is interesting how sharp a transition there is between a darkened top layer of some 0.25 mm to 0.30 mm thickness and the fresher lower layer; the darkened top layer is not seen at all in control images taken of fresh samples or short-time aged samples. Further exposure to PD doesn't seem to increase the depth of the top layer, but leads to further darkening, different 'fracture morphology' (see the larger spaces in the top layer of figure 17) and some thin channels leading in to the non-darkened lower layer; these channels were not reliably distinguished as microcracks or electrical trees. The thickness of the upper, darkened, layer cannot be attributed to degradation by short-lived discharge

<sup>&</sup>lt;sup>3</sup>formic acid: 'methanoic acid',  $CH_2O_2$ , melts at 8 °C, miscible with water; glycolic acid: '2-hydroxyethanoic acid',  $C_2H_4O_3$ , melts at 75 °C, low water solubility; nitric acid: HNO<sub>3</sub>, melts at -42 °C, miscible with water; glyoxylic acid: (misspelt in paper?), 'oxoethanoic acid',  $C_2H_2O_3$ , melts at -93 °C.



Figure 17: Optical micrographs of epoxy cross-sections at long and longer PD exposure durations; note that only a pseudo-glow discharge would have existed between the times at which these two samples are taken. From [Hud94].

products or ozone; the only mechanism considered reasonable is 'photochemistry' by UV of sufficiently long wavelength (>160 nm) to penetrate this far into the polymer.

Summary: absence of detectable PD pulses need not signify absence of dischargeinduced wear; PD regimes, at least on plain epoxy, change greatly during aging, as relatively conductive compounds form on dielectric surfaces, able to increase conductivity of epoxy by a factor of  $10^6$ .

[Hol94] J.T. Holbøll, M. Henriksen, A. Jensen, F. Sorensen, 1994

PD-pulse characteristics in rotating machine insulation

The authors are from a university and a machine user. The aim is a relation of PD pulse shapes to the nature of the PD source and the applied voltage.

It is acknowledged that voids in real stator insulation may have variation in shape and in gas composition. Here, air-filled cylindrical artificial voids have been used, some with one boundary being a metallic electrode.

The insulating material was 0.25 mm thick tape, of mica flakes about  $100 \mu \text{m}$  wide in a B-stage (not yet fully cured when assembled) epoxy filler, on a glass-fibre backing. Intenal voids were formed as a 5.5 mm diameter hole punched the middle of three layers; voids by electrodes were formed by one of two layers being punched. The voids, in an epoxy covering, were built into stator bar insulation around a solid aluminium bar, which after curing was in a simulated stator slot of 5 mm steel.

PDIV without the artificial defect was between 5 kV and 6 kV (rms values seem to be meant, judging by a later sentence); tests at voltages of (4, 5, 6, 7) kV were done, with no effect from natural PD sources at the lower two values. A half-hour of applied

voltage was used before any measurements. A stator-slot coupler ('SSC': a pick-up coil in the iron slot) was used for measurements, at the slot end or right by the PD source.

The results are some time-domain curves of pulses, admitted to be probably mainly affected by the response of all the surroundings rather than the pulse at the source. Pulse amplitude distribution for metal/dielectric bounded cavities was approximately an exponential increase of number toward smaller values of signal. Three types of measured pulse shape were found: a fast pulse with similar shape for each occurrence; a slower pulse with varied shape; and multiple fast pulses. All were over within about 10 ns.

#### **[Flo95a]** B. Florkowska, 1995

Assessment of temperature influence on partial discharges in epoxy/mica insulation

The author is at a university, investigating PD wear mechanisms with funding from a state research organisation.

The test objects were specimens of 6 kV motor coils, with end-winding corona protection. Measurements were made with a PD pulse detection system, at temperatures of room and 135 °C at up to three times the inception voltage, with classic  $N^+$  and  $q_m^$ sort.

Some general points are made about epoxy-mica insulation (independent of the later experimental results). PD sources are affected by the presence of a metallic electrode on one side (cavity next to conductor) as opposed to being purely dielectric-bounded; small voids and the larger delaminations also have differences of PD.

In 'micro gas-cavities' with an electrode in contact, PD inception depends on fieldemission (FE) of electrons, whose current density is described by the Fowler and Nordheim formula<sup>4</sup> dependent on the local electric field at the metal, which can be as much as hundreds of times the average field in the void, and the work function of the metal; choosing a metal/dielectric (dielectric=gas?) work function of about 1 eV and a 'few hundred times' enhancement, the inception could be at about 1 kV to 3 kV, with a general reduction in work function for contaminants of the metal such as metal oxides and gas adhesion.

In internal delaminations (no metal electrode present; why this distinction of 'small cavities by an electrode or delaminations without an electrode' rather than treating size/shape and electrode present/not as independent parameters?) the discharges 'can be incepted' by emission from electron traps in the dielectric surface, whose depth is estimated (based on a 1988 paper by Lewis) between 0.7 eV and 1.2 eV, of which the upper limit requires fields of about 3 kV/mm to 10 kV/mm, with emission from traps being a statistical effect due to distribution of trap energies.

PDIV ( $U_{ci}$  in this paper) increases with presence of electronegative gas, e.g. with normal air (including O<sub>2</sub>) compared to just N<sub>2</sub> or H<sub>2</sub>. If PD is thought to depend mainly on electrons from surfaces, rather than from within the gas, then PDIV depends first on the field then on (in the dielectric case) previous discharges.

<sup>&</sup>lt;sup>4</sup>Derived in 1928, a quantum-mechanical formula for FE from metals, on assumptions of 1D model, atomically smooth surface, and more: condensing to a and b such constants as work function, Fermi level, electronic mass and charge, etc., the relation of field to current density is  $J = aE^2e^{b/E}$ .



Figure 18: PD charge-distributions related to inception voltage  $U_0$ . From [Flo95a].

PD extinction voltage ( $U_{ce}$  in this paper) depends on neutralisation of charges. For delaminations in epoxy-bound insulation, the initial stages of PD, in which the insulation is not physically changed by the PD activity, are with surface conductivity  $10^{-15}$  S to  $10^{-16}$  S; the PDs need not, then, occupy much of the delamination volume. The difference  $\delta U$  between the  $U_{ce}$  and  $U_{ci}$  is used here as a measure of the 'charge collection'.

It is found that with the applied voltage between one and two times the PDIV: the + and - pulse counts increase linearly with voltage, and are not equal to each other; inception is at higher voltage than extinction for the delamination but the levels are similar for void with a conducting surface; inception is at a lower voltage for a void with conducting surface than for a delamination.

The permittivity is related to temperature by approximately a power-law. Temperature affects also the charge storage and charge diffusion. Spherical cavities have internal field of  $E_c = 3\varepsilon_d E_d/(2\varepsilon_d + 1)$ , while delaminations (much greater diameter than height, height in field-direction) have  $E_c = \varepsilon_d E_d$ , with subscript d denoting the solid dielectric. Change in  $\varepsilon_d$  with temperature is considered responsible for much of the change in PD effects; the difference between smallest and largest PDs increases with temperature. PDs of hundreds of picocoulombs cause modification of surface structure, changing the inception and extinction properties.

*Summary:* the English is hard to grasp at some points, and the title doesn't have very much relation to the content; but, as well as some general theoretical consideration



Figure 19: Changes due the stage-I aging, shown at two temperatures. The change with temperature is the more interesting point! From [Flo95b]

of PD cavity surfaces, there are some interesting results such as the linear relation of PD-count to voltage.

# [Flo95b] B. Florkowska, 1995

# A study of the partial discharge mechanism during the aging of epoxy/mica insulation

The test objects are  $10 \text{ mm} \times 25 \text{ mm}$  copper bar, with 3.3 mm stator (epoxy with mica, presumably) insulation around, and an outer electrode of the semiconducting layer. Conventional PD quantities were studied, at room temperature and at  $135 \,^{\circ}\text{C}$ , with electrical stresses up to  $3 \,\text{kV/mm}$ . Voltage was increased from 1.25 to 2.50 times the PDIV over 30 s, then held for 2500 hours. Measurements were made of short-term (stage I, after 12 hours) and long-term (stage II, after 2500 hours).

The results presented are rather poorly described; the number of samples and the number of cycles are not given, so the significance of e.g. a ten percent difference in PD charge is quite lost.

The short-term test suggested no significant permanent aging in that 12 hour time. Pulse-number had a largely linear increase with  $U/U_{\rm O}$  up to about  $2U_{\rm O}$  (but not proportional — the plot very clearly passes near to  $U = U_{\rm O}$ , not to 0). PD charges were higher at 135 °C than at 20 °C, but inception voltage was lower (i.e. ease of inception was higher); Reasons advanced were higher field in the cavity, due to increased permittivity, and easier electron emission from metal or traps.

Measurements at 20 °C before and after the long aging showed a large change in the shape of the PD distribution, with more of the small PDs (see figure 21), and a reduction



Figure 20: Voltage-dependence of D(n,q).  $U_{\rm O}$  denotes PDIV. From [Flo95b]

in the maximum, average and total charges but largely the same number of PDs.

The conclusions state that: the permanent changes from long aging affect mainly the epoxy;  $O_2$  originally present in the void ends up in compounds (so the gas isn't so electronegative); surface conductivity increases even after just 200 hours; the observed change due to the aging is a shift to more, smaller, PD pulses, and to the inception and extinction voltages becoming quite similar; higher temperature is 'complementary' to PD, accelerating the aging.

Summary: Presence of  $O_2$  has an important effect on the PD, higher temperature eases inception and increases pulse size, short term (12h) permanent changes are negligible, and long-terms (> 1000h) makes PD pulses more and smaller, with similar inception and extinction voltages.

#### [Zio96] W. ZIOMEK, H. MOSCICKA-GRZESIAK, E. KUFFEL, 1996

Assessment of the state of mica-resin insulation using PD charge analysis and dielectric loss measurements

The authors are at universities. The aim is to find suitably sensitive indices of insulation condition, by PD or dielectric-loss measurement.

Samples of mica paper and epoxy resin were made either with correct hardening or with excess temperature; 'silver varnish' electrodes were used, of diameter 40 mm. Plots of count/charge, D(n,q), were used to compare the two types of object and several voltage levels. The two types of object were also compared by loss measurement. The most sensitive indicator of the overheated specimens was cumulative charge measurement including just the largest pulses; loss measurement was not very sensitive. The



Figure 21: Effect of long-term aging on distribution of PD magnitudes. From [Flo95b].

introduction has claims that the D(n,q) distribution relates to the molecular structure of the insulation, citing [Mau95].

Summary: there is hardly anything here on the discharge side; the largest pulses seem the best indicator of 'damage', perhaps because there are a few extra, bigger, cavities in this case. There is no mention of the impracticality of such indices unless variation between different insulation systems or different days (temperatures, etc.) is not too large compared to that between 'good' and 'bad' cases that one seeks to distinguish.

# [Kim97] H.-G. KIM, H.-S. KIM, Y.-K. PARK, 1997

A study on the analysis of degradation mechanism for generator stator windings

The authors are from an electric power research organisation and a university. The aim is assessment of directly measurable changes in the insulation as a result of electric aging.

Stator bars of the type for a water-cooled 500 MVA 22 kV generator are used; they have conductor-bundle cross-sections of about  $31 \text{ mm} \times 54 \text{ mm}$  and total cross-sections of  $41 \text{ mm} \times 65 \text{ mm}$  including the cured epoxy-mica main insulation and semiconductive bonding tape. A stress of 5.5 kV/mm was used rather than the normal operating value of 2 kV/mm - 3 kV/mm; a 1969 paper is cited as showing that beyond 6 kV/mm the aging progresses 'abnormally'. The frequency seems to be 420 Hz; it's not clear whether this is for all cases or just for some cases with hydrogen. The environments was atmospheric air, or hydrogen pressurised at 4 bar.

When insulation breakdown occurred, the insulation around the breakdown site was inspected. The tree channels within the insulation were seen to have, for air, a diameter of 10  $\mu$ m to 20  $\mu$ m and length of 200  $\mu$ m to 400  $\mu$ m, and for hydrogen a diameter of 1  $\mu$ m to 5  $\mu$ m and length of 10  $\mu$ m to 50  $\mu$ m. The trees in air started at the central conductor, usually at a corner, with the tree diameter increasing by some tens of times in going away from the conductor; there were highly carbonised traces in the channels; the large cracks in the mica are claimed to be from PD. The trees in hydrogen were smaller at the outer side, perhaps due to the hydrogen and its pressure; their 'microcracks' were claimed to be due to replacement of K with H atoms in the mica.

*Summary:* it was difficult to comprehend this paper, but the basics of large differences between the common air or hydrogen atmospheres are clearly strong.

#### [Dym02] J.H. DYMOND, N. STRANGES, K. YOUNSI, 2002

#### Stator winding failures: contamination, surface discharge, tracking

The authors are with a machine manufacturer. The aim is an exposition of the practical importance of breakdown that starts on surface contamination rather than in the classic situation of voids near the central conductor.

Some surprising failures have occurred in machine insulation in environments with a lot of contaminants: it seems that the presence of varied surface concentration of (semi)conductive contaminants is critical to their contribution to tracking, since this provides areas of local field enhancement; examples are given where breakdown doesn't happen when clean or when immersed in contaminant solution but happens when removed, or where cleaning and baking a winding allows trouble-free testing at ten times the voltage that previouly gave rise to discharges. The varnish is important; some types performed many tens of times worse than others with respect to endurance time. A standardised test method is claimed to be needed.

Summary: surface discharges (PD) are important in this mechanism of insulation breakdown, but there's nothing about the PD itself in this paper.

#### **[Fen03]** M. FENGER, G.C. STONE, 2003

#### How humidity affects partial discharge activity in stator windings

The authors are with a consultancy. The aim is a simply a description of the title subject: this is relevant to condition monitoring, where apparently significant changes in PD may be due just to changes in the atmosphere or machine temperature.

A transparent climate chamber was used, with PD measurements using an oscilloscope connected through a 30 Hz to 1 MHz filter on a coupling capacitor (which seems to be 80 pF in the figures, and 320 pF in the text). PDIV of the circuit without test object was much higher, >40 kV, than was ever used in tests. The test objects were lengths of EPR-insulated cable, without their sheaths; they were connected either in pairs, to the earth and HV electrodes, or just to the HV, with earth being a bare metal plate. Surface-separation distances of 0 mm, 2 mm and 4 mm were used, at temperatures of 25 °C and 50 °C.



Figure 23: Insulator-plane PDIV, with varied humidity at 25 °C and 50 °C. From [Fen03].

Figures 22 and 23 show the change in PDIV for the two configurations of electrodes, each plotted against relative humidity (RH) for varied temperature and gap. The peaks in the PDIV are at around 50 % RH; the change in PDIV over the humidities below this peak (where increased electronegative 'gas' is claimed as the dominant influence) is really quite small — perhaps ten percent — while the change due to the high humidities (where surface droplets are blamed for the change) is more than a factor of two.

It is also interesting to note the relation of a real machine's PD activity to the (relative) humidity, when monitored over two days of operation (figure 24).



Figure 22: Insulator-insulator PDIV, with varied humidity at 25 °C and 50 °C. From [Fen03].



Figure 24: Relation of PD to humidity for an operating machine over two days. From [Fen03]

*Summary:* There are laboratory measurements with non-stator insulation, and some real online stator PD results. I don't follow the claims about the importance of absolute compared to relative humidity; this seems unjustified by any of the paper's content.

[Zha05] XIAOHONG ZHANG, CHUNXIU HU, JUNGUO GAO, QINGJUAN HU, 2005 Microscopic characteristic and signal analysis of aging defects in epoxy/mica insulation bar under different stresses

The authors are at a university, interested in the determination of wear by acoustic and electrical spectra.

Electrical, thermal or mechanical stresses of respectively 6.5 kV/mm at  $180 \,^{\circ}\text{C}$ , and  $100 \,\text{Hz}$  vibration at amplitude of 1 mm, were applied for 2000 hours, to 'large model bars'. PD measurement was by an oscilloscope over a  $50 \,\Omega$  resistance in series with the test object. It is unfortunate that the actual results (screenshots, within a poor pdf file) are completely indiscernible.

It is mentioned (as general knowledge, not as deduction from any experimental evidence from this work) that PD activity changes the surfaces and gases in the voids, that these lead to 'micro-cracks' around the void; and that thermal aging tends to produce delaminations more than the other forms of aging, electrical aging causing mainly treeing. As usual, there is no mention of how many similar samples were taken so as to get an idea of the variance of results.

[Flo06] B. Florkowska, P. Zydron, 2006

Analysis of conditions of partial discharges inception and development at non-sinusoidal testing voltages

The authors are at a university; the aim is to see the effects of waveform on PD.

An aged stator bar (bars?) was used as the test object, in a conventional PD measurement configuration, with the detection impedance in the arm of the test object, filtered at 10 kHz to 200 kHz, and sampled at  $\sim 5 \,\mu s$  intervals. Test voltages up to twice the inception level were used: sinusoidal, triangular and trapezoidal (peak at  $\frac{\pi}{4}$ ) at 50 Hz; from the paper's fig.1, the peak value seems to be the common factor between these waveforms.

PD count is used as the dependent variable, and seems to be strongly related to the slew rate: triangular form has least PD, trapezoidal has most. Continued but diminishing PD after the peak is reached is blamed on the supply filter resistance delaying the actual test-object voltage (couldn't delays in the presumably many small voids be a good explanation too?). The maximum count varies by more than a factor of two between the triangular and trapezoidal cases. Approximate linearity of count to voltage, pulse density and 'phase range' of activity is found for the sinusoidal and triangular cases.

# [Wei06] T. WEIERS, Y. CORRODI, R. BRUTSCH, R. VOGELSANG, 2006

Partial discharges in VPI winding insulations in dependence on the impregnating resin The authors are from a university, a machine manufacturer and a machine insulation supplier. The aim is a comparison of PD activity in various vacuum-pressure impregnated (VPI) stator insulation systems, during aging.

Various popular PD 'indices' are mentioned: maximum single charge in e.g. a minute; 'quadratic rate', a sum-square measure; mean apparent charge; pulse repitition rate (too high for their equipment, dealing with multi-cavity machine insulation); statistical moments.

Five specimens were used for each of two impregnating materials. 360 mm of 'slot' section high-conductivity tape was used in the middle of the bar-lengths, with 240 mm of stress grading at each end; external cross-section was  $15 \text{ mm} \times 35 \text{ mm}$ , and insulation thickness was 2.15 mm of  $155 \,^{\circ}\text{C}$  insulation.

Very high overvoltages were used: 38 kV rms, at 50 Hz, giving breakdowns at 25 hours for system-1, and 60 hours for system-2. PD measurements were by a coupling capacitor and 40 kHz to 800 kHz PD system.

Mean charge had little change during aging for either impregnation system. It was about 0.5 nC for system-1 and 1 nC for system-2. Maximum charge and quadratic charge had a fairly steady increase by several times, before breakdown, but no useful warning increase just before the breakdown. Pattern skewness varied monotonically between about 0.5 and -0.1 during aging, but was in opposite directions in the two impregnation systems — system-1 has a straight increase (earlier in phase) of skewness with aging, and system-2 had a  $\frac{1}{x}$ -like decrease. It is noted that the behaviour of system-2 is typical of the behaviour of stator-insulation as seen in other investigations; system-1 is considered to be not very 'voltage endurant', while system-2's behaviour is thought to have to do with stopping of tree growth by formation of conductive 'channels' (conductive surfaces around cavities?). *Summary:* beyond the practically oriented results that the examined indices gave no clear warning of imminent breakdown (during very artificially fast aging), there is the claim, mainly from other work, that skewness generally decreases in aging stator insulation, i.e. the mean phase becomes later.

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