

Measurement of partial discharges

A literature review

Nathaniel Taylor, ETK, KTH

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Introduction

The physics of partial discharges has been considered in another review. A largely independent matter is that of what associated quantities we get to *measure*, and how these relate to the PD event. This independence exists because the PD event happens generally more rapidly than the external circuit can respond, and the change in voltage at the test object terminals is generally a very small proportion of the applied voltage: the event can be regarded as a rapid change in dipole moments, affecting, but not affected by, the external circuit.

For my work with offline measurements mainly on stator insulation, using applied voltages at varied low frequency (0.1 mHz to 100 Hz), the classic IEC-60-270 PD measurement method, using frequencies below 1 MHz, has been used. For this method it would be good to get some other peoples' ideas about detection sensitivity, wise choice of relative component values, limitations, advantages, good practice in making connections, etc. As a matter of general education it would be good also to get a brief idea about other methods of PD measurement, such as non-electrical methods and methods using higher frequency-ranges.

Several books and papers have been read; their content is summarised all together in the following section, and then synopses of the most relevant works are given separately in the final section.

Summary of reviewed works

Thoughts about our PD measurements

Here I consider, in more detail than I've done before, my use of PD measurements. This draws partly on ideas and models I have used earlier (sometimes slightly erroneously) and partly on some points that this review stimulated me to consider, about analysis of the detection circuit and about the fields in the cavity and insulation.

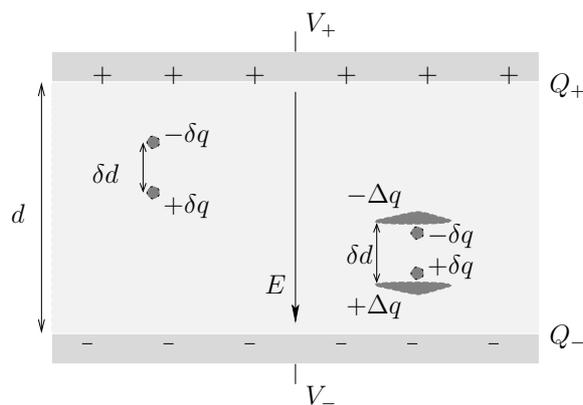


Figure 1: Definition of notation for study of dipole creation in the field between plane electrodes. To the left, a dipole moment is created by separating a small charge $\pm\delta q$ by distance δd parallel to the applied field. To the right, the same situation has occurred but with the space-charge Δq from earlier such movements already present, modifying the field through which the considered δq must move.

From PD-source to test-object terminals

The three capacitor ‘*abc*’ model is certainly the common introduction to this source-to-terminal relation of cavity PD: the test object is reduced to three lumped capacitances, one of which gets dollops of charge shifted between its terminals to represent discharges in a cavity. I have for long based my thinking about PD charge movements and apparent charge upon the description of dielectric polarisation well expounded in [Jon83].

SCENARIOS. Consider the following extreme cases, to permit the investigation of different influencing factors in isolation. The factors are the effect of the changed dipole moment on the field through which charges move, the effect of polarisation in the surrounding dielectric, and the effect of time-dependence (delay) of this polarisation.

Separation of small charge, in vacuum, parallel plates. By ‘small’ charge is meant that the field experienced by the charge is not changed during the movement.

From test-object terminals to recorder

What *are* the component values, really, for the detection impedances we use? Does the familiar ‘3.9 mH inductor’ really fit that description within the frequency range of interest (up nearly to 1 MHz with the full system bandwidth)? How much inductance is there in the measurement circuit loop, even in an optimal case in the lab with a small test-object?

Details of reviewed works

Books and longer articles

[Kre64] F. H. KREUGER, 1964

Discharge detection in high voltage equipment

As the main theme of this book, and of the current report, is the *measurement* of PD, the introductory material about the PD events themselves has been put into the ‘physics of PDs’ report; just the measurement-related matters are summarised in the following.

CAVITY PD. The classic *abc* circuit is shown (a is the shunt capacitance of the rest of the dielectric, assumed large; c is the capacitance of the PD cavity; b is the capacitance of the dielectric in series with the cavity). Optional shunt conductances are shown, particularly for the DC case. The *abc* model is used for the analyses. A suitable measure of discharge magnitude is investigated: the change in charge at the two faces of a cavity, supposedly equivalent to an injection of charge across capacitor c , gives a change in cavity voltage of $q_i = (b + c)\Delta V$, assuming $a \gg b$, but this is not directly measurable; the change in charge to maintain specimen voltage is $q = b\Delta V$ (apparent charge), and the associated initial change in specimen voltage is $\Delta V_s = \Delta V \frac{b}{a+b}$, either of which quantities is measurable; the discharge energy is analysed on an assumption of multiple total discharges of the cavity on each quarter cycle, to show that the integrated energy in the cavity and at the supply terminals are equal (on these assumed conditions) and that the apparent charge therefore can reflect discharge magnitude; the relation between local and apparent charge is $q_i = (1 + \frac{c}{b})q$. Considering the effects of geometry and material upon the *abc* values, a decreased apparent charge for an increased thickness of insulation is expected, given a particular cavity.

DETECTION. There are many PD phenomena: electric pulses and losses, EM radiation, light, heat, noise, gas, chemical changes; electrical measurements can allow single pulses to be seen. Terminology: detection determines presence or absence of PD at some level; measurement establishes a magnitude; location estimates the source. The sensitivity (presumably apparent charge?) of optical detection varies from about 1 pC on surfaces to 50 pC for internal PD in translucent dielectrics; for sonic detection 5–50 pC is possible in fortunate conditions. Electrical detection is claimed all to be reducible to the basic PD circuit of test object a , coupling capacitor k , and detection impedance Z somewhere in their loop. If Z is essentially conductive, the voltage across it during a PD event is a rapid rise to the change in voltage of the test object, then a monotonic fall to zero as charge is supplied from k and (later) the supply; with a shunt inductance, there is an oscillation, but the peak is the same; a shunt capacitance in Z should reduce this peak; the peak of the impulse voltage across Z is independent of its conductance part, but the decay time depends on this value and the series capacitance of a and k shunted by any capacitance in Z ; a k much greater than the capacitance in Z is needed in order to see the full impulse size. The spectrum of output from an RC detection impedance is largely flat in amplitude up to $1/2\pi T$ where T is the time constant of the detection resistance and the total capacitance shunting it (due to C a and k). The spectrum of output from an RLC detection impedance is a band-pass peak, centred on the resonance

of the L and the total capacitance. In either case, the amplifier should have higher bandwidth; in the case of measurements on inductive apparatus, a wide-band measurement is considered desirable for avoiding local maxima and minima in the response spectrum. Variations on the detection circuit are used to reject interference (balanced detection).

EQUIPMENT. Descriptions are given of some 1950s equipment. The first one looking really like modern ‘standard’ detection is the 1952 ‘ERA’ detector model I: with 10 kHz bandwidth it can resolve about 7000 pulses per second, down to 0.02 pC sensitivity for a 1 nF object, displaying on an oval trace of the voltage phase; calibration is straight across Z . Discriminators depending on supply voltage polarity are mentioned. Plain ‘tan δ ’ methods (non-pulse) are claimed to do no better than 50 pC sensitivity for a 1 nF object. Some more specialised circuits for transformer measurements are mentioned; reduced bandwidth seems favoured (some hundreds of hertz, around about 10 kHz) for reduced effect of source location.

ELECTRICAL DETECTION: SIGNALS. The classic detection circuit is analyzed, with a , k and Z in series, a charge injection q being made across a to represent a PD event in a . The initial step in voltage on Z is then $v = q / [(1 + C/k)a + C]$, where C is the shunt capacitive component of Z ; if C is negligible compared to the other capacitances, then the full change in voltage of a appears across Z initially, i.e. the high-frequency circuit is open at Z in this case. The voltage across Z decays as the capacitance of series a and k in parallel with C , discharging through the other components of Z which are first taken to be just a resistor R ; the time-constant is thus $\tau = R(\frac{ak}{a+k} + C)$. The amplifier is considered as a further RC low-pass filter and ideal amplifier, fed from the voltage across Z . If the filter components are R_f and C_f with time-constant α , then the ratio of impulse heights out of and in to the amplifier filter is $\xi = \hat{v}_o / \hat{v}_i = (\tau/\alpha)^{\alpha/(\alpha-\tau)}$, i.e. a fast response of the amplifier compared to the decay of the signal, is needed in order for the signal peak to be not much reduced. A negative overshoot of the amplifier output is mentioned for the case when the amplifier rejects low frequencies.

ELECTRICAL DETECTION: NOISE. The detection sensitivity when limited by *amplifier noise* is approximated as $q_{\text{det}} = 2V_{\text{noise}}((1+C/k)a+C) / \xi$ on the assumption that the peak into the amplifier must be at least twice the mean envelope (my term for a vaguely described oscilloscope concept) of the noise; note that for large a this minimum level is proportional to a . With amplifier noise increasing as the square-root of bandwidth, the optimum amplifier time-constant for balancing higher signal (ξ) against higher noise is $\alpha = \tau$. With the -3dB bandwidth approximated by ignoring small bands of LF cutoff to give $B = 1/2\pi R_f C_f = 1/2\pi\alpha$, the detection circuit time-constant should be kept such that $B = 1/2\pi\tau$; this implies varying R when the test object a is changed. The detection sensitivity when limited by *circuit noise* is treated as a theoretical effective noise voltage over the detection resistor R , $V_{\text{eff}} = \sqrt{k_B T / C_n}$ where C_n is the total capacitance shunting R , T is the thermodynamic temperature, and k_B is Boltzmann’s constant. (there’s a bit of confusion here at least about definition of $n = a/k$ which is defined as a reciprocal of this in one case). No bandwidth term is seen: the expression is for all frequencies, and it is claimed that the noise voltage would only be increased by some 30% by this assumption compared to limiting the calculation to the typical amplifier bandwidth. The noise seen

on an oscilloscope (by the definition used previously, for amplifier noise) is claimed to be more than this, $V_{\text{noise}} \approx 2.5 V_{\text{eff}}$ (equation 2.20 has apparently an error in an exponent, which should be 4×10^{-10} rather than 4×10^{-4}). This gives the minimum charge sensitivity due to amplifier noise as $4 \times 10^{-10} \sqrt{n+1} (1/\xi) \sqrt{(1+C/k)a+C}$. Thus the relation of sensitivity to total capacitance across Z is a slower (square-root) impairment of sensitivity with increased capacitance, for the circuit-noise case, compared to the direct proportionality of the amplifier-noise case. In the case of an RLC detection impedance, the major change in the working is that the response factor ξ is changed to ζ , including the effect of amplifier bandwidth upon the measurement of the noise (?).

ELECTRICAL DETECTION: RESOLUTION. The signal and noise voltages determine the sensitivity, as described above. The resolution is the closeness in time to which pulses can be resolved. It is noted [not obvious to me first, until thinking of the difference of charge-impulse or voltage input] that the effect of multiple PD pulses into the detection circuit too close in time to be resolved causes the output to be increased, looking like a single larger pulse, while the effect of pulses into a low-bandwidth amplifier too close to resolve is just an overlapping without addition of size. About 1.5–3 times the amplifier time-constant should be the interval between pulses for sufficient resolution.

LOCALISATION. PD source locations can be inferred by several means. In long objects such as cables, and some transformer or machine windings within a low enough frequency range, the times between pulse peaks at different points can help to locate an (infrequent) PD source; the application of penetrating ionising radiation, swept over the test object, can locate a source by the change in PD activity; electrical shielding can be used in systems with multiple PD pulse measurement electrodes, to focus the detection on signals from a particular area.

DISTURBANCES TO DISCHARGE DETECTION. Mains interference is likely, and can be filtered. EM radiation from radio broadcast can be largely avoided by staying under 100 kHz [even more true now, I suppose]; screening by metal gauze or screened room may be needed in other cases. All components in the test circuit should be checked for PD freeness: coupling capacitor, filter, terminals, HV connection, HV source. Contact noise from bad connections in the test circuit or even in capacitors with pressure (non-welded) contacts can be enough to disturb a measurement. External PD may be induced by the test connections' high potentials acting on extraneous conductors. Note that low resolution (long time-constants) risks adding different events into one, making results appear to be those of PDs of increased magnitude. Many such possibilities can be easily investigated if such circuit properties as the time-constants can conveniently be changed to test their effect. The circuit should be tested with a PD-free test object at the full intended voltage.

RESULTS OF DISCHARGE DETECTION. Small cavities: little change in maximum magnitude above inception, largely symmetrical pulses in positive and negative half-cycles; this is a clear indication of a limited cavity in a solid dielectric. Voltage-hysteresis is possible in impregnated dielectrics; an example is given for an epoxy resin cavity with some moisture, where the same PD magnitude is seen with the voltage approximately halved on the way down through the voltage levels. Peak-voltage centred asymmetric

PD is from corona. Contact noise is largely present throughout the cycle, rising quite continually with applied voltage amplitude.

[Kuf00] E. KUFFEL, W. S. ZAENGL, J. KUFFEL, 2000

High Voltage Engineering: Fundamentals

This is a general-purpose book with only a little space for PD methods. As a different explanation of measurement methods, and a more modern summary of industrial practice than was described in [Kre64], it is included here.

PD: EFFECT AND DETECTION. Changes to adjacent insulation material are caused by ‘each PD event’; some weak materials such as PE may break down in just days under feasible in-service stress and PD. Measured phenomena are electric pulses, electric loss, EM radiation, sound, gas pressure, and chemical change (straight from [Kre64]). The discharge event is on a nanosecond scale, and the external circuit with its much longer response times is consequently irrelevant to the event itself. In gas, the discharge may rise in less than 5 ns from the fast avalanche processes (movement of electrons) then fall in a longer time as positive ions and attached electrons are cleared; the fall is generally not more than 100 ns in atmospheric air.

ELECTRICAL DETECTION. The *abc* model is presented, as usual; its justification is that ‘the use of partial capacitances is possible as long as no space charges disturb’ the field. The explanation of the classic measurement circuit is charge-based: ideally a coupling capacitor C_k is used that is much greater than the test object capacitance C_t , and the supply source is fully decoupled; the total apparent charge then comes from C_k and is measured by a charge integrator; with realistic C_k the measured value is reduced to about $C_k/(C_k+C_t)$. The apparent charge is a good quantity to measure, as it is not so directly dependent on C_t , and as it reflects the total dipole change of the PD charges; the IEC standard is slightly criticised even for weakly implying that the ‘actual’ PD charge at the site might have been of relevance if only it were accessible. The PD currents in the detection circuit may be of interest in their time-dependence: this is a hard thing to measure, due to the requirements on bandwidth and the presence of a continuous load current due to the AC excitation voltage. Increasing the resistance R of the conductive branch of a detection impedance Z causes higher voltage for pulses (and for the load current) but also makes stray capacitance across Z become more significant and delays the transfer of charge in the detection loop, so the higher frequencies in the signal are filtered. A transmission line (co-ax) with matched termination should be used to connect to the measuring device; alternatively, a high bandwidth amplifier may be connected directly to Z . Only with low-capacitance objects can the pulses be distinguished easily from the load current. The effect of the detection and measurement circuits on the pulse affect all the measurements of PD time-dependence. With significant inductance in the detection circuit (or test object) the measured current will be oscillatory, but the total charge transfer will be unchanged.

MEASUREMENT SYSTEM SPECIFICATIONS. The detection impedance Z is here called a ‘coupling device’ (CD); it may be in the lead of C_k or C_t : supply/stray capacitances reduce the PD current in C_k ; troubles with using C_t are accessibility of an open conductor

to connect to Z , high load current, and possible damage to the measurement system if there is breakdown of the test object. Measurement system transfer impedance $Z_t(\omega)$ is the ratio of output voltage amplitude to sinusoidal input current. The lower and upper limit frequencies f_1 and f_2 are the points where Z_t is 6 dB below the passband value; the midband frequency f_m is halfway between f_1 and f_2 , and the bandwidth Δf is the difference between f_1 and f_2 . Apparent-charge measurement is considered a band-pass situation, where power frequency and low harmonics, as well as high frequency signals, are removed. Pulse resolution time T_r is the minimum time between similar consecutive pulses such that both are resolved with no more than 10% error in magnitude. ‘Integration error’ is when f_2 is high enough for the signal spectrum to have significantly reduced level within the detection bandwidth. The measurement band should be contained fully within the PD signal’s band, which in turn should be within the calibration pulse’s band (rather strange claim if we believe PDs to rise in a few nanoseconds but require calibrators only to rise in some tens of nanoseconds? but this is in the standard, too).

WIDEBAND MEASUREMENT. Recommendations, from the IEC standard, are:
 $30 \text{ kHz} \leq f_1 \leq 100 \text{ kHz}$, $f_2 \leq 500 \text{ kHz}$, and $100 \text{ kHz} \leq \Delta f \leq 400 \text{ kHz}$.

The response to a non-oscillatory PD current (i.e. if the detection circuit doesn’t introduce oscillation) is usually a well-damped oscillation. The response of an RLC coupling device (Z) to an impulse of current is $V_o(t) = (q/C) e^{-\alpha t} [\cos \beta t - (\alpha/\beta) \sin \beta t]$, where $\alpha = 1/(2RC)$ and $\beta = \sqrt{1/(LC) - \alpha^2} = \omega_0 \sqrt{1 - \alpha^2 LC}$. A quality factor $Q = 1$, achieved with $R = \sqrt{L/C}$, gives an efficient damping for avoiding oscillations and consequent superposition errors. The resonance frequency is ‘typically’ about 100 kHz, with resolution time of about 10 μs . The shunt capacitance due to the detection circuit (series C_k and C_t) is also important in the response (but this was not mentioned until after the analysis of the detection impedance). The components of Z (in particular, R , presumably) should be changed according to specimen and coupling capacitances, to keep the resonant frequency in the right range for the band-pass filtering of the amplifier and measurement instrument, often from about 10 kHz to 100 kHz (presumably this is just f_1 and f_2 ? or is the amplifier a further, optional component as well as the measurement instrument?).

NARROWBAND MEASUREMENT. Recommended values are:
 $9 \text{ kHz} \leq \Delta f \leq 30 \text{ kHz}$, and $50 \text{ kHz} \leq f_m \leq 1 \text{ MHz}$; a fast decline of gain outside the passband is desirable. These systems are rather like the swept-frequency RDV (radio disturbance voltage) systems, but in a lower frequency range where the apparent charge is the desired measurand. Pulse resolution time is long, due to the small bandwidth; typically $T_r \geq 80 \mu\text{s}$. The detection impedance seems to be said to be usually a RC type with a time-constant less than the period of the measurement system’s frequency (the words are ‘coupling devices providing high-pass characteristics within the frequency range of the instrument’). The assumption in the following analysis is then that the input to the instrument is a decaying exponential, with total time-integral proportional to the apparent charge. The amplitude spectrum is then approximately flat at low frequencies, with a -3 dB point at $\omega_c = 1/T$ where T is the time-constant of the decaying input

signal; for practical values of T , determined by the detection impedance, the spectrum falls off not far from 1 MHz, i.e. one needs to be careful about choice of f_c in the flat part. The response from the narrow-band filter is then an oscillation at its f_c , amplitude-modulated into an envelope of a decaying oscillation ($\sin(x)/x$) at about Δf ; all the polarity information of the signal is lost. The narrowness allows checking that the amplitude spectrum is indeed flat. The delay between the start of the input pulse and the peak of the output is the system delay time; an assumption of instrument phase-response proportional to frequency is considered reasonable for narrow bands. Lower quality instruments use a fixed LCR circuit; higher quality tunable ones use heterodynes (mixer circuits).

HIGHER FREQUENCIES: RFD, UWB. Radio-frequency disturbance is measured usually with a 9 kHz bandwidth. These measurements are in wide use, interesting particularly for open sources of PD such as transmission lines. A psophometric (weighted for the detectability by people) filter can be applied to scale the spectrum. For PD pulse measurements intended to locate the source along a large object, a higher bandwidth is needed than in the classic apparent charge measurement. For cables, going beyond some 10 MHz is considered pointless (attenuation, e.g. semicon?). Ultra-wideband PD measurements up to and a little beyond 1 GHz are of use in locating sources in GIS, since here the construction is conductive tubes in gas, with very low attenuation, and since the PD source in SF₆ give rise to particularly rapid pulses with spectra well into this band. The apparent charge is not measured by these, non-integrating, methods.

CALIBRATION. Calibration is necessary for the full PD detection and measurement setup, for the obvious reasons of dependence of q upon relative values of various capacitances, and frequency bands of signals and components. Voltage steps across a well-known capacitance are used to give well-known charges. Rise-times not more than 60 ns are specified for the voltage generator. The 2000 version of the IEC standard has introduced tighter but still not very tight criteria for the transfer impedance of the measurement system and for the calibration of calibrators, which can be assumed to be within the greater of 5% or 1 pC. Accredited laboratories' calibrations have been found to be within about 3%.

DISTURBANCES AND THEIR REJECTION. The sources are split by dependence on energisation of the test circuit: these can be found in [Kre64], the only addition being power-electronic switching in e.g. motor drives. Screening and filtering, besides PD-free test-equipment, are the most effective countermeasures. Where these conditions are not met, other means may be used to reduce disturbance. A differential PD bridge (apparently the same as was called a 'Schering bridge' detection circuit in [Kre64]) has the test object and coupling capacitor as HV arms in a bridge where the LV arms are variable resistances. A variable shunt capacitor can be added to one or other of the LV arms, as ever is necessary to get balance: with the coupling capacitor being determined more by PD freeness than by 'standard capacitor' (low loss) criteria, it is not clear which HV arm will be more lossy, hence the need of choice of arm for the LV capacitor. If the two HV arms have similar frequency-dependence of loss, then balance can be found over a wide frequency range [but what about the LV capacitor, and the frequency-

dependence of capacitance?]. PD from the test object causes a differential voltage, but external impulses and excitation current are largely balanced across the bridge. A polarity discrimination circuit has a similar layout to the differential PD bridge, but with regular coupling devices as the two LV arms; these are connected to an instrument whose logic permits registration only of those pulses that appear valid (presumably, that are simultaneous and opposite in the two arms). Gating certain time-windows in a cycle can be used to remove known periodic disturbances.

OTHER PD QUANTITIES. The ‘largest repeatedly occurring magnitude’ of PD apparent charge is often specified, but the deterioration process in insulation is ‘certainly a result of all discharges and is not limited to the maximum values only’ (but, how important is lots of really small distributed wear, to possible breakdown, compared to large single sources?). The *average discharge current*, $\sum_{n=1}^{N(T)} |q_n|/T$, is little used but some interesting relevance to lifetime has been shown (cites IEC-60270, 2000, but the only reference there is paragraph 4.5.3, which says nothing about interpretation – wrong citation?). The *discharge power* is $\sum_{n=1}^{N(T)} v_n q_n/T$ where v_n is the applied voltage at the moment of the n th pulse. It is claimed that ‘as discharge energy is directly related to discharge power, this quantity is always directly related to insulation decomposition’ (cites a CIGRE report, of degradation of paper-oil insulation) [What ‘directly related’ means is far from clear to me, and nor is it clear that the product vq at the terminals is proportional to the local PD energy, unless all sources discharge by the same extent; the dielectric polarisation in the rest of the insulation may matter; the apparent charge is dependent on the dipole moments, not directly on the potential through which charges have moved at the PD site, if such movement changes the cavity voltage]. The *quadratic rate* is basically the average discharge current calculation but using the squares of charges; it ‘appears to have no advantages compared to measurement of the maximum values of q only’.

[Bar90] R. BARTNIKAS, 1990

Detection of partial discharges (corona) in electrical apparatus

BACKGROUND. Audible or visible detection was around 1900; the effect on electric loss was measured around 1920 (Schering bridge); oscilloscope studies of voltage waveforms across spark-gaps and wire-plane objects around 1930; detection of internal discharges in transformers and cables was around 1940, with further work on the wear effects of PD around 1950. Early pulse measurements, quite well established by the 1950s, used RLC detection impedances for the advantages of greater sensitivity and rejection of external noise, or RC detection impedances for higher bandwidth and consequent better reproduction of the shape of the pulse current; the position of this impedance either in the ‘specimen’ (test object) or the ‘blocking capacitor’ (coupling capacitor), or both for balanced measurement, was already established.

Calibration was first by a standard ‘spark gap’ (point-hemisphere?), but then by a step voltage applied to an injection capacitor. The step should rise in $T_r \leq 0.04/f_0$, where f_0 is the resonant frequency of the RLC detection circuit, typically in the range 30–70 kHz.

‘Narrow-band detectors with low resonant frequencies’ have ‘intrinsically higher sensitivities’, ‘require fewer adjustments and are more simple to use’, and ‘respond primarily to the charge component of the discharge transient’ (the works cited are both focused on PD in cables rather than small lab-type objects; this may go towards explaining the claims?).

The *abc* model was used (Whitehead, 1953) as a simple description of the PD in a cavity, and has since been used to suggest a relation of local and measured charge; no ‘direct relation’ exists, but the apparent (measured) charge is ‘convenient and expedient’ and ‘can be used to calculate the energy released by the discharges’. Pedersen’s (then recent) work is cited, but not as though it were anything not already said — just that it demonstrated a connection of polarisation charges to induced electrode charges (a later publication by Pedersen actually contradicted the above claim that the pulses are a direct measure of energy at the PD site).

SOME COMMON SPECIMENS. Capacitors are compact, but the usually high capacitance makes sensitive pulse measurement difficult. Cables need PD-free terminations, and possibly a matched termination. Location in cables has been done by pulling the non-shielded cable through a short bath of slightly conducting water, or by localised X-ray, or by reflection. Transformers are often excited for PD measurements by direct excitation of the LV winding; smaller transformers are sometimes excited from an external test transformer. Radio noise meters (here also called ‘radio interference voltage’, RIV) reading in microvolts are often used in the US, but pulse measurement in picocoulombs is more popular elsewhere; the relevance of pulse charge measurement to expended energy is again mentioned. A ≤ 500 pC or ≤ 100 μ V level at 150 % rated voltage for 1 hour is specified. There have been efforts to use travelling pulse methods to locate PD sources in transformers, but the interactions, e.g. capacitance between turns and windings, make this more awkward than with cables, and the same troubles of resolving multiple sources and frequent pulses exist as for cables. Comparison of arrival times at the two ends of a winding has been tried. Checking inception voltages when exciting the transformer (magnetically) with varied winding configurations gives some idea of what part of the winding the sources are in, since the potentials of different parts of the winding can thus be varied.

ROTATING MACHINES. These are the most awkward for charge measurement: calibration is not attempted. (But, there’s no claim here that it’s impossible; just that one needs at least a better idea of frequency response of machines in general; this paper was before the flurry of measurements in the 1990s that I looked through last year.) Machine insulation is unusually resilient against PD, but large discharges can ‘progress rapidly’. Slot discharges are particularly dangerous, and were identified as such in the early 1950s. Machine PD measurements have been on neutral earthing points and by coupling capacitors on phases. Sometimes the excitation has been the machine’s own excitation and rotation, possibly done offline to permit variation for measurement of inception and extinction. Some HF measurements (80 MHz) are mentioned. Due to the relatively dense PD in machines as compared to other specimens, bridge (i.e. non-pulse) techniques can be used without such a trouble from their lower sensitivity; there is then

the advantage of multiple pulses not interfering with each other. Schering bridge and current-comparator methods are used, looking at tip-up, often on individual phases (this we know as common practice still). Interestingly (with relation to my project, and work on measurement of total PD charge by DS), a measurement of total PD charge and energy per cycle was implemented in the 1960s, following on from work on corona loss as early as 1928. The early methods used oscilloscopes displaying PD charge versus voltage; the area of the loop is then interpreted as per-cycle energy. The advantages over pulse detection include the measurement of all types of discharge (including glow / pulseless); it is claimed to be ‘somewhat astounding that [this method] does not command a higher degree of attention and popularity’, but the trouble of end-winding grading is not mentioned at all. Capacitive and inductive probes of varying description have been used to detect and localise PD sources, sometimes requiring removal of the rotor.

A FEW MORE POINTS. Industrial PD measurement has contributed ‘perhaps more than any other type of measurement in improving the quality of high voltage power apparatus’. Sometimes the mere inception and extinction voltages are used, while sometimes a measured level is important. Distributions of pulse magnitudes have become commonplace for machines. This has drawn a lot of research, perhaps to the detriment of other methods such as bridge-like measurement of total loss. Work including experiments in 1968 and 1985 has confirmed the existence of pseudo-glow PD that cannot be detected by pulse measurement systems. Theoretical studies suggest that gaps discharging around the inception voltage favour glow-type discharge, and those discharging with overvoltages favour pulse-type. Actual PD sources tend to have some of each, so pulse measurement reveals only some of the total. ‘It is thus hoped that in the future, bridge detection methods that respond to all types of discharge will receive more attention in both the applied and fundamental research areas.’ A major remaining problem is an acceptable level, and the relative harm from more smaller pulses rather than fewer larger ones.

[Har73, Vai85] Transformer μV vs pC

Two works cited in [Bar90], about PD calibration.

[Har73] For transformers, the ratio pC/ μV varies by a factor of 5, but for simpler objects such as bushings and switchgear it is close to unity. Charge measurement is useful for the ability (approximately) to calibrate the apparent charge, and to measure each pulse (broadband case). The relation between the two methods is derived, with similar connection points but taking into account the capacitance across which the voltage is measured. In the discussion, Bartnikas claims it pointless to advocate the charge method over the voltage method, as there is not good evidence that ‘apparent charge’ reflects the damage caused, but the *energy* would be more meaningful; this is strange, as the energy is closely related to the apparent charge, there isn’t good evidence for the dissipated energy being really important, and the PD may be more ‘symptom than a cause’ although transformers would be more easily damaged than machines. Hickling (of Parsons Peebles) notes — and most presciently too, if I may say so Minister, in view of results twelve years later in [Vai85] — that: the capacitances for converting between

pC and μV measurements are generally not known; several measurements, on different terminals, are a good idea, for getting an idea of the attenuations; and the ratio can vary by as much as 100.

[Vai85] is a thorough study by Hydro-Québec of the relation between RIV measurements as practised in North America, and broadband or narrowband PD charge measurements *à la* IEC 60270 as used in Europe and much of the rest of the world. Comparisons were performed with simultaneous measurement on over 100 transformers of sizes up to transmission level. The inverse relation of RIV amplitude to capacitance made this method undesirable, due to its hiding the PD more in important large apparatus. The ratio of readings by the two methods varied by as much as a factor of 100, making it clear that claims of equivalence were unfounded. That wear is dependent on PD charge is mentioned as a conjecture that would further support the use of pC measurement. The wide-band apparent-charge (pC) measurement was found to be the best at giving consistent results yet not losing too much information about pulses. A band of 40–200 kHz was used. The discussion of the paper included a claim that in fact the consistency of apparent charge measured at the terminals for a certain injected value in different parts of different transformers was better with a narrowband method e.g. of 10 kHz bandwidth around 100 kHz; the authors responded that the travelling and capacitively coupled signals are both included in the broadband measurement, giving a smooth response, while the narrowband signal includes mainly the pure travelling wave which has peaks and troughs in frequency such that certain PD locations may be missed. The low frequencies around 100 kHz are desirable for the very slow rise-time PDs that can occur in oil.

[Cri88, Ped89, Cri89, Ped91, Ped95b, Ped95a]

A. PEDERSEN with G. C. CRICHTON, I. W. MCALLISTER, P. W. KARLSSON, C.1990.

Theory and Measurement of PD: relation of PD event and induced charge

In the late 1980s and early 1990s this group at DTU worked on some experimental and theoretical investigations of PD, driven mainly by the application of PD diagnostics of GIS spacers. Several papers during this time considered the relation between a PD event and the charges detected in a PD measurement made on some terminals of the test object; there is a large amount of common material in these papers, which is not very surprising when one notes that the suggestions of necessary changes to conventional ways of explaining and calculating PD quantities went largely unheeded (for example, [Bar90] mentions one of these works, but makes no apology for going on to the *abc* model for its analysis).

WHAT IS WRONG WITH CIRCUITS AND *abc*? The popular *abc* model is derided for applying circuit ideas such as implied equipotential (conductive) surfaces of a capacitor to the the case of cavity walls that need not at all have a single potential. The *abc* model also is oriented to a simple situation of uniform field between two electrodes between which the excitation and measurement are made; but a real situation may have several electrodes and not make measurements on the same ones as the excitation is applied. PD charges and their effects on electrodes should instead be treated as a

field problem of dipole moments and induced charges, which can be generalised to a case where there are many electrodes and arbitrary distributions of charge. Emphasise that the induced Poissonian charges are independent of the external circuit, and arise practically instantaneously. The external circuit determines how quickly the Laplacian charges can be compensated.

A PHYSICAL DESCRIPTION OF THE EFFECT OF PD. Consider an electrode in space, with no overall charge on it, and a point charge at some point outside the electrode. The electric flux from the charge spreads out from it, so that any enclosing surface has this same flux passing through it. Some flux will contact the surface of the electrode that faces the charge; it will contact normal to the electrode as the electrode is conductive and therefore has no tangential surface field in an electrostatic situation. Since the electrode has zero total charge, the same flux must come out on the other side: there cannot be a flux inside, as there cannot be any electric field in the conductive material. These conditions are all satisfied by the surface charges on the conductor, induced by the external charge forcing electrons to one side to counter any internal field. The authors refer to the surface charge facing the external charge as the ‘Poissonian induced charge’ (as it is induced by the field from the external charge). [Note that, if the simple case of a large pair of parallel electrodes is used, then the charge on each one would be about half of the value of the external charge; of course, a real PD case has a dipole rather than a single point-charge.] The potential of the electrode is altered by the presence of the external charge. One way of seeing that this must be true is to regard the potential relative to some reference point beyond the electrode: with extra electric field passing between the electrode and that point, the difference in potential between them has changed, and can only be restored if the electrode is given an overall charge equal to the Poissonian induced charge. If the electrode is connected to a source of whatever the electrode was at in the absence of the point charge, a charge will flow to restore the electrode’s potential by removing the excess charge on the other side: this is referred to as the ‘Laplacian induced charge’. A point to note, that is easily missed if one is used to seeing calculated field patterns, is that the charge induced on the electrodes, i.e. the electric flux from the point charge that impinges on the electrodes, is dependent only on the point charge and the electrode positions, not on the potentials of the electrodes. By all means, the induced charges on electrodes can then induce further charges on other electrodes, but the first part of the calculation is simple.

THE RELATION OF PD CHARGE TO ‘APPARENT’ CHARGE. Functions are derived for the induced charge on a particular electrode due to the appearance of a dipole moment at any point in the space around the electrodes.

The λ function does this for a ‘Maxwellian’ model in which polarisation of a dielectric material is represented as an instantaneous relative permittivity, giving rise to the electric flux-density variable D instead of just $\epsilon_0 E$. For some point in space \mathbf{r} , $\lambda(\mathbf{r})$ gives the ratio of the potential at \mathbf{r} to the potential of the electrode being considered, if all other electrodes are at zero potential.

Therefore, $\lambda(\mathbf{r})$ is a solution of Laplace’s equation $\nabla \cdot (\epsilon \nabla \lambda(\mathbf{r})) = 0$, with boundary conditions 1 and 0 on the considered and other electrodes. The charge induced at the

(facing) surface of electrode i for which the λ_i function has been calculated is then $q_i = -\mu \cdot \nabla \lambda_i(\mathbf{r})$, where μ is change in dipole moment due to a PD event. For the more general case when monopoles may exist, the sum of all volume and surface charges' products with λ of their positions can be used, $q_i = -\iiint \lambda_i \rho d\Omega - \iint \lambda_i \sigma dS$.

This is a more formal way of writing the grounds of my previous energy-based considerations, where the input energy is due to the loss in moving a PD charge by a certain distance in a field; the simple consideration is however wrong when it goes on to assume all of that energy to have been dissipated in the movement of charge, if the local field in fact reduces during the PD event.

The $\varphi(\mathbf{r})$ function is used when working with the polarisations throughout the material, intended for situations of more 'research' orientation: it is the free-space simplification of λ , and material polarisations are then included with PD-induced charges in the total polarisation to consider for the calculation of q_i .

PREDICTIONS OF PD MAGNITUDES. Based on expressions for the field within ellipsoidal and spheroidal voids as a proportion of the field in the surrounding dielectric, and on models of gas discharge inception and extinction for attaching and non-attaching gases, predictions are made of the PD magnitude for various gases as a function of void size and gas pressure.

SIGNIFICANT CLAIMS (AND MY CRITICISM).

— The use of circuits to explain PD is inadequate and plain wrong.

(Certainly it is possible to take circuit analogies too far, for example by expecting a reduced 'small-signal' capacitance after the 'short-circuiting' of capacitance c in the abc model; but it's a very good approximation in many cases where one doesn't anyway know all the changes in dipole moments to better than a factor of two, or more!).

— The widespread term 'apparent charge' is misleading, and should be changed to 'Laplacian charge'.

(I really don't see the problem with *apparent* charge; it's a pretty good name for what is, after all, the charge that ultimately can *appear* for measurement in the leads of a test object. It may be widely used with implications that it measures the 'PD charge' or some very important property of PD, but changing a name is hardly going to change people's lack of detailed understanding. The terms Laplacian and Poissonian were not at all obvious to me as good names.)

— Capacitance is a concept reliant on Laplacian fields, for otherwise, given arbitrary space charges, the charge on the capacitor is not in direct proportion to voltage. Capacitance also supposes defined equipotential electrodes, rather than insulating surfaces with varied potential.

(True if treating a large cavity. But for simple models where PD is fairly homogeneous in a small cylindrical cavity, it's not such a bad thing, if partial capacitances are taken to imagined electrodes on the cavity 'top and bottom'; again, the available knowledge of the PD charges makes ultra-precision pointless.)

— The pulse energy at the terminals isn't directly related to local PD energy.

(This is true even considering polarisation in the dielectric as being instantaneous, i.e. loss-free, and it is an interesting point since the energy claim is so widespread and

I had gone for it too from a simple analogy with dielectric polarisation. On further consideration, now bearing in mind that with PD a dipole creation affects the field for later dipole creations, the energy at the cavity is seen to depend on the energy seen at the terminals according to much collapse there is of the cavity voltage. [Significant polarisation delay should be considered too.]

DEIS Magazine series

The IEEE DEIS Magazine, ‘*Electrical Insulation*’, ran a series of twenty-five articles about PD, mainly during the early 1990s:

[Bog90c]	1	Partial discharge: overview and signal generation
[Bog90a]	2	Detection sensitivity
[Bog90b]	3	Cavity-induced PD in solid dielectrics
[Ste91]	4	Commercial PD testing
[Che91]	5	PD in polymer-type line insulators
[Koc91]	6	PD testing of printed circuit boards
[Sto91]	7	Practical techniques for measuring PD in operating equipment
[Cha91]	8	PD testing of solid dielectric cable
[Bau91]	9	PD in gas-insulated substations-fundamental considerations
[Bau92]	10	PD in gas-insulated substations-measurement and practical considerations
[Lau92]	11	Limitations to PD as a diagnostic for deterioration and remaining life
[Hut92]	12	Partial discharge detection in rotating electrical machines
[Lun92a]	13	Acoustic partial discharge detection — fundamental considerations
[Lun92b]	14	Acoustic partial discharge detection — practical application
[Fuj92]	15	Improved PD testing of solid dielectrics using X-ray induced discharge initiation
[Har93]	16	Ultrasonic sensing of PD within large capacitors
[Nat93]	17	The early history of partial discharge research
[Kre93]	18	Errors in the location of partial discharges in high voltage solid dielectric cables
[Tri95a]	19	Discharge in Air Part I: Physical Mechanisms
[Tri95b]	20	Selection of line conductors
[Ele95]	21	Acoustic emission based PD source location in transformers
[Bog96]	22	High frequency attenuation in shielded solid dielectric power cable . . .
[Sto96]	23	The use of partial discharge . . . condition of rotating machine insulation
[Mor97]	24	The analysis of PD in HVDC equipment
[Sto98]	25	Calibration of PD measurements for motor and generator windings . . .

The first few of these are a simple description of the basics of practical PD pulse measurement. Among the last few are some works of mild interest to my rotating-machine focus. Most of the others have little to add for our purposes of electrical (and primarily ‘IEC 60 270’ type) measurements, but a few points of interest are summarised here anyway.

[Bog90b, Bog90c, Bog90a] S. A. BOGGS, 1990

First three in IEEE EIM PD-Series:

Signal generation, Detection sensitivity, Cavity PD in solids

The most common PD sources are corona, voids and floating components.

A numerical example is given for a GIS spacer with a small gas gap (a floating component); here the large difference between local and ‘apparent’ charge is noted, along with a claim that the local charge is ‘somehow related to the damage therein’ (I suppose the ‘somehow’ gives a good deal of semantic flexibility). Given a particular size and form of cavity, much smaller than the distance between the electrodes, and given a linear scaling of dielectric thickness with voltage level, the detected apparent charge

varies in inverse proportion to voltage level, meaning that detection of a particular defect becomes harder at higher rated voltages.

Corona pulses die out either because the high-field region is too short to develop a fully formed breakdown channel, or because the field falls to so low a value that even continued propagation (much easier than formation) is impossible. (The following must be the first time I've seen someone bother writing about the creation of PD currents in conductors, due to corona; usually it's just voids that are treated, and I'd say, contradicting this author, that these are easier!) The corona of ionised gas around a conductor might initially be seen as extending the conductor, thereby increasing its capacitance to earth, although there is not a subsequent return of charge when the corona dies out, so the model breaks down here. The space charges dissipate by separation of electrons and ions towards the electrodes, causing further currents; the currents from the initial ionisation and electron dissipation can take ns to μ s, but the dissipation of ions can take ms; the ion current is therefore usually not detectable as a pulse.

Void PD is 'probably the most technologically important' source of PD, but a description of 'why' void PD causes a signal in the external circuit is 'non-trivial' (this is peculiar — I see nothing less awkward about for example the case of corona, or indeed of the floating component, although the circuit model is more obviously justifiable for a floating electrode; the exact form of the PD event to external charge relation may be complicated by cavity geometry and polarisable dielectric, but the 'why' is hardly a mystery; I bet this claim wouldn't even have been made if Pedersen's works, cited, hadn't been known of). A brief summary of the gas-turning-into-conductor model is given, anyway (though not daring to draw *abc* ...); extra points are that some movement of charges to the cavity walls continues after the main pulse, that cavity PD typically takes 1–3 ns, the pattern is similar to floating-component PD, but smaller, and much more variable because of changes in surface and statistical delays, the electron generation in atmospheric air from naturally occurring radiation is about 3 electrons per cm^3 per second, and higher voltages increase the electron generation and the volume in which the critical field is exceeded.

Electrical treeing involves PD, but the practical use of PD measurements to detect it is doubtful, since in practical insulation the treeing can take years to initiate and usually doesn't produce easily detectable PD until very close to failure. PD in liquids has some commonality with treeing in solids, being the formation of PD channels through a heavier medium albeit much less viscose than a solid insulator; it has in common with corona that the medium is largely self-healing, although the time taken for dissipation of charges and chemicals from a PD event is longer than in the gas.

There exist defects that could be PD-free (to reasonable detection levels, at least) in short industrial tests, yet could cause breakdown in hours to months in working conditions; an example is a 'conducting asperity' at the edge of cable insulation, from which the high microscopic field could initiate treeing. PD measurements should therefore not be a substitute for other carefulness.

In some measurements the PD is important as an indicator of defects or ongoing wear, and some permissible criterion will be determined for the particular type of system, such

as no detectable PD at some level and voltage, or a maximum apparent charge; in other cases, the PD is important only as a disturbance, and some property such as RIV is of relevance.

PD events are usually just a few ns: in SF₆ coaxial transmission lines such signals are well preserved, but in normal solid dielectric cables they are very distorted.

The fundamental noise limit of a detection circuit is the Johnson (thermal) noise, $V_n = \sqrt{4k_B T \Delta f R}$, where the variables are Boltzmann's constant, absolute temperature, bandwidth and resistance (and V_n is presumably r.m.s.); for common conditions of $R = 50 \Omega$ and $T = 300 \text{ K}$ this gives about $1 \text{ nV} / \sqrt{\text{Hz}}$. Over the band where a PD pulse has largely constant amplitude spectrum, it makes sense to increase measurement bandwidth to improve the signal-to-noise ratio (SNR), since the signal then increases in direct proportion while the thermal noise increase as the square-root. Optimal detection bandwidth, possible with a 'matched filter', is well approximated by a rectangular filter; the optimum for a 1.5 ns Gaussian pulse is about 350 MHz.

The transmission line PD measurement circuit, with the (small) test object between conductors of a gas-insulated coaxial or parallel-planar transmission line, provides a lumped-component-free source with well-known source impedance for the high frequencies, and no resonance within the sort time of the PD. Measurement may be by a capacitive divider somewhere within the transmission line, giving fast response but reduced signal amplitude, or by a coaxial lead from the low-voltage side of the test object to a detection impedance. The time-constant involved is given by the test-object capacitance and the series resistance of the transmission line and any further measurement lead on the LV side (surge impedances). When the test-object capacitance reaches 10 pF the measurement circuit time-constant, even with the divider measurement method, will start to dominate the response if the PD is of the ns scale. An example calculation given for the transmission line system, assuming a need of $\text{SNR} \geq 3$, shows the limit of detection sensitivity for a 1.5 ns pulse against thermal noise to be 2 fC, 'over an order of magnitude better than is attainable with the more conventional techniques', or some 25 % higher if including extra amplifier noise. The time-constant is important for detection sensitivity. Distributing the same charge over a longer time means more total noise energy is included; as another way of putting it, reducing the peak current reduces the signal. Decreasing the signal bandwidth, and therefore the optimal amplifier bandwidth, reduces signal energy directly but noise energy as the square-root. Even trying to maintain the rapid pulse in a large test object by reducing the transmission line impedance is doomed, as the source noise varies as the square-root of the change, so is reduced less than the signal is reduced (why is the thermal noise equation valid even for things that aren't really resistances made of jiggling-about stuff?, i.e. surge impedance).

More 'real world' PD measurements use the familiar C_t, C_k, Z_{det} circuit. Since this consists of lengths (even in the order of metres) of simple single conductors in a large loop, it is a combination of an RC lumped element circuit and some badly matched high-impedance transmission lines. One expects, then, that the circuit's response to a ns-scale pulse would be to make nasty oscillations (ringing), but nevertheless the integral of the signal should tend to the total apparent charge from a PD event (if $C_k \gg C_t$, at least; or

at least proportional to the total apparent charge). A detection impedance is chosen with a shunt capacitor C which would, in the absence of shunting components, end up with a charge changing in the proportion $CC_k / (C_t C + C_t C_k + C_k C)$ of the apparent charge, after the damping of the oscillations over the scale of μs . The assumptions described in fig. 4 of [Bog90a] state that the relation $C \gg C_t$ is ‘normally the case in practice’, which may be true for small lab objects but seems rather surprising as a general rule. The shunt resistor R within Z_{det} is included to restore C to zero before the next impulse. (This is not just another route to the same answer in analysing the detection impedance and its function: it is, compared to for example Kreuger or Kuffel and Zaengl, a different opinion about the purpose of the C and R components of Z_{det} , based on the assumption that the detection loop current needs integration. With C large, as suggested here, the whole-loop oscillations may indeed be slow enough and large enough to annoy; with a very small C the loop’s series capacitance is low and any oscillation would be quick as well as being damped by the shunt R .)

‘If one ignores the initial ringing in the circuit, which will not generate much of a voltage across the detection capacitor as a result of its low impedance at high frequencies’ then the sub-megahertz picture of the voltage over Z_{det} is of a rapid rise followed by exponential decay. The quoted part in the last sentence is puzzling; even assuming that a comma after ‘capacitor’ would have made more sense: I’d been thinking of the oscillation as being due to the series LCR circuit of the test loop inductance, total series capacitance, and moderate series resistance, in which case the oscillation would be expected to push more than the total final change in charge through the circuit (as the inductive element keeps ‘pushing’ even after the equilibrium point is reached); however, if the oscillation is due to other features such as wave reflections and local loops, the point can be understood, although another way of putting it would be just that the total charge involved in such an oscillation is small even if the current is, due to the high frequency of reversal of the charge movement, able to be large.

‘The PD detection signal across C is generated as a result of the charging of C_t back to ...’: this again is a different approach where large C is expected rather than seeing a resistive Z_{det} as a way to measure the initial change in voltage of C_t .

An inductive shunt component L within Z_{det} is seen as a way to reduce the voltage drop due to the power frequency current, at the expense of an extra oscillation, not as any end in itself for PD detection; again, this contrasts with e.g. the mention in Kreuger’s book of analysis of the sensitivity of the old ERA detector with RLC versus RC detection impedance.

The optimum amplifier has bandwidth B corresponding to the time-constant of the shunt RC circuit consisting of the resistance R within Z_{det} and the total capacitance C_{tot} connected across it, so that $\tau = R \times (C + C_t C_k / (C_t + C_k))$. The upper 3 dB point is thus $f_{3\text{dB}} = 1/(2\pi\tau)$, causing about a 60 % reduction in signal compared to wideband amplification, but getting the optimal SNR. If the amplifier is fixed, then R needs to be adjusted to match each different value of the total shunt capacitance in the above expression for τ . Given these assumptions that $B = 1/\tau$ and that τ is held constant by varying R to match the total capacitance, the expression for the noise voltage may be

rewritten as $V_n = \sqrt{k_B T / C_{\text{tot}}}$, and then with further assumptions a sensitivity independent of amplifier bandwidth and detection time-constant can be derived. If the charge in the detection circuit is used as the measured quantity, rather than using the voltage across Z_{det} , then the dependence of sensitivity on low values of C is removed; this hasn't been implemented much in practice. A variable-ratio signal transformer placed between Z_{det} and the measurement allows matching of the apparent value (seen at the secondary) of R to the optimal value for the amplifier.

Increased sensitivity implies reduction in C , which further requires a means of reducing the power-frequency voltage drop; the shunt inductor is such a means. The quality of methods of shunting extraneous currents, and the stray capacitances in the circuit, are the practical limits on sensitivity, in contrast to the high-frequency transmission line methods in which the theoretical noise limits are approached. This industrial type of measurement has sensitivities optimistically 10 times worse than the theoretical limits. Its advantages include the ignoring of test-circuit ringing, relative insensitivity to pulse waveshape and duration by means of its charge rather than instantaneous signal sensitivity, and its applicability to a wide range of apparatus. Apart from sensitivity, the main disadvantage comes from the low bandwidth, which limits the resolution of closely-following pulses; a time-constant of 10 μs is given as the example here of a detection circuit.

Measurement of the change in charge to maintain constant voltage on the test object after a PD, gives a value independent of the amount of shunt capacitance in the test object, although the relation of the apparent charge to the local PD charge is still dependent on insulation thickness (and thus voltage level); measurement instead of the change in voltage across a floating capacitor with fixed charge, gives a value that reduces with a larger test-object capacitance.

'Even given that we understand cavity PD in solid dielectrics ...' is pushing things a little: all that has been covered is some presumptuous theory about inception and extinction in sufficiently small cavities, and the derivation of charge movements at terminals given that we know just what charge movements occurred during a PD event; nothing is mentioned about what form a PD really takes in a cavity, the effects on, and of, cavity surfaces, etc.

[Ste91] J. P. STEINER, 1991

Partial discharge IV — Commercial PD testing

Specifications are often more about 'no detectable' than 'no more than', but for industrial measurement methods this generally means 'no more than $\approx 1-5$ pC apparent charge, with typical background noise levels. *In situ* measurements are at a disadvantage due to the noise. For testing at manufacture, different types of apparatus-optimised test system may be used. 'Single-input' detection systems, as opposed to for example balanced detection systems, are sometimes also known as 'straight' detection systems. Detection systems are usually band-pass, excluding a power frequency component as well as everything below some upper cutoff; the meaning of 'broad' or 'narrow' band is generally about whether the bandwidth is high enough to allow pulse at an expected

repetition rate to be resolved. Broadband systems measure individual pulses, generally requiring tens or hundreds of kHz of bandwidth. Narrowband systems integrate multiple pulses, losing the distinction of many small or fewer larger ones; the bandwidth varies from sub-hertz up to about 15 kHz. Ultrabroadband measurements allow resolution of features of individual pulses, going up to hundreds of MHz. RIV measurements are a narrowband method, often having 9 kHz 6 dB-bandwidth, with a centre, possibly variable, around 1 MHz. Loss-measurement can be seen as a low-frequency narrowband method. Broadband rather than narrowband detection has advantages of distinguishing individual pulse magnitudes and polarities, and increased sensitivity against (at least) thermal noise; its disadvantages are greater susceptibility to external sources of interference and to unclear signals from distributed or oscillatory test objects. Gating can be used to remove pulses that are thought to be external, e.g. by using balanced detection circuits. RF noise can be measured then subtracted (in some proportion) from the measured PD signal, sometimes with 20 dB improvement. Manufacturers don't like changing measurement methods, as accumulated data cannot then be compared to new measurements. In transformers the shift to apparent charge rather than RIV is going on, but there isn't a direct relation [should see some other, later, sources claiming there pretty much is]. Yet another name for detection impedance Z_{det} or coupling-device (CD, IEC-60270) is introduced: power-separation filter (PSF); again, I'll use here R , C and L as its possible shunt components. The PSF is shown as being in the LV side of the coupling capacitor of a standard IEC-60270 PD measurement circuit. C is 'included to influence the transient response of the network' and may be as small as just the stray capacitance (a very different situation from that in the previous papers in this series); L bypasses the power-frequency current. Most measurement systems are broadband. When measuring on distributed (low lumped- C) objects, and with C low, this detection circuit can become a high-pass filter, of everything well above power frequency; then measuring with large capacitances, the response is usually a low- Q resonance. (Note that the circuit is here treated without explicit series inductance or transmission-line properties.) The test object usually affects mildly the lower, and strongly the upper, cutoff frequency of the detection circuit. The measurement amplifier and instrument then may impose further limits. The bandwidth is often dictated by the requirements of standards on superposition error. The lower cutoff may be increased to avoid some conducted interference such as harmonics of the power supply. The upper cutoff is sometimes determined by avoidance of broadcast radio or HF interference sources. Relative spectral amplitudes of signal and noise can also determine the bandwidth. The PSF sometimes includes a the coupling capacitor, a voltage divider output, and possibly a pre-amplifier. A broadband bridge detector measures the difference in signals between points where the two arms of test object and a matched capacitor meet balancing resistors; with good balancing, an 80 dB rejection of external noise is possible. Badly matched HV parts lead to balance only for a particular frequency. A more primitive form is the differential PD detector, passing the currents from test object and matched capacitor straight into opposing (and tapped) windings of a transformer; a 20 dB rejection is quoted for this, but in more 'realistic' and not well matched conditions, making comparison with the full bridge de-

tector unfair. Pulse-based measures such as average current, quadratic rate and apparent power loss are mentioned, with definitions being the obvious ones given in [Kre64]. For practical measurements, the avoidance of disturbance becomes a big part of the work. A screened environment with a clean power supply would be a good start, but is often not possible. Cleaning of conducted disturbances in the power supply is done by filters that are typically LC ladder networks, reducing in-band noise by some 80 dB; common-mode noise is reduced by use of an isolation transformer. Supply filtering should be before any of the coupled circuits associated with PD measurement. Shielding radiated interference is often necessary, as practical HV measurements have large loop areas for coupling. Fully screened rooms are often not possible; screening close to the source, for locally generated disturbances, may be worth considering. The measurement circuit should of course be PD-free, i.e. PD-undetectable for the intended measurement, but if the supply (e.g. transformer) is not, a filter may be used. Earthing is important even with other precautions in place; proper earthing provides safety in the event of a breakdown, and avoids disturbances being conducted between parts of the measurement system; fig. 8 in [Ste91] shows an example circuit where the PDF earth is a common point connected to source, test object, filter and screen-room earths. Calibration is nowadays by a voltage step behind a capacitor: this may be ‘HV’ where this capacitor is a HV one connected across the test object and remaining there during the actual PD measurement, or ‘LV’ where the injection capacitor is removed before the actual measurement, or ‘indirect’ where the PSF capacitance C is used for injection; in the LV or indirect case some corrections are needed (sounds like the back part of for example [AST07]).

[Sto91, Hut92, Sto96, Sto98] G. C. STONE, W. HUTTER

PD in rotating machines: detection, effect, condition-assessment, calibration

PD are a symptom and a cause of deterioration in solid dielectrics. On-line measurements tend to suffer more from noise, in spite of obvious advantages of continuous monitoring and reduced testing downtime. External noise sources include PD in other objects, floating electrodes, arcing at poor electrode contacts with high current, arcing at brushgear or welding, power-line carrier signals, power-electronic switching and broadcast radio signals. Some are well defined in frequency or (power-frequency) phase so can be removed by filtering or gating; others might be screened away in laboratory tests but are a problem in the field. Some features of PD that may help distinguish different sources are the (power frequency) phase, the spectrum, the magnitude and polarity, the repetition rate and the location. Most PD sources have quite even amplitude spectrum into hundreds of kHz, but sources located within e.g. a transformer will have lost some of the higher frequencies before leaving it. The other sources of electrical arcing can generate inconveniently similar spectra. Discrimination methods such as bridge or pulse-discrimination with two balanced HV arms can much improve external noise rejection. Transmission-line type objects can use multiple measurement points to determine the source of a pulse, or can use reflections from changes in characteristic impedance. PD methods for rotating machines are very varied. Neutral-point voltage-pulses have been monitored in old methods. Neutral-point currents have been measured using a current-transformer and

narrow-band filtering. Coupling capacitors and quite ‘IEC-60270 sounding’ detection have long been used by for example Ontario Hydro, for which the equipment was temporarily attached 375 pF capacitors on the phases, with a 30 kHz–1 MHz filter and an oscilloscope display. The ‘PDA’ test uses transmission-line properties of the circuit-ring buses of hydro-generator end-windings, with at least two equally spaced (from the generator terminal) 80 pF coupling capacitors on each. The outputs, in similarly long cables, go to a differential amplifier; external noise arrives simultaneously [and I don’t quite follow why not ‘blind’ parts of the winding, too — perhaps the placement of capacitors avoids this].

Electrical (rotating) machine insulation is a tradeoff of machine efficiency and maintenance requirements, since the space taken by insulation is so critical. The mica-based system chosen as optimal can tolerate PD, unlike the insulation of most other HV equipment. Monitoring is generally cost-effective, given the ‘degree of randomness’ in the rate of degradation, and the ‘relatively low cost of monitoring’. The cost of in-service failure is usually more than of preventive maintenance. ‘A large generator has more than 100 ms² of insulation area, with stresses of more than 2 kV/mm’, hence many low value discharges. There may be total lengths of hundreds of metres of winding elements, with complicated propagation characteristics. Typical places of operation tend to have large amounts of EMI. Off-line measurements have been done for some 40 years (then!), progressing from a skilled technician watching an oscilloscope screen, through to pulse capture into phase-resolved patterns and statistical analyses, which permit a lot of the expertise to be done away with since the long-time assembly of measurements gives a more repeatable result. Coupling at the phase end is done by capacitors; at the neutral end, capacitors or HF transformers are used. The ambient noise can well be higher than the PD, so methods such as time-of-arrival (in hydro-generators) or measurement and removal of RF interference can be used. ‘Pulse shaping’ is used to limit the bandwidth of a PD signal, then peak detection and dead-time are performed. Use of pulse pattern methods along with higher bandwidth time-domain measurements to show pulse waveform is suggested as useful: an emphasis in the work is that each method is an extra part of a fuzzy picture of the insulation condition. ‘Redundant acquisition, elimination of interfering signals, plausibility tests, . . .’ The measurement methods along with processing programs form part of the ABB ‘PADIS’ and ‘PAMOS’ off-line and on-line PD measurement systems, for which a database of some 2000 generators over 30 years exists.

Actual breakdown of machine insulation is usually at a time of ‘lightning, power system disturbance or operator error’, stimulating the worn insulation. A method that gives a measure of insulation goodness, with high reliability, is the desired industrial thing; more detail is too much. Due to the distributed inductive nature of the stator, a pC measure of PD is confusing, leading people to think that results can be compared with those from other instruments and test setups. In almost the same breath as denouncing pC results, ‘virtually all stator windings (both air and hydrogen cooled) operating above 6 kV have PD in excess of 100 pC, and readings up to 100000 pC are not uncommon’. Plenty of other sources (e.g. PD from cable terminations, the supply transformer or insulators) can have the same form as classic cavity PD in stator insulation, and other

stator defects can have quite different patterns such as a more voltage-peak-centred pattern shown for end-winding PD, or a more after-voltage-peak pattern for early slot-discharge. A PD (pulse measurement based) ‘acceptance test’ is rare for machines, but is required for ‘most types of high voltage apparatus’. The (non-pulse) tip-up test is quite sensitive for single bars or coils, but is ‘relatively insensitive’ for whole windings, due to the end-winding stress-grading. Calibration isn’t about measuring the charge moving in the PD event, which may differ by orders of magnitude from the apparent charge, but about different equipment/operators getting similar results. The largest PD pulses imply the largest numbers of electrons, on an assumption of sources of similar form in locations of similar field. PD calibration as pC is useful in avoiding the influence that the total test-object capacitance has on other parameters such as voltage. Since PD in stator insulation is generally a symptom of insulation wear from other causes, the actual value of charges, rather than the change in level with time, is particularly unimportant. The main cases where PD *is* a main wear mechanism are sizable cavities next to conductors, where electrons attack the solid turn insulation, and end-winding tracking where the magnitude is an indicator of rate of tracking. The inductive/capacitive distributed nature of stator windings leads to resonance peaks and troughs in the response, making the terminal values of PD signal for a particular internal PD source be very dependent on frequency; this is distinct from the case of a simple small test object where the PD signal is expected to have a very wide flat amplitude spectrum. The measured value therefore depends upon the chosen frequency band.

[Che91, Koc91, Cha91, Bau91, Bau92, Lau92, Lun92a, Lun92b, Fuj92, Har93, Nat93, Kre93, Tri95a, Tri95b, Ele95, Bog96, Mor97]

The rest of the IEEE EIM PD-Series articles, on wide-ranging subjects:

PD in different apparatus, nature of PD in air, other means of detection,

This series has several references to PD in non-HV equipment, e.g. in printed circuit boards where the distances are small but the fields are nonetheless high enough for PD.

[Che91]. PD detection in polymeric line-insulators: difficult because of the weak coupling between a PD event and the small, distant electrodes (the ‘small’ can be seen to be relevant in so far as it reduces the field away from the centre line; else, the separation would seem the only important point). The weak coupling has made RFI measurements, around 10 MHz, preferable, but still such measurements haven’t been a good indicator of impending failure.

[Koc91]. Using PD measurement methods at relatively low voltages and very small spacings, on printed circuit boards, there is a big advantage of the large apparent charge for a given cavity surrounded by a given field.

[Cha91]. ‘Laminar’ cable insulation such as waxed/oil paper, had some advantages of independence of defects between layers. ‘Solid’ (i.e. homogeneous? artificial polymeric) dielectric cables have stringent testing, particularly at transmission levels. Capacitance is typically some 200 pF/m, so a shipping length of 1 km is about 200 μ F. Such a high capacitance has, for conventional quite low bandwidth measurements, a fundamental sensitivity limit around $1000\sqrt{C}$ pC, i.e. 0.45 pC in this case. The improvements from

very high-bandwidth methods aren't possible here because of the poor HF properties of the semiconducting screen. Non-matched terminations or connections pose another problem; the polarity of the return pulse depends on the termination impedance. The important defects are contaminants in the polymer, protrusions of semicon layers (only 'conductor' semicon is mentioned) into the dielectric, and cavities in the dielectric. An analysis of minimum discharge voltage of a cavity is done using the work of Crichton, Karlsson and Pederson in [Cri89]. PD-detectors for these cable measurements need to have strong damping of oscillations (' α -response') in order to reduce negative superposition errors. A detector system with $f_1 = 20$ kHz, $f_2 = 110$ kHz and $C = 4$ nF is mentioned for the quite demanding specification of 5 pC measurements on a 0.5 μ F cable section. Means of avoiding PD at the cable ends range from resistive and geometric grading methods up to some 100 kV and water-terminations beyond this.

[Bau91, Bau92]. These papers have a focus of SF₆-insulated switchgear. The classic measurement systems is seen as a coupling device ('PSF' in [Ste91], Z_{det}), a signal transmission medium, an integrating device for charge, and a means of recording the data. The output should be the apparent charge. Continued corona-like discharge in GIS is mainly around negative points, by field emission; positive electrodes generated electrons by detachment within the gas, giving rise to large single discharge pulses. The positive pulses are generally detected at a lower voltage than the negative PD, in SF₆ GIS. There is information about the PD source available even without calibration, from the PD pattern. 'Regular patterns' formed from sources with abundant initiating electrons are typical of larger cavities, voids adjacent to metal electrodes, and floating components; in these cases the number of discharges per half-cycle is of interest (although mainly, one assumes, if one knows that there's just one source?). 'Statistical patterns' are governed by scarcity of electrons; the ratio of maximum to minimum discharge magnitude, and the envelope of the pattern, are important parameters. PD measurements on GIS are desirable because SF₆ decomposition products of PD are bad for the solid materials. By using gas-insulated test equipment, the entire system for PD measurement can be screened by the GIS casing, allowing less noise even in UHF measurements. Quality assurance PD tests are often at low frequency, up to 100 kHz, using a large coupling capacitor around 1 nF and a detection sensitivity of 2 pC. In the field, a large coupling capacitor requires an inconveniently large HV supply, and is bulky in itself too; a capacitive divider formed by a plate within the GIS can be used as a detector; this may have a HV capacitance 0.2 pF and LV capacitance 20 pF, forming a *high*-pass filter if feeding into a resistive measurement load: 160 MHz for a 50 Ω load; the filtering not only removes power frequency but also attenuates more of the spectrum of the lower-speed PDs that happen in air.

[Lun92a, Lun92b, Har93, Ele95] These papers are on acoustical detection of PD. Electrical methods lose sensitivity when dealing with high-capacitance test objects, and they are generally not good for location of sources. The terms 'pressure wave' and 'shear wave' seem to be popular in acoustics as synonyms for 'longitudinal' and 'transverse'. Solids permit the transverse form of sound transmission as well: the velocity of the transverse form is about half that of the longitudinal form for the several solid metals

and insulators listed, the metals having longitudinal wave velocities of some 3000—6000 m/s, and the insulators are about half of this, apart from ‘glass silicate’ at $v = 6000$ m/s and with very low absorption. Air and N_2 have (unsurprisingly) quite similar sound transmission properties, both with velocity $v \approx 340$ m/s, and air with absorption coefficient $\alpha = 4 \times 10^{-3}$ dB/m (at 50 kHz) then N_2 about three times this absorption; SF_6 stands out against this with $v = 130$ m/s and $\alpha = 80$ dB/m! As with electrical detection, a narrower bandwidth of detector can be useful in providing a resonance (high Q) but time-resolution is worsened. Acoustic/electrical transducers from audio up to 1 MHz are used in detectors: accelerometers can be used up to 50 kHz, with the advantage of flat frequency-response; condenser microphones can go up to some 150 kHz; lossy resonant sensors using piezoelectric transducers are used from about 30 kHz to 1 MHz. Acoustic detectors with parabolic reflectors and ultrasonic detection have become popular for detection and location of PD sources in outdoor air-insulated switchgear. Microphone-on-hot-stick has been used in lower voltage air-insulated switchgear. In SF_6 systems acoustic detection is widely used, detecting about 10–80 kHz; the high attenuation removes high frequencies quickly, and the geometry of the apparatus makes the results complex to use compared to the simple open-air cases. Transformers have routine manufacturing tests by acoustic PD methods, sometimes taking advantage of filtering away frequencies that travel slower in oil, so that the initial signal can be assumed to have come through the shortest oil path.

Detection of ≈ 10 pC in capacitors is possible acoustically. Capacitors are a trouble for sensitivity of electrical methods — recall the $\approx 1000\sqrt{C_t}$ pC fundamental limit for a capacitive object C_t . Not only have individual HV capacitors high capacitance, but several (or several groups) are generally used in series, reducing the apparent charge of a given discharge when seen at the terminals of the whole bank. Fairly small, i.e. 10 %, changes in voltage can give an order of magnitude or more change in PD, making ‘borderline’ cases easier to spot. Passing an impregnated capacitor through the impregnation again may solve problems with trapped gas at foil edges; continued problems suggest poor internal connections. A lot more detail is given about capacitors, failure modes, bandwidths of various sensors, and characteristic results for various faults: it’s too component-specific to justify summarising further here.

Acoustic location of transformer PD is described in [Ele95], done with at least 10 ‘acoustic emission’ piezoelectric sensors of resonant frequency 150 kHz placed on the transformer’s external surface and connected to a measurement system with bandpass of 100–300 kHz, using triangulation to locate PD sources. The PD signal in transformers is about 20–30 dB above the ambient noise. RIV measurements are impractical with the transformer in service, due to general electrical noise.

[Fuj92]. High-voltage cables with solid insulation can have very small cavities whose presence one nevertheless wants to detect. Conventional measurements require a regular repetition in order to be confident of the existence of a PD source. Very small cavities can require a very long time (many minutes) to have any initiating electron at all, and test voltages during inception measurement can end up raised very high until inception is helped by field-related electron generation. Results of conventional PD tests are then that

an unreasonably high inception voltage is measured, and the phase-resolved PD pattern has a lot of spread in magnitudes depending on cavity ‘overvoltages’. By irradiating a cable when performing PD measurements, even small cavities can have plenty of chance of a PD if the field is sufficient: a lower inception voltage is then measured, and the PD pattern has its points clustered around the minimum values. The ability to sweep the beam provides a form of PD source location. An actual measurement was done where an inception voltage $V_i = 400$ kV was found for a non-irradiated cable, although only with a few small pulses, ≈ 3 pC, near the detection limit; irradiation resulted in $V_i = 25$ kV.

[Nat93] The low centre frequency and relatively small bandwidth of (now ‘conventional’) low-frequency electrical PD detection systems provide measurements that are independent of high-frequency attenuation in the apparatus and of most oscillations in the test configuration, and yet usually permit individual pulse measurement. Much lower ‘bandwidth’ systems such as loss detectors were also developed, suitable for systems ‘designed to operate in [PD]’. ‘Spark gaps’ (point-hemisphere?) were an early form of calibration of PD measurement systems, but later electronic calibrators have the advantage of low voltage and easy variation of value. The nature of the internals of electrical equipment means that regardless of calibration the terminal measurement may bear little relation to the situation close to a PD source. PD specifications for claims of ‘PD free’ require[d] an extinction voltage above the operating value, as detected with a reasonably achieved laboratory measurement, giving about a 5–10 pC apparent charge limit.

[Kre93] PD source location in a cable can be attempted by comparing times of arrival of the direct signal and the reflection from the far end. Besides instrumentation limitations and poor knowledge of the cable length, the accuracy is affected by the effect of semiconducting screens. The progressive removal of high-frequency components during transit provides a less sharp reflected pulse. Narrowband systems help to make the direct and reflected pulses have more similar response, but the narrowband systems have fundamentally less time-resolution. The range 10–20 MHz is considered optimal for common propagation characteristics and tested lengths. Results are complicated by frequency-dependent reflection at the far end and by variation in PD pulse spectra at the source. Sources near the far end can have their direct and reflected pulses too close to be distinguished. A 590 mcable was found to have a detection sensitivity of 3.5 pC when tested in this way.

[Mor97]. Although almost all work with practical diagnostic PD measurements assumes an AC supply, there are plenty of DC insulation systems too: industrial processes and X-ray tube supplies, up to hundreds of kV, and HVDC power transmission components. Assuming some bulk conductivity of the dielectric, a cavity PD can be expected to continue even under long-term DC applied voltage, unless the cavity surface is so conductive as to prevent critical voltages occurring in the cavity. An AC system requires just tolerance of AC conditions, with capacitively governed field. A DC system requires not only adequate performance in the space-charge-mediated resistivity-governed field, but also adequate performance in the capacitively governed field (possibly including residual space-charge from DC operation) during switching; for this, AC PD tests may

be useful too. The detection used for HV DC PD-tests is similar to that for AC, being an IEC-60270-style circuit; the difference comes in the processing and display, where phase-resolved patterns make no sense. Various distributions are used instead of the AC-oriented $N(q, \phi)$. The parameter ϕ is commonly replaced with Δt , the time between discharges: this may be the time from previous discharges or the time to successive ones. Some idea of the PD source may be gained from such plots as charge magnitude versus previous discharge charge magnitude, or charge magnitudes against one or other form of Δt . For example, a discharge in a cavity or in a corona has magnitude independent of its predecessor, and the corona case has very consistent charge; for surface discharges, on the other hand, the magnitude alternates, giving a negative slope to a q_{suc}/q plot. A pattern-recognition algorithm has allowed a computer to use a database of measurement data to give quite reliable classification of PD sources.

[Tri95b] The main source of corona-induced losses is motion of ions of either polarity: for AC lines this occurs close to the conductors, within only tens of centimetres; for DC lines ions travel between phases or to earth. Some hundreds of kW of loss per line km is possible in bad weather conditions. EMI from corona is due to streamer discharges causing current pulses in the conductor; the harmonic content reaches tens of MHz (i.e. the rise is a lot slower than for cavity PD). The use of bundled conductors on overhead lines reduces the field greatly, its maximum level being more dependent on the bundle diameter than on individual conductor diameters.

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