# Differences between PD charges measured by Partial Discharge and Dielectric Spectroscopy systems

Nathaniel Taylor and Hans Edin School of Electrical Engineering, KTH, Stockholm

#### Abstract

In some rather idealised cases, similar values of Partial Discharge (PD) apparent charge may be obtained using a PD pulse measurement system or a capacitance and loss measurement system such as Dielectric Spectroscopy (DS). In many practical diagnostic situations, however, the results are widely different, for several possible reasons. The relative virtues of the two types of measurement are discussed here, on the grounds of useful diagnostic information. Some work on simultaneous measurement by these two methods is presented, and measurements from simple test objects are shown as examples of the factors limiting capture of the full PD charge by pulse measurement.

# 1. Introduction

Dielectric spectroscopy and partial discharge measurements are both widely used for condition assessment of high-voltage insulation. The apparent charges of PD pulses make a contribution to the current measured by DS methods, as has been treated in [1] by derivation of this contribution, with examples on canonical objects, and in [2] with an aged stator coil.

Industrial practice, in diagnostic measurements used for insulation condition assessment, includes measurement of PD as pulses, measurement of capacitance and loss with the intention of thereby measuring PD current, and measurement of capacitance and loss with other aims. Classic PD pulse measurement systems measure individual current pulses due to rapid movements of charge in PD events; calibration with a known charge is used to determine the apparent charge of each pulse. This pulse measurement is widely used for assessment of the stator insulation of high voltage rotating machines, where some PD activity is quite expected but where the 'pattern' of magnitude and phase of pulses may, together with trending of a machine over time, help the identification of problems within the insulation. Pulse measurement is widely used in other equipment, generally with much lower permitted PD levels. Singlefrequency capacitance and loss measurements, such as the Schering-bridge measurement, are also widely used, making an integrated measurement of the current due to PD activity, together with all the other current in the dielectric. PD activity may be an easily observable proportion of the total current, in stator insulation, and its voltage-dependence helps to distinguish it from the measured capacitance and loss of the solid dielectric. The 'tan-delta tip-up' (loss increase) test performed on stator insulation is aimed at voltage-dependent changes of loss that signify PD activity, although the voltage dependence of the nonlinear materials of high voltage

end-windings also contributes to this tip-up. Extension of these capacitance and loss measurements to a range of frequencies of the applied voltage, is DS, which has been usefully applied in applications with transformers and cables, although the detection of PDs is not usually the purpose of DS in this case.

Measurements of PD pulses by PD and DS systems are not necessarily convertible; the two measurement methods capture quite different views of a phenomenon, with different limitations. The extent of similarity of the views may be of interest if considering the use of DS-type measurement systems in place of PD systems for some applications. The extent of difference of the views may be of interest in obtaining more information about the state of an insulation system, for example by the use of DS measurements that include the total apparent charge of PDs within apparatus with high repetition rate and dynamic range of PD, together with PD pulse measurements that identify the largest pulses. This paper presents some examples from work on stator insulation, where there are large differences between the total PD charge seen by DS and PD pulse systems; recent work with simpler objects is later presented, where the two methods can see very similar amplitude and phase of the total PD charge. It is proposed that an extension of conventional fundamental-frequency (capacitance and loss) measurements of total PD charge, by including some harmonics in a frequencydomain measurement or by using time-domain DS measurement with averaging, may be useful in providing a view of the magnitude and phase distribution of PD charge, while being more able to detect all these charges in apparatus that is large, inductive, or otherwise troublesome for good PD pulse measurements.



**Fig. 1** – PD current measured by a PD pulse detection system and by a DS system. This is on the stator coil shown in fig. 3, an inductive object with high repetition rate, for which the PD pulse measurement is unable to capture the full PD charge. From [2].

### 2. Machine insulation: large differences

Fig. 1 and fig. 2 show measurements made by DS and PD systems on a severely thermally aged stator coil with a lot of PD activity. The construction of the coil is shown in fig. 3. A significant feature of fig. 2 is the scaling factors such as "PD x 20", on each plot.



**Fig. 2** – Example of differences in stator coil PD current measured by PD (pulse) and DS (integrated) measurement systems, with different frequency of the applied voltage. The sinusoidal dashed black line is the applied voltage, the solid blue line is the guarded DS measurement after removal of the linear current in the insulation, and the similar looking dashed red curve is the current measured by the PD system *after* scaling by a large and varying factor shown in each plot. The applied peak voltage is 9 kV. From [2].

The DS measurement of PD current has been obtained by 'compensating' for the dominating effect of the testobject's bulk capacitance in the total measured DS current. This is done by measurement of the current in the test object at the voltage amplitude of interest, then again at a voltage of the same frequency but a lower amplitude well below the PD inception voltage (PDIV). The values of capacitance and loss determined at the lower voltage are then used to calculate the current expected at the desired measurement voltage in the absence of the non-linearity of PD; this current is subtracted from the measured current. The DS system records some harmonics of the applied voltage, which can be used for even greater accuracy by subtracting from the corresponding harmonic currents the currents that these harmonic voltages would cause in the testobject capacitance. In the case of the stator coil of fig. 3, the currents in the nonlinear stress-grading coatings in the end-windings were guarded away from the electrometer, so that the DS measurement included the insulation of just the straight (stator slot) parts of the coil, conveniently eliminating a source of nonlinearity other than the PD. Guarding of the end-windings is not practical for measurements on a whole machine or even on coils that will later be used in service; in these cases a good judgement of total PD current would require a good model of the voltage-dependence of the endwinding current, which is only likely to be adequate if the PD currents are of the same order of magnitude as the end-winding currents.

The PD current measured by the PD system has been filtered in the frequency domain to remove components beyond the 8<sup>th</sup> harmonic; this was done for easier comparison of shape, because DS system's output is limited to the first 8 harmonics. This current has then been scaled by the large factors shown, until its amplitude matches that of the PD currents measured by the DS system. The shapes match well, but the amplitudes vary by up to 50 times, with the DS system measuring the larger currents. Note that if the estimated non-PD current subtracted from the DS system were severely wrong, this being the main cause of the difference between the systems, then the resulting PD current would have a much more sinusoidal shape.



Fig. 3 – The stator coil measurement object, photo (left) and dimensions (right); the coil was manufactured for a motor of 7.2 kV rated rms line voltage. There are 'guard breaks' at the ends of the semi-conducting outer screen of the straight sections, permitting sensitive DS measurements on the straight sections without the nonlinear influence of the end-winding stress-grading materials. The whole semiconducting screen of the slot part was covered in tightly bound metal foil for the measurements, to keep the series resistive loss low.

### 3. Reasons for the differences

The results in fig. 1 are from separate DS and PD measurements: they were taken on the same object, on the same day, but not at the same time. PD activity is stochastic, so some variation can be expected. However, the variation that was usually seen between repeated charge measurements using either the DS system or the PD system, was only in the order of some few or ten percent, particularly when given a suitable 'warm-up' time on voltage before a measurement.

A PD pulse detection system is limited in which pulses it can include. The measurement circuit (fig. 6) picks up noise from radio and mains-borne sources as well as from nearby equipment; the minimum apparent PD charge that it will include in a measurement has to be above some threshold in order to avoid measuring this noise 'floor', but this threshold must not be so high as to lose many of the real pulses. A large dynamic range of PD magnitudes may give rise to problems at the top end of the charge scale, when the limited quantisation range causes larger pulses to be registered only as the system's upper limit. Some test objects have only a

narrow range of PD magnitudes, making the struggle of detection threshold and limited range less of a problem. Measurement circuits can produce oscillations in reponse to a PD pulse, known as 'ringing'. To avoid detecting as a set of PD pulses the subsequent peaks of the decaying oscillation due to a single discharge, a PD measurement system may have a considerable 'dead time' after each detected peak, during which no further peak voltages on the detection impedance will be recorded. In fig. 4 an example is given where in case (a) the pattern with very short deadtime and low threshold shows a strong cluster of pulses at the lowest charges; in (b) the threshold has been rather more than doubled, which removes the extra cluster but without knowing whether that cluster came from a real PD source or was just ringing from large sources; in (c) the threshold is at the low setting again, but the deadtime is doubled, and the disappearance of the lowest cluster of charges indicates that they were just 'ringing' from the real PD pulses. Note also that having prevented the pulse detection system from wasting time including measurement of ringing, there are higher counts of the large discharges around 400 pC; this was confirmed by repeated measurement, so is not just an effect of random variation between measurements.



**Fig. 4** – Example of choice of threshold and deadtime to optimise PD measurement for the simple case of the cavity object of section 6, at 8 kV, 60 Hz, 120 s. Note that the negative parts are omitted to save space, but are strongly symmetric to the positive parts. In the first case (a), the threshold is at 4%, just above background noise, and the deadtime is at its minimum 5  $\mu$ s, with the pattern showing a strong cluster of pulses at the lowest charges; in (b) the threshold is 10%, still with 5  $\mu$ s deadtime; in (c) the threshold is 4%, with 10  $\mu$ s deadtime. The count scale is in per-cycle.

Increasing deadtime gives the undesirable effect of increasing the time during which further, real, PD pulses will be missed from the measurement. In objects with many PD sources this becomes a problem if a good measure of the total PD charge is desired, and it may be a problem even for measurement of largest PDs. The rate of PD pulses in practical machine insulation systems may be as high as 100 000 per second.

Large, inductive measurement objects are a case where simple models of a PD source, as a discharging capacitor within another capacitor, are not valid. The many possible resonances and reflections, and the possible time variation in arrival of different components of a PD pulse at the measurement system, mean that a long deadtime may be needed to avoid picking up reflections, but this conflicts with the desire to capture all (most) of the real PD pulses. The difference in the signal transfer characteristics of paths to the measurement system from the place at which calibration is done, compared to paths from the places at which PDs occur, causes the charge calibration problem; some work has been done on finding suitable frequency bands for minimising the effects of pathdependence [3], but reduced bandwidths imply reduced resolution of PD pulses that come close in time, a conflicting requirement.

# 4. Measurement systems

The measurement systems used here are the ICM partial discharge detector from *Power Diagnostix Systems Gmbh* of Aachen, and the IDAX-300 insulation diagnostic system from *Pax Diagnostics AB* (now Megger) of Täby. These systems are industrially applied in diagnostic measurements, and are used in our work with DS and PD measurements extending to low frequencies, <1Hz, of the applied voltage.



Fig. 5 – Operating principle of the DS (dielectric spectroscopy) measurement system. 'FB' denotes a feedback component, set automatically or manually. Instrument earth is floating, so that real earth can be either connected directly to it or can be connected to the 'measure' electrode if the measurement object is unavoidably earthed.

The DS system, fig. 5, measures all charge into the 'measure' electrode: the current electrometer adjusts its output voltage so as to permit this current to flow through the feedback elements FB(i), a parallel resistor and capacitor, holding the measure electrode to instrument earth potential.

After the very rapid small changes in charge distribution in the circuit and measurement object following a PD event, the potentials return to their quasi-static (i.e. much more slowly changing than the PD pulses) values by the movement of charge through the HV supply and the electrometer feedback. As long as there are not conductive paths that allow PD-induced changes in potential of the 'measure' electrode to be restored by charge that bypasses the electrometer, and the measurement system has sufficient filtering properties that the rapid PD pulses produce slower changes at the digitiser that are therefore not missed, the total PD apparent charge is recorded, as well as the current in the other capacitances and losses. One way, indeed, of thinking of the movement of charge in a PD is as a polarisation that is delayed until a high field is reached, and then happens with many charge-carriers moving at once in a matter of nanoseconds.



Fig. 6 – Operating principle of the phase-resolved (PR) PD pulse measurement system: Ck is the coupling capacitor, Cx is the measurement object. The detection impedance Zdet was in the earth connection of Cx in the measurements presented here.

The PD system, fig. 6, measures an amplified and filtered voltage across a detection impedance Zdet placed in a high-frequency loop of the test object and a coupling capacitor. In the configuration that we use, the measurement bandwidth is 40 kHz to 800 kHz, and the detection impedance is a 1 k $\Omega$  resistor, shunted with a 3.9 mH inductor to pass the normal load currents, and shunted with the capacitance of the ~10 cm co-axial cable that connects to the high input-impedance pre-amplifier.

# 5. Relative merits of DS and PD methods

Several ways have been described, in section 3, in which there arise differences between measurements of PD pulses by DS and PD pulse measurement systems. Diagnostic measurements on practical high-voltage apparatus can seldom be expected to approach the ideal measurement situation with regard to noise, variation of PD pulse size, repetition rate, and position-dependent attenuation of pulses; the situation is particularly severe in rotating machines. It can therefore be expected that PD pulse measurements on such apparatus will miss a lot of the total PD apparent charge. Largest single pulses are, however, often considered as a more important criterion than aggregate measures of PD [4], so in some cases a pulse measurement may be preferable even if it misses a lot of the pulses. DS methods can include current not only from all the PD pulse sources but even from the glow and pseudo-glow discharges that can occur in heavily aged cavities and that are invisible in PD pulse measurements [5]. As a complement to PD pulse measurement, or as an alternative for some applications where largest single pulses are not of overriding importance compared to total PD charge, the DS method may have some utility. Modern DS measurement systems can provide more detail than just a capacitance and loss: the capture of some low harmonics in the system used here provides the noise-rejection of a tuned-frequency system while also permitting the shape and phase of the PD current to be seen, although only the PD pulse measurement can tell whether the current is due to many small or a few large PD pulses. A disadvantage of DS methods for measurement of PD is that the current due to PD is generally so small compared to the total current in the insulation system. The dominance of non-PD sources is

less in the loss component of the current, and generally still less in the harmonics of the current, but such parts as rotating machine end-windings or cable terminations can produce considerable loss and harmonic components in the current.

# 6. Combined measurements

Use of DS and PD pulse measurements simultaneously is desirable if they are to be used as complementary diagnostic methods: it saves time when measuring, particularly if using time-consuming low frequencies, and direct comparisons can be made between the results without there being differences due to the stochastic nature of PD sources between measurement occasions.

Our measurement systems have recently been put together with the aim of simultaneous DS and PD measurements at a wide range of frequencies and amplitudes of the applied voltage, on objects from small laboratory air-gaps up to complete stator windings in field measurements. The phase-resolved (PR) PD measurement unit from fig. 6, with its pre-amplifier and detection impedance, is then included in the circuit with the DS system of fig. 5.

Some problems arise in this combined use: construction of the desired circuit arrangement in spite of several terminals of the measurement systems or field test objects being connected to earth; noise from the HV supply that is no trouble to the highly frequencyselective DS measurements but increases noise in PD measurements: effects on loss measurement of attempts at resistive filtering of such noise; need of including in the DS measurement only the current in the measurement object, without any from the coupling capacitor and connections. All the problems may be avoided: for example, the task of voltage measurement could be split from the HV supply unit so as to allow filtering after the supply; an electrically isolating PD pre-amplifier could be used; measurement instruments could have floating chassis potentials. The optimal way is not yet clear, of how to run combined DS and PD in both lab and field situations, without major changes to the systems that would make them less accurate or less easily used on their own, or would reduce their compactness for field measurements.

Two examples of combined DS and PD measurements of PD are now shown. The single-cavity object consists of a stack of three 1 mm thick plates of polypropylene between 80 mm diameter brass electrodes extended radially with epoxy, the middle one of these three plates having a 10 mm diameter hole through its middle. Some phase-resolved PD patterns from this are shown in fig. 4; the positive and negative parts are largely symmetrical. The point-hemisphere gap has a 95 mm diameter at the open end of the hemisphere, 35 mm from the point to the centre of the hemisphere's inner surface, and the point just fits in a a 0.5 mm gap.

The PD pattern of the point-hemisphere gap is shown in fig. 7; it is very compact, the charges being of quite similar magnitude; there is no trouble with wide dynamic range. The pattern is highly asymmetric, with no positive discharges seen at these voltages.



**Fig.** 7 – PD patterns for 60 Hz, 5 s measurements on the point-hemisphere object. All four subplots have the same axis values; only the peak voltage differs. Just the negative half-cycle of voltage is shown; there was no detected PD on positive voltage until  $\sim$ 8 kV. The count scale is in per-cycle.

The PD currents measured by the DS system were compensated as described for the stator coil in section 2, by subtraction of currents calculated from the complex capacitance measured at sub-PD-inception voltage. In the present state of the combined measurement system the total current of the measurement object and coupling capacitor is measured by DS; the PD currents are therefore around a thousandth of the total current magnitude. Fig. 8 shows an impressive similarity of the results around the regions of large PD activity, but also some apparent noise in the compensated DS current in the PD-free parts of the cycle. This cannot be explained by the limited harmonics, since the harmonic-filtered PD current does not share this feature; it seems most likely to be noise in the measurement of harmonic currents and voltages.



**Fig. 8** – Single cavity object, 7 kV, 60 Hz: comparison of PD current seen by DS and PD pulse measurement systems.

Fig. 9 shows much less similarity of the results, for the point-hemisphere object, although the two measurement methods give magnitudes still much closer than for the stator coils. This object has a high repetition rate, which goes some way to explaining the difference. It also has a low capacitance for calibration. Earlier work suggests that the high DS current in the positive half-cycle, where there are no PD pulses recorded, is real, and is due to a more glow-like discharge that does not appear

as strong pulses at this voltage level; this fits with classic descriptions of positive and negative corona. The harmonics from the DS system, and in the correspondingly filtered PD pulse current shown here, have no d.c. term, and must therefore have zero mean, hence the artificial non-zero value of the harmonic-filtered PD pulse current in the positive half-cycle.



**Fig. 9** – Point-hemisphere object, 9 kV, 60 Hz: comparison of PD current seen by DS and PD pulse measurement systems.

### 7. Conclusions

Dielectric spectroscopy including harmonics allows measurement of total PD charge including information about the phase distribution of the PD charge. The information is in many practical cases complementary to PD pulse measurements, able to include the total PD charge without the limitations due to calibration, varied attenuation, deadtime and thresholds. Extraction of PD current from the much larger linear DS current is practical when PD is the main nonlinearity.

# 8. References

- J.T. Holbøll, U. Gäfvert, and H. Edin, "Time domain PD-detection vs. dielectric spectroscopy", *Conference on Electrical Insulation and Dielectric Phenomena*, 1997, pp. 498–503.
- [2] N. Taylor, "Diagnostics of stator insulation by dielectric response and variable frequency partial discharge measurements", licentiate thesis, KTH, Stockholm, 2006.
- [3] J. Wood, H. Sedding, W. Hogg, I. Kemp, and H. Zhu, "Partial discharges in HV machines; initial considerations for a PD specification", *IEE Proceedings on Science, Measurement and Technology*, 1993. 140(5), pp. 409–416.
- [4] G.C. Stone, A. Boulter, I. Culbert, and H. Dhirani, *Electrical insulation for rotating machines*, IEEE Press, 2004.
- [5] C. Hudon, R. Bartnikas, and M.R. Wertheimer. "Spark-to-glow discharge transition due to increased surface conductivity on epoxy resin specimens", *IEEE Transactions on Electrical Insulation*, 1993. 28(1) pp. 1–8.