Pulse-Sequence Analysis: a new method for investigating the physics of PD-induced ageing

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Indexing terms: Dielectric materials, Electric fields, Partial discharges

Abstract: A new method is presented of partial discharge data analysis for the investigation of space charge and degradation phenomena in high-voltage insulation systems. The basic principles of the Pulse-Sequense-Analysis (PSA) are illustrated and the characteristic differences with regard to standard procedures that have been established during the past few years are outlined. A description is given of an electronic partial discharge acquisition system, which is designed on a plug-in interface board for a standard PC to perform long-term measurements of all the discharge parameters required for the succeeding analysis. Electrical treeing in polyethylene is used to demonstrate the usefulness of the method. It is shown that information on the physics of treeing phenomena especially with regard to the influence of local space charges and their build-up and decrease over time as well as the development of the local degradation can be obtained by considering correlations between consecutive discharge pulses. Some experimental results from different stages of the electrical tree growth are analysed and their meaning with regard to the local microscopic phenomena inside the tree or in the vicinity of the tree tips discussed. This paper is based on an oral presentation at the international conference on *Partial discharge*, September 1993, Canterbury, titled 'Pulse-sequence analysis, a way to get a better insight into the physics of discharges'.

1 Introduction

Since the electric stress imposed on HV insulating materials has been increased significantly over the past few years, there is a greater need for monitoring the actual stage of insulation ageing or deterioration. The existence of local defects within the dielectric material may result in a local overstressing by a nonhomogeneous electric field causing the occurrence of partial discharges and ultimately leading to a further insulation degradation that reduces the lifetime or the reliability of the HV equipment. Thus there has been increasing interest in using PD measurements to indicate electrical insulation degradation, and nowadays it seems to be a well-accepted method that permits an early detection of an impending insulation fault.

The major weakness in PD analysis does not lie in the detection of discharge signals with sufficiently high measuring sensitivities, but rather in the interpretation of the real physical phenomena involved in partial discharge activities during the degradation process. For this reason a lot of more or less sophisticated procedures have been published, all providing interpretations for these complex processes that apparently exhibit significant statistical scatter in the commonly accepted discharge quantities. Above all, several PD pattern recognition methods have been developed with the aim to identify various types of defects [1].

To level off the apparent statistical scatter, the standard methods for analysing partial discharges usually examine accumulated data sets by extracting characteristic parameters from the statistical distributions of specific discharge quantities [1], but without considering any correlations between consecutive pulses. Consequently, important information on some basic physical phenomena is lost, as shown in this paper.

Recently it has been shown that the evaluation of direct pulse/pulse correlations (PSA) permits a better insight into the physics of space charge and degradation phenomena as well [2–4]. This method seems to be especially effective if solid-state phenomena determine the degradation process, which is generally the case during the early stages of ageing where local space charges influence the ignition of the following discharge pulse. If the influence of these space charges is not taken into account, the externally measurable voltages at which the discharges occur seem to be erratic. Applying the PSA at this stage of ageing the apparently stochastic behaviour of discharges disappears.

The existence of a so-called memory effect owing to the influence of residuals from previous discharges on the initiation and development of subsequent pulses has also been clearly proven by measuring conditional and unconditional PD pulse amplitude and phase distributions (Van Brunt [5–7]). The direct pulse–pulse correlations with regard to the voltage differences between consecutive discharges however have not been considered so far.

2 Basic aspects of PD analysis

2.1 Physics of partial discharges

A partial discharge, which is a locally confined electrical breakdown, occurs if the local electric field exceeds a critical value that depends on the polymer material. As a consequence of this electrical overstressing in a small region of the insulation, an extremely rapidly progressing

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avalanche of charge carriers occurs that starts within the critical field region and stops as it reaches regions with a lower electrical stress or a material with a higher electric strength. The charge carriers give rise to a local accumulation of space charges which in turn change the local electric field. Thus there must be considerable influence on the initiation and development of the subsequent discharge pulses.

According to the Poisson equation, space charges influence the local electric field by superposing an internal space charge field on the externally applied AC field. Since the decay of the space charge during the mean time between consecutive pulses is negligible, the space charge field can be assumed to be a DC field. Thus the actual value of the local electric field within the specimen is determined by the external voltage, the geometric dimensions of the electrodes and the local space charges within the electrode gap. As a consequence of these space charges, the highest local electric stresses in general will not occur at the highest values of the externally applied voltage. A unipolar space charge, which increases step-by-step because of discharge events, will lead to a step-by-step reduction of the local electric field for one polarity of the applied voltage and a corresponding increase of the local electric field for the other polarity. Consequently, a change in the external voltages where partial discharges occur provides information on changes of the local space charges over time.

2.2 Basic principles of standard analysis methods

The basic idea of all standard analysis methods is to accumulate discharge data collected during a certain recording time. The entire measuring time with numerous voltage cycles is transformed into one reference cycle of the applied voltage. Thus only a range of phase angles between 0 and 360° occurs, which is divided into a certain number of phase windows. All discharge pulses are superposed within the reference cycle and synchronised to the beginning of this cycle. No correlation between pulses in the same or in different cycles of the applied voltage is taken into consideration (Fig. 1).

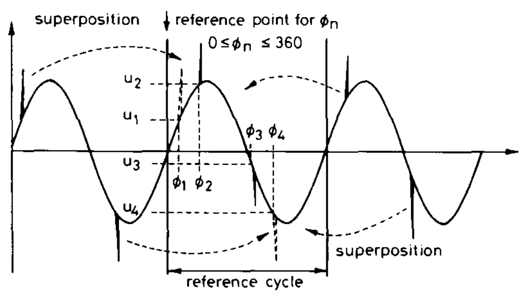

Fig. 1 *Basic principles of standard PD analysis methods*

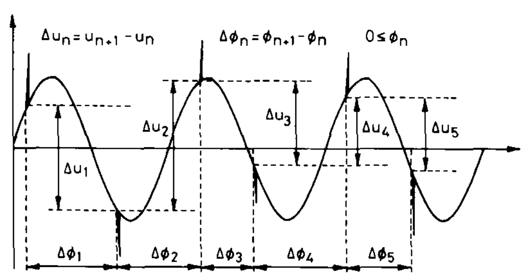

Fig. 2 *Basic principles of PSA method*

The parameters of interest here are the pulse height q_i and the voltage u_i or the phase of occurrence ϕ_i of each discharge pulse relative to the beginning of each voltage cycle. The subsequent interpretation of the discharge activity consists in analysing so-called ϕ–q, ϕ–n or three dimensional ϕ–q–n characteristics with some more or less meaningful statistical parameters.

2.3 Basic principles of PSA method

Since space charges from the previous pulses that remain near the discharge site affect the ignition conditions of the following pulse, strong correlations between consecutive discharge pulses must be expected. This means that successive pulses cannot be considered to be independent events without a correlation with preceding discharges especially at the early stage of insulation ageing, where space charges play a decisive role. In accordance with the theoretical background of the PSA method, the important parameters are not the absolute value of the external voltage or the phase angle where the discharge occurs, but the local electric field and its change or the elapsed time between consecutive discharge events. Thus, taking external parameters, the most significant parameter is the voltage change which occurs before the next discharge because the corresponding change of the local electric field at the discharge site determines the ignition of the next pulse. Consequently, it is physically more meaningful to investigate the discharge behaviour by means of direct pulse/pulse correlations of consecutive pulses over the entire measuring time, applying an appropriate set of parameters as shown in Fig. 2.

Analysing the mutual influence of discharge pulses and their nonstationary behaviour with continuing insulation degradation provides a better understanding of physical processes involved in partial discharge phenomena. It reveals basic information on space charge buildup and decrease, the corresponding time constants and the field modifying influence of positive and negative space charges as well [8].

Figs. 3 and 4 provide examples of frequency distributions of the external voltage levels and the corresponding

standard analysis:
evaluation of accumulated data sets
transformation of data into one cycle
no correlations between pulses

statistical distributions:
ϕ–q characteristics
ϕ–n characteristics
ϕ–q–n characteristics

computation of statistical parameters
skewness, kurtosis, etc.

pulse-sequence analysis:
evaluation of discharge pulse sequences
no transformation into one cycle
correlations between consecutive pulses

pulse-pulse correlations:
$q_{n+1}(q_n)$, $q_{n+1}(\Delta u_n)$, $q_{n+1}(\Delta\phi_n)$
$u_{n+1}(u_n)$, $\Delta u_{n+1}(\Delta u_n)$, $\Delta u_{n+1}(\Delta\phi_n)$
etc.

evaluation of pulse sequences
$u_n(t)$, $\Delta u_n(t)$

voltage changes, determined for different stages of electrical tree growth in polyethylene. The experimental conditions are described in earlier work [2]. The distributions

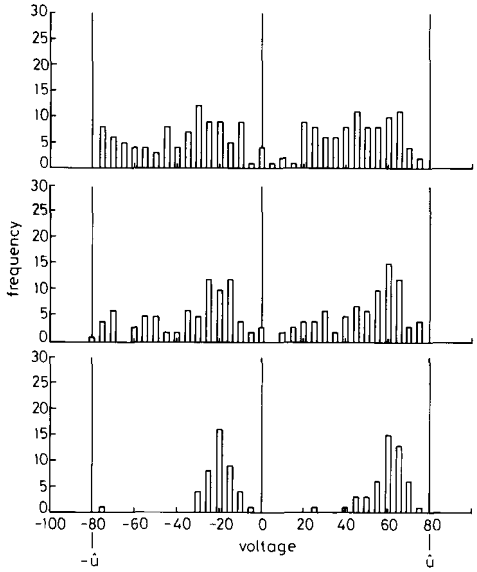

Fig. 3 *Frequency distributions of voltage levels at which discharges occured*

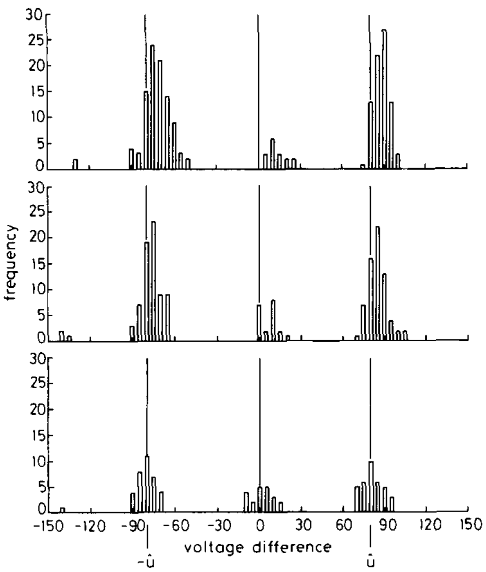

Fig. 4 *Frequency distributions of voltage differences between consecutive discharge pulses*

of voltage levels where discharges occur, which are equivalent to the usual ϕ–n characteristics, reveal an apparently erratic behaviour with no preferential voltage value for the occurrence of discharges. In contrast, the distributions of voltage changes which occur between neighbouring discharges show a characteristic pattern and exhibit a deterministic behaviour of discharge pulses even at the early stage of ageing. There is nearly no statistical scatter but a distinct grouping of voltage differences. With regard to the development of these voltage changes with continuing tree growth, the initial nonsymmetric behaviour disappears.

It is also important to differentiate between discharges occurring in neighbouring halfcycles and those that are separated by nearly one full cycle of the applied voltage or more. This can also be used to characterise different stages of electrical tree growth and it provides information on the influence of gas pressure during the degradation process [3, 8]. Performing correlations between discharge quantities such as voltage difference and pulse amplitude or amplitudes of consecutive pulses etc. [2–4, 8] allows meaningful information to be gained with regard to the basic physical mechanisms of local degradation phenomena that cannot be obtained by the usual methods for PD analysis.

3 PD-evaluation system PSA-SYS

The partial discharge evaluation system PSA-SYS (Pulse-Sequence Analysing SYStem) is a computer controlled system for partial discharge data acquisition that allows long term measurements of all the relevant discharge parameters mentioned below to be performed and that comprises a software based offline data analysis according to the principles of the PSA method described.

For PD recording an electronic system has been designed consisting of a multitude of analogue and digital signal processing components, which are realised on a printed circuit board that can be plugged directly into a standard PC. This plug-in interface board can be used as an attachment to any standard PD detector.

As shown in Fig. 5 the two analogue input signals to the interface board are the amplified PD signal, which is generally the bandpass filter output voltage of a conventional discharge detector, and a synchronising AC-signal in phase with the excitation voltage. This signal can be derived from the PD coupling impedance or from a separate voltage divider.

Conventional PD detectors usually incorporate filter characteristics with a limited bandwidth of a few hundred kHz. Because of the quasi-integration effect the apparent charge of the discharge signal is proportional to the peak value of the oscillating filter output signal. Consequently it is necessary to detect the appropriate peak of the output voltage. This is realised by a fast peak-detection circuit which provides the analogue input signal for a high-speed 12-bit AD converter.

The following quantities are recorded and stored for each discharge signal:

- discharge amplitude (including pulse polarity)
- pulse position (related to the phase of the sine wave)
- absolute cycle number (related to measurement activation)
- instantaneous voltage at each pulse.

Since the PSA method is not intended for evaluating discharge pulse shapes which are strongly dependent on the characteristics of the signal transmission path from the PD source to the detector and whose registration requires a high-frequency coupling, other parameters are not necessary.

To monitor the degradation process over a long period of time, it is sufficient to record the partial discharge activity at preset times over a given period of registration. Therefore the operator can feed in a complete schedule of discharge registration times with the corresponding intermittent pauses where the detection circuitry is blocked. The duration of different intervals can be chosen arbitrarily in terms of time, voltage cycles or number of discharge pulses.

with an electrode gap of 2 mm and low-density polyethylene as insulating material in which needles of about 5 μm tip radius have been moulded, data have been collected at different stages of electrical tree growth. To evaluate the influence of additives, investigations have been made with dry polyethylene samples and water saturated samples as well. For the acquisition of the data, the voltage was slowly increased to the discharge inception voltage and the partial discharges recorded during the first 100 cycles after discharge inception at constant voltage. This procedure was repeated after different periods of constant voltage load, during which the tree increased in size.

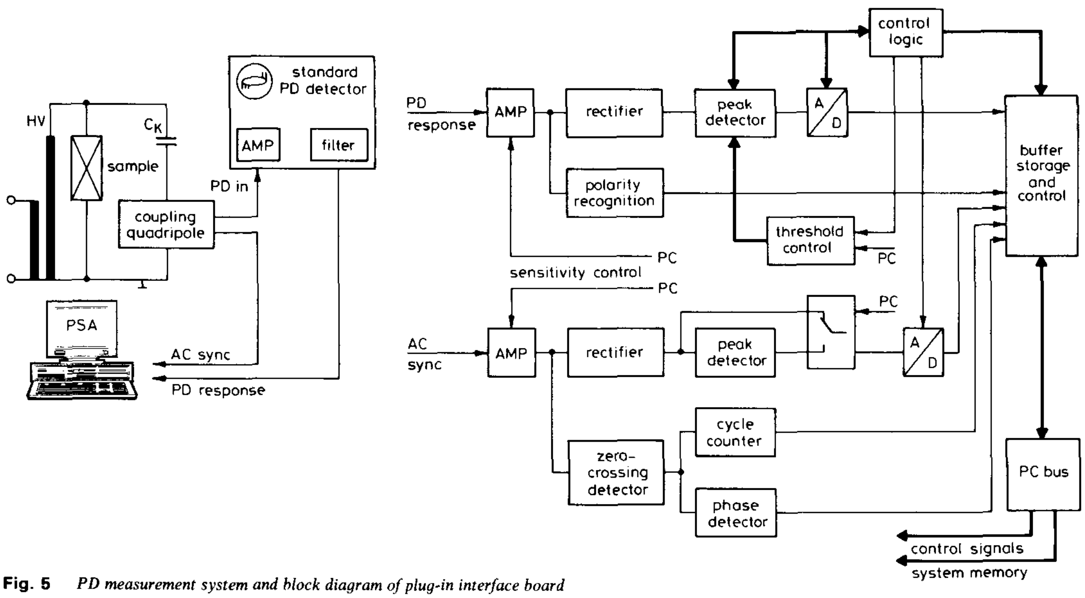

Fig. 5 *PD measurement system and block diagram of plug-in interface board*

All the data supplied by one discharge event are temporarily stored as one data record in a first-in first-out memory which is designed to store a maximum of 32,000 data records. Extension of storage capacity can be easily carried out. The data are continuously read out from the buffer storage by the control software without affecting the data collection process. Usually there are discharge free time intervals such that no risk of data loss owing to buffer storage overflow arises. Thus the complete history of the discharge activity with all the relevant parameters belonging to one discharge event can be stored for further analysis. The only limitation is the storage capacity of the hard disk being used.

In Fig. 5 a block diagram of the plug-in interface board whose operation is completely software controlled is shown. The minimum pulse resolution time depends only on the filter characteristics of the PD detector that is used, because the AD conversion time is comparatively small. The sensitivities for discharge detection and test voltage measurement can be adjusted by software control. To achieve a data reduction, it is possible to set different thresholds to define a particular range for pulse amplitudes of interest. The phase-angle resolution within one cycle is about 1.5 μs and the absolute cycle number is not limited. To attain a smallest detection time, a dynamic acquisition circuitry has been designed that does not depend on the filter bandwidth of the applied discharge detector.

After a single measurement or the series of tests is completed, the stored data are ready to be processed according to the fundamentals of the Pulse-Sequence Analysis.

4 Experimental procedure and results

Electrical treeing has been used to examine the usefulness of the PSA method. Taking a needle–plane arrangement

4.1 Sequences of voltage values where discharges occur

When examining the direct sequence of voltage values at which the discharges occur in the case of dry PE samples a conspicuous discharge behaviour with a periodicity over a few cycles of the applied voltage can be observed. The series of 20 consecutive cycles shown in Fig. 6 indicates a nearly deterministic behaviour of the discharge occurrence which is especially characteristic of the early stage of tree growth, during which solid-state phenomena within the polymer around the needle tip play the decisive role.

In general, there is only one discharge event within a halfcycle of the voltage and the positive voltage values where the discharges occur increase gradually from cycle to cycle, whereas the discharges during the corresponding negative halfcycles occur at gradually decreasing voltage values. The voltage differences, however, are nearly constant. After a discharge near the positive crest voltage there is a discharge at a very small negative voltage, which is followed by a comparatively powerful discharge near the negative crest voltage. This 'reset' after four or five cycles restarts the periodical process. The nearly predictable space charge dominated behaviour changes considerably with advancing electrical tree growth as has been demonstrated in References 3 and 4.

When comparing the results of dry and water saturated samples, a distinct difference with regard to the development of pulse sequences can be observed. As shown in Figs. 7 and 8 for two different stages of electrical treeing, in the case of water saturated samples, the step-by-step change of the voltage heights where discharges occur can also be found in the opposite direction.

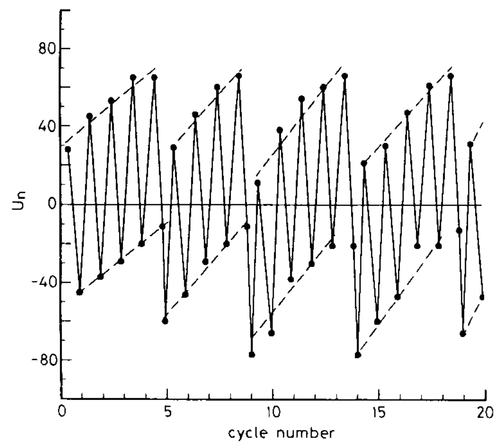

Fig. 6 *Sequence of voltages at which discharges occur for 20 consecutive cycles*
Dry PE sample, early stage of electrical tree growth

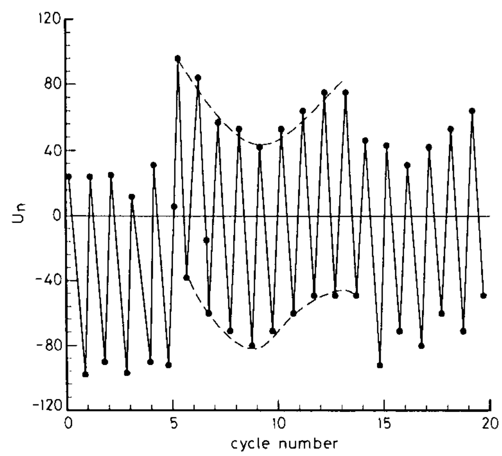

Fig. 7 *Sequence of voltages at which discharges occur for 20 consecutive cycles*
Water saturated PE sample, early stage of electrical tree growth

A few cycles later, a gradual increase of the positive voltages according to Fig. 6 is possible as well. Another important aspect is that the periodicity, which may be an indicator for the time constant of space charge buildup and decrease, differs from that of dry polyethylene samples.

For advanced tree growth there is more than one discharge event within one halfcycle of the voltage, which may be assigned either to different discharge sites within the deteriorated region, or to more than one discharge at the same site during one halfcycle [8]. For different discharge sites there could be individual periodicites with regard to the space-charge behaviour.

4.2 Space-charge development

Depending on the space charge remaining in front of the needle tip or the tip of a tree channel after the reset, the discharge behaviour in Fig. 6 can be attributed either to a decreasing negative space charge or to a step-by-step buildup of positive space charges within the polymer or at the walls of the tree channels. It is more likely to be a combination of both processes which is indicated by the higher negative voltage value of the first negative discharge, compared with the voltage value of the first positive discharge after the reset. This means that a negative space charge exists within the polymer close to the needle tip, which is gradually reduced owing to electron extraction by positive discharge events, ultimately leading to an accumulation of positive space charges. Each discharge seems to compensate the local electric field that initated the discharge, and the next discharge occurs owing to the local electric field generated by the external voltage change. Intense electron injection into the tree channels and/or the polymer seems to occur, especially for the negative pulse which occurs near the negative crest voltage and that restarts the periodic process.

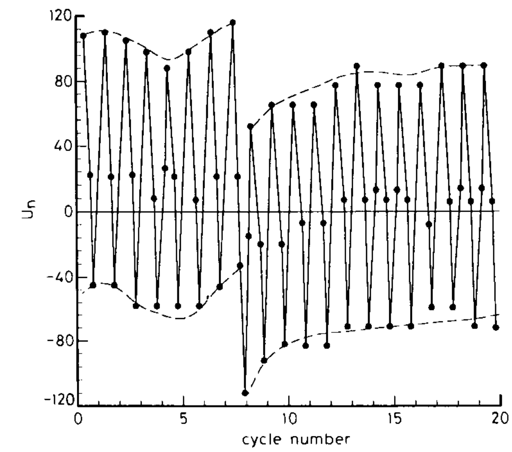

Fig. 8 *Sequence of voltages at which discharges occur for 20 consecutive cycles*
Water saturated PE sample, advanced stage of electrical tree growth

After a certain number of cycles, and actually after a discharge at nearly the positive crest voltage, the internal DC field generated by the positive space charges is high enough to compensate the AC field at the positive crest voltage. After the following decrease of the AC field, the DC field remains unchanged and leads to a negative discharge at nearly no external voltage, by which electrons are injected from the needle tip into the polymer that compensate the positive space charge. During the succeeding negative halfcycle another negative discharge pulse follows, that produces a negative space charge and causes the next discharge in the positive halfcycle to occur at a low external voltage.

If there were no space charges as a consequence of partial discharges, the electric field due to the externally applied voltage would be the only decisive parameter. Then the voltages where discharges occur should only vary if, as a consequence of degradation processes within the polymer, the local electric field necessary for the ignition of a discharge has changed.

According to the voltage changes in Figs. 7 and 8, in the case of wet specimens the space charge buildup can occur with both polarities. The time constant for space charge increase or decrease is signficantly longer for wet polyethylene.

As can be seen from Fig. 9 at an intermediate stage of the tree growth, during cycles 50 to 85 of the recorded

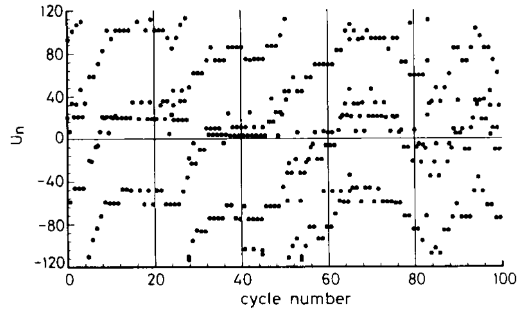

Fig. 9 *Voltages at which discharges occur*
Water saturated PE sample, intermediate stage of electrical tree growth

data, the voltages at which the discharges occur show a tendency to lower magnitudes of the negative voltages as well as some periods later a tendency to higher negative voltages. Around cycle 50 there must be a negative space charge which is first compensated or overcompensated by a positive space charge (until cycle 70) and then restored. Even in this complex situation, the discharges occur almost exclusively after characteristic voltage differences. As shown in Fig. 10*b* there is a grouping of the voltage differences around three distinct values.

4.3 Voltage changes between consecutive discharges

When analysing the voltage changes that occur before the next discharge, the characteristic behaviour shown in Fig. 10 can be observed for dry as well as for wet polyethylene. In contrast to the apparently erratic voltage heights at which discharges occur (Fig. 3 and 4), the corresponding voltage changes at an early stage of tree growth concentrate around two distinct values, and the positive voltage changes seem to be slightly higher than the corresponding negative ones. At the intermediate and late stage of treeing the voltage changes tend to concentrate around three distinct values with a comparatively small scatter (Fig. 10*c*).

The finding that at the initial stage of tree growth the absolute value of the voltage change, which is necessary before a positive discharge, is slightly but signficantly higher than before a negative discharge (Fig. 10*a*) may be attributed to a higher dissipation rate for negative charges. If the negative space charges diffuse away easier or quicker than positive space charges, a few milliseconds after the discharge event their field-modifying influence is less pronounced than that of positive space charges.

5 Conclusions

Since strong correlations between consecutive pulses must be expected owing to field modifying space charges from previous pulses, it is physically more meaningful to analyse direct pulse/pulse correlations instead of only evaluating accumulated data sets which have been transformed into one reference cycle. A computer-controlled PD-evaluation system for partial discharge data acquisition and analysis has been described. Electrical treeing in dry and water-saturated PE samples has been used to show that information on space charge buildup and decrease can be obtained, examining the direct sequence of discharge pulses. The PSA method can be used to

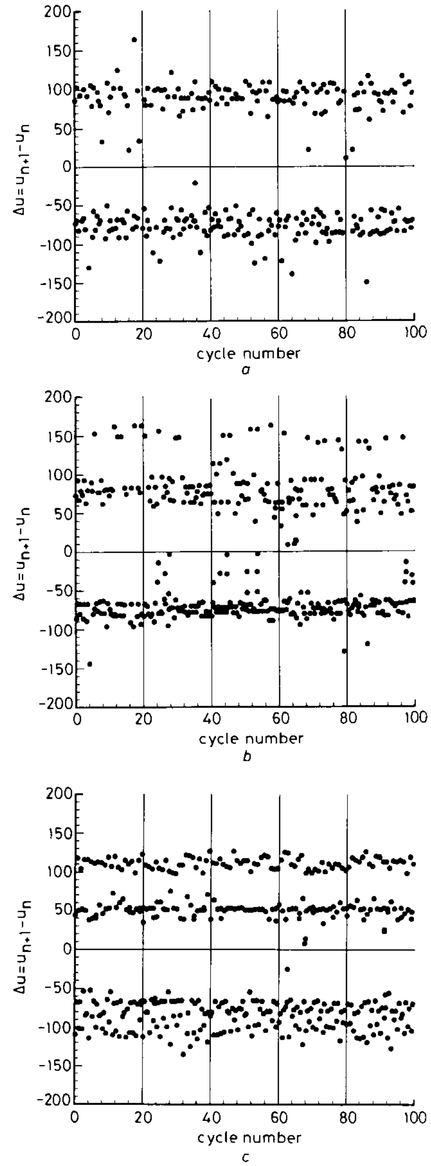

Fig. 10 *Voltage changes between consecutive discharges*
a Water saturated PE sample, early stage of electrical tree growth
b Water saturated PE sample, intermediate stage of electrical tree growth
c Water saturated PE sample, late stage of electrical tree growth

clarify the influence of space charges on the degradation processes in polymers. The method is especially effective when solid-state phenomena determine the degradation process, which is generally the case during the early stages of insulation deterioration.

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Erratum

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On p. 62 at the end of Section 4.1 the circuit parameters C_1, C_2 and C_{sn} should be as follows:

$$C_1 = C_2 = 9.4\mu\text{F}$$

$$C_{sn} = 0.047\mu\text{F}$$