

# Effect of Detector and Analyzer Settings on Partial Discharge Measurement and Representation

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## ABSTRACT

Partial discharge (PD) measurement is usually performed with PD detector and analyzer system. The data collected during the test is generally represented as distributions. These distributions are interpreted to reveal the PD phenomenon and the state of the insulation. The paper demonstrates the effect of instrument characteristics on measurement and representation of PD phenomenon with experimental results obtained from short time PD endurance tests on oil pressboard samples. The instrumentation, a combined narrowband detector and multi-channel analyzer (MCA), is analyzed for the effect of the detector resolution and gain settings on the PD distributions. The results show the instrument dependence in the PD characteristics due to differences in measurement ability at various instrument settings. These differences in representation lead to multiple interpretation for the same phenomenon or state of the insulation and hence to wrong classification. The paper emphasis is that interpretation of the results should be made to account for the measurement ability of the instruments in use.

Index Terms — Partial Discharges, PD measurement, PD interpretation, PD analyzer, PD pattern recognition and Insulation aging.

## 1 INTRODUCTION

PARTIAL Discharge (PD) tests are important for diagnostic assessment of insulation. Proper diagnosis is feasible with reliable measurement, selective analysis and good representation. A typical diagnosis scheme for PD phenomenon is illustrated in Figure 1. In the figure the roles of measurement, analysis and representation are highlighted with examples.

The PD phenomenon is generally measured by apparent charge magnitude and phase position [1, 2]. PD measurement is performed with the help of PD analyzers that are available with many sophisticated features for data acquisition and analysis. Analyzers are capable of streaming large amount of data when used in an experiment. The large amount of data is usually organized as PD pulse amplitude histograms commonly referred as PD distributions for comprehension. Many analyzers perform organization of data at the hardware level and output directly PD dis-

tributions while others perform organization of data later at the software level from the acquired raw data.

Analyses are generally focused on obtaining characteristics features from distributions to correlate with PD phenomenon and ageing process using statistical [3,4], image processing [5–7], neural [8] and transform techniques [9]. For example, “skewness” as a feature of a distribution is used to correlate ageing in insulation [10].

It is a common practice to use distribution patterns and various derived parameters from analyses to represent the PD activity. It may be noted that almost all the analyses techniques for PD recognition and expert system development are based on inputs obtained from PD distributions. Exceptions are with techniques such as pulse sequence analysis [11–13] which have representations other than PD distributions.

True characterization of PD phenomenon and successful recognition with expert systems are very much dependent on the ability to acquire representative patterns. Therefore, investigation of acquisition and representation ability of PD patterns is of prime importance and crucial for proper understanding of PD phenomenon. The paper

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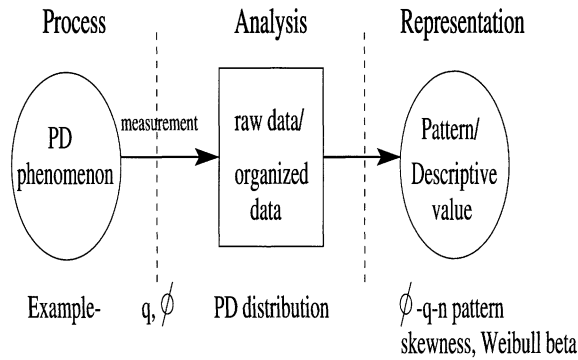


Figure 1. A typical scheme for PD diagnosis.

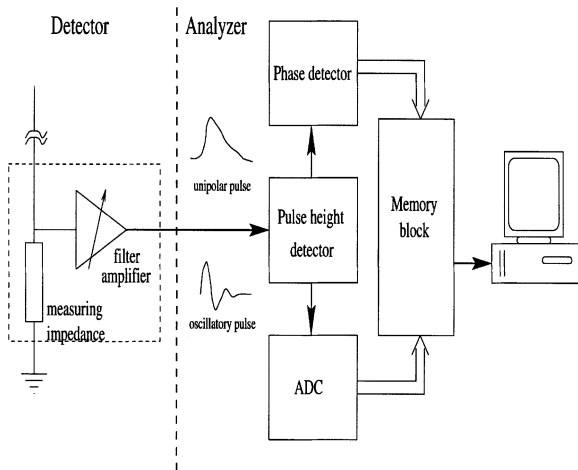


Figure 2. Schematic block diagram of detector-analyzer system.

presents investigation results for a narrowband detector and multi-channel analyzer (MCA).

## 2 PULSE DETECTION AND ACQUISITION

PD current pulses are picked up with the help of a PD detector and recorded with a PD analyzer. Figure 2 shows the schematic block diagram of a typical detector-analyzer system. The detector performs quasi-integration of PD current pulses with a bandpass amplifier characterized as wideband or narrowband based on its bandwidth. Quasi-integration is the process by which the pulse height of detector output (quasi-integrated output) becomes proportional to the area (charge) of the input pulse (current). The quasi-integrated output may be unipolar, bipolar or oscillatory depending on the amplifier and shaping network used in the detector.

The analyzer captures only the pulse height of the quasi-integrated output from the detector for PD magnitude quantification. Analyzers basically consist of pulse height detector, ADC, phase detector and memory block interfaced to a personal computer (PC). The pulse height detector detects valid quasi-integrated PD pulses and captures the correct pulse peak with a pulse peak detector.

The digital values of pulse height and phase position are provided by the ADC block and the phase detector block respectively. Some analyzers using a very fast ADC may digitize the quasi-integrated pulse and then numerically compute the pulse peak. For such analyzers, electronic pulse height detection block does not exist separately. The analyzer based on its design feature either organizes the data acquired in the memory block as distribution (with help of built-in microprocessor using the memory as matrix to save pulse count information) or uses the memory block as a buffer to transfer the acquired data (raw) to the PC for offline analysis.

### 2.1 DETECTION AND ACQUISITION LIMITATIONS

The ability of a detector and analyzer system is judged with the help of following parameters:

#### 2.1.1 DETECTOR PULSE RESOLUTION TIME $t_r$

The pulse resolution time is the shortest time interval between two consecutive input current pulses of very short duration, equal shape and magnitude (same charge magnitude) for which the amplitude of the pulse response will change not more than 10% of the magnitude of a single pulse.

Typically, wideband detectors have resolution time around  $10 \mu s$  and narrowband detectors have resolution time around  $100 \mu s$ .

#### 2.1.2 DETECTOR AMPLIFIER RANGE

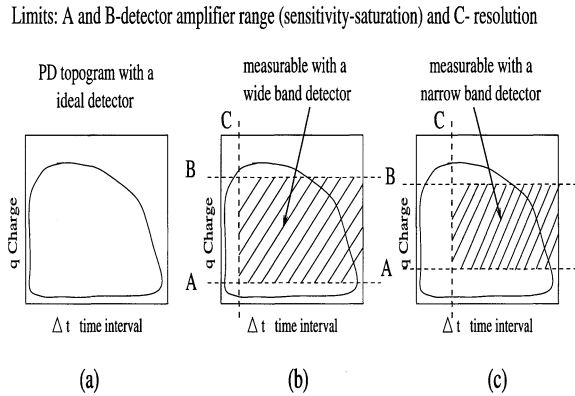
The detector amplifier setting decides the range for the PD measurement. The pulse height value saturates for PD pulses having greater magnitude than the range. The amplifier sensitivity and the ambient noise level picked up by the measurement setup dictate the minimum measurable pulse height value.

Wideband and narrowband detectors may have different sensitivity levels.

#### 2.1.3 DEAD TIME $t_d$

The dead time of an analyzer is the time the analyzer is not available (busy) to make a new measurement. It is usually the time taken to process a pulse, which is typically less than  $10 \mu s$ .

The dead time of the measuring system (detector and analyzer) also includes the time for which the analyzer is idle performing no measurement when PD pulses are active. An example of the idle state is seen during the acquisition of overlapping unipolar pulses at which instant the pulse detection mechanism (those based on providing trigger at the instant pulse crosses the preset threshold) fails to detect the presence of overlapping pulses. This time is variable and cannot be easily determined.



**Figure 3.** Measurement limitations with detector-analyzer system.

The effect of resolution time and amplifier gain setting on PD representation can be appreciated conceptually with the help of Figure 3. The figure shows hypothetical contours of charge magnitude and pulse time interval (time between pulses) along with the limits that exist on measurements performed with PD detectors. Figure 3a is a plot with all the pulses measured using an ideal instrument with no resolution and magnitude range limit. Figures 3b and 3c are plots measured with practical detectors; the hashed regions depict measurable pulses with wideband and narrowband detectors respectively. The limits on measurement; A and B are limits due to detector amplifier range (sensitivity-saturation) and C is the resolution limit, shown with dotted lines. The area other than the highlighted one is generally unknown to the user as it is not measurable with the detector in use.

Analyzers record only the pulses detected. Pulses around the limiting conditions get treated (conditioned and quantified) in variety of manner depending on the design of the analyzer and the nature of the detector-analyzer interface. The errors caused by detector-analyzer system are quite well known and are as follows: (a) superposition errors due to resolution limitation causing inaccurate measurement of the overlapping pulse [14] and (b) multiple measurement [15] or no measurement [16] in case of detector resolution time mismatch with the dead time of the analyzer [17]. The effect of these limitations is subtle in nature and their detection is often difficult because of stochastic behavior of PD. However, comparative evaluations with different settings can provide hint on the influence of detector-analyzer systems. The following sections deal with design, conduction and results of experiments for this study.

### 3 EXPERIMENTATION

PD experiments depending on the type of model insulation system can exhibit a single point or multipoint discharge process. Single point discharges for example corona discharges in air exhibit stationary characteristics with

pulses having magnitude within a definite range and repeating with a definite regularity. On the other hand, multipoint discharges for example surface discharges at the edges of an electrode placed on a dielectric can exhibit varying characteristics with a wide range of pulse magnitude and time interval. A multipoint discharge model is therefore used for experiments to observe differences in measurement at different settings.

The experiments conducted are grouped into two categories; (a) experiments to evaluate the instrument representation ability and (b) experiments to evaluate PD process representation with distributions. The set of experiments to evaluate instrument representation ability were performed at different detector settings to observe the ability of an instrument to represent PD activity. And the set of experiments for PD process representation were performed to observe fidelity of PD distributions to representation changes related to the process.

The model insulation system used for experiments consisted of an oil-impregnated pressboard (2mm thickness, 50mm diameter) placed between  $7\pi/12$  Rogowski electrodes (30 mm overall diameter) and immersed in transformer oil. The pressboard samples were stressed to produce PD pulses. PD occurred in the wedge shaped oil gap between the pressboard and the electrodes causing degradation of the pressboard sample. A sample was stressed till failure of pressboard (puncture) occurred at which stage the experiment was terminated.

The measurement setup consisted of a narrowband detector (tuned at 500 kHz) used along with a Multi-Channel Analyzer (MCA - EG&G model 931) having 512 channels and a wideband detector (10 kHz-300 kHz) used along with a Computer-Aided Discharge Analyzer (CADiA - indigenously developed [18]) having 4096 channels. MCA and CADiA measured pulse height in the range of 10V but the detectors saturated at 8 V. The pulse resolution time of the narrowband detector was set to 60  $\mu$ s and that of the wideband detector was 6  $\mu$ s. The dead time of the MCA system was 1.5  $\mu$ s and that of the CADiA system was 10  $\mu$ s. A digital storage oscilloscope (DSO- Tektronix TDS 684A) was used as the reference instrument connected to the detector in use. PD distribution records of ten seconds each were collected continuously along with oscilloscopic records.

#### 3.1 SOME RELEVANT DETAILS

To study the effect of detector resolution time on PD distributions the analyzers need to be matched. It may be recalled here that the analyzer used along with a narrowband detector will perform no measurement of pulses appearing within the resolution time of the detector essentially because the analyzer cannot detect the presence of overlapping unipolar pulses. Note that the analyzer detects only the pulses that jump beyond the preset threshold value (trigger reference) and overlap conditions in

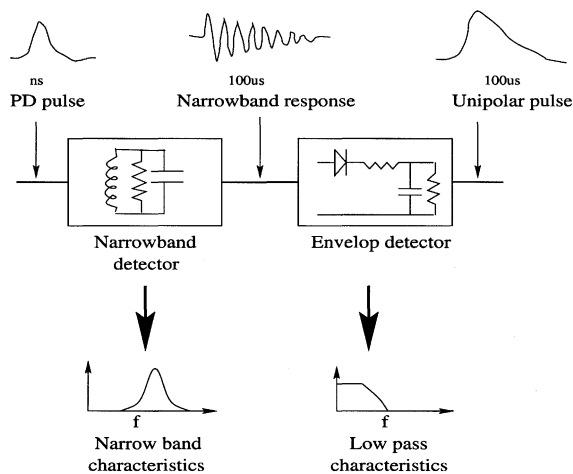


Figure 4. Details of a typical narrowband detector.

unipolar pulses does not allow the voltage level to relax to zero causing delay in baseline restoration. For the same reason, the effect of detector resolution cannot be studied independent of dead time of the analyzer.

The narrowband detector used (Figure 4) consisted of filter-amplifier system and envelop detector to capture variations in the rectified underdamped quasi-integrated response. In the case of a wideband detector the response is often oscillatory. The oscillatory response is handled specially by analyzers [19, 20] to capture correct peak and pulse polarity. The performance of one analyzer can differ from another depending on the technique used for pulse peak detection particularly during overlap conditions (causing polarity error [14], multiple measurement [15] or no measurement). Therefore, the technique used to condition the pulse and detect the peak is important for analyzer behavior studies using a wideband-analyzer system.

For valid comparison of narrowband-MCA and wideband-CADiA systems, the error during overlap conditions with wideband-CADiA system is restricted to only counting error resulting from no measurement of overlapping pulses. This was possible with CADiA because of its input block design that modifies the wideband detector response to unipolar response with absolute value detector and low pass filter. The detector-analyzer interface for the wide band detector along with pulse response at different stages is shown in Figure 5. The implemented input block of the analyzer, CADiA, provides uniform interface to all PD detectors.

Another factor concerning uniform performance is detector "sensitivity". A wideband detector can have a different sensitivity (in pC) compared to a narrowband detector due to its large bandwidth. The narrowband detector measured PD pulses only above 250 pC when used in the range of 5000 pC while the wideband detector in the same range measured pulses of less than 50 pC. An ad-

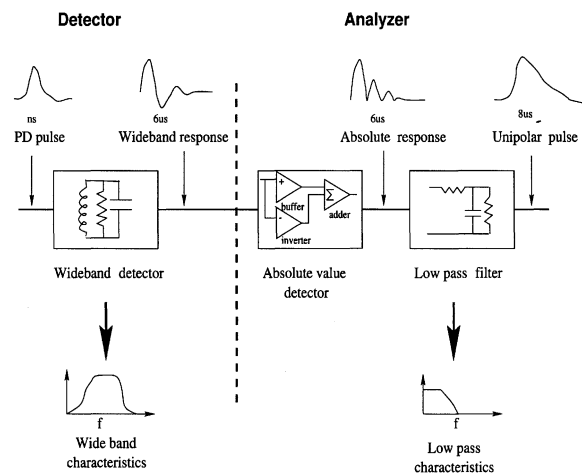


Figure 5. Wideband detector-analyzer interface.

justment was made in the analyzer (CADiA) connected with the wideband detector to measure pulses only above 250 pC by adjusting the presetable threshold level for pulse detection in order to give the two systems the same measuring range. The analyzer (MCA) connected with the narrowband detector had the factory setting for pulse detection.

Partial discharge experimentations generally present the problem of repeatability of results even with uniformly and identically prepared samples when tested under similar conditions using the same setup. To study repeatability of results, experiments were performed with number of samples under identical conditions. Figure 6 gives uncalibrated ten second PD records for four samples tested at 13 kV/mm obtained at 5 minutes after application of voltage with the narrowband-MCA setup. The figure also depicts the number of pulses measured and the distribution skewness values. The values show a large variation in pulse count (on the first sight, differences in the peak counts are visible). The peak counts are approximately 5500, 7200,

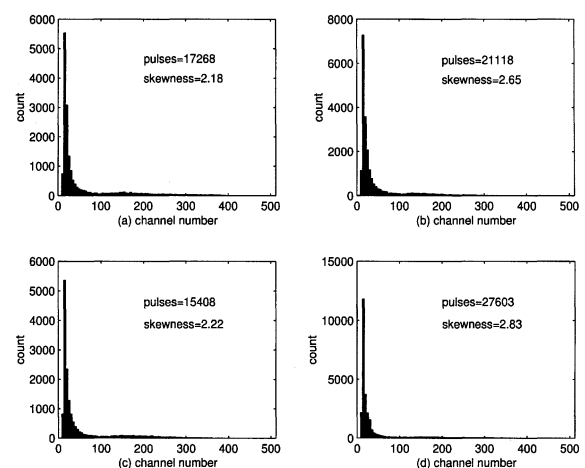


Figure 6. Initial records from different samples tested at 13 kV/mm.

5500 and 12000 for distribution (a), (b), (c) and (d) respectively in the figure). However, the shapes of the distributions show identical characteristics (also reflected in skewness values). Therefore judgments based on distribution shape (and not on pulse count) are used to draw conclusions from experiments involving different samples.

### 3.2 PD INSTRUMENT REPRESENTATION ABILITY

PD distributions are observed for the following experiments:

#### 3.2.1 EXPERIMENTS TO STUDY EFFECTS OF RESOLUTION TIME WITH WIDEBAND-CADiA AND NARROWBAND-MCA SYSTEMS

PD distributions were obtained in two separate experiments on oil impregnated pressboard insulation stressed at 13 kV/mm with wideband-CADiA and narrowband-MCA measuring systems. The detectors were operated in 5000pC range.

Typical distributions obtained are shown in Figure 7. The distributions show charge magnitudes (uncalibrated) in terms of analyzer channel numbers (top scale) and in pC (bottom scale). The figure also gives the number of pulses measured and skewness value for the two distributions. Although skewness values do not show drastic differences in the two distributions, visually the nature of distributions appears different. The shape of the distribution appears to have Gaussian nature for the wideband-CADiA system and an extreme nature for the narrowband-MCA system. A close look at distributions show that the maximum charge magnitude is measured more or less identical (3000 pC) by both the systems. The difference in representation appears prominent for the lower discharge magnitude. The distribution shape for the large discharge magnitude (greater than 1000 pC) may be considered similar.

#### 3.2.2 EXPERIMENTS TO STUDY EFFECTS OF GAIN SETTING WITH THE NARROWBAND-MCA SYSTEM

PD measurement was performed with the narrowband-MCA system at (a) 200 pC range and at (b) 1400 pC range to study the effect of gain setting on distributions. The sensitivity of the detector changed from 12 pC in case of 200 pC range to 150 pC in 1400 pC range. During the course of experiment on oil-pressboard sample stressed at 13 kV/mm (5 minutes after application of voltage on the sample), the gain setting was changed from 200 pC range setting to 1400 pC range setting. The distributions obtained at these two ranges (just before and after the change in gain setting) are given in Figure 8. (The difference in distributions (shape) in three ranges may be appreciated

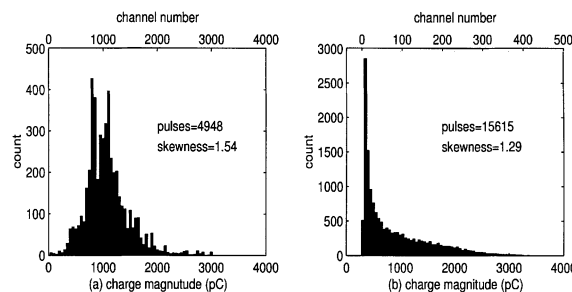


Figure 7. Distributions. a, Wideband-CADiA system; b, Narrowband-MCA system.

by considering the distribution obtained at 5000 pC range shown in Figure 7b.)

The distribution obtained at 200 pC range is negatively skewed ( $-0.6$ ) while those obtained at 1400 pC range and 5000 pC are positively skewed ( $0.54$  and  $1.29$  respectively). It may be noted that skewness is a popular measure of insulation condition [3, 10] and often suggested for PD phenomenon interpretation. But in this case, interpretation and assessment of the state of insulation with distributions obtained at different amplifier setting is likely to vary.

The results can be also compared on the basis of pulse count since the distributions were obtained for the same sample during the course of experiment. Number of pulses measured at 200 pC range is more by an order than that measured at 1400 pC range. Also, the 200 pC range shows PD pulses distributed around midrange (around 300<sup>th</sup> channel) with very few pulses saturating (at 425<sup>th</sup> channel). In 1400 pC range too, very few number of pulses are seen towards saturation. Considering that there are very few pulses saturating compared to the total number of pulses measured respectively in the two amplifier range and that the analyzer outputs uncalibrated PD distributions (in terms of channel number), the task of selecting the most appropriate amplifier gain setting for meaningful interpretation is difficult.

Figure 9 gives the oscillograms obtained at these two settings along with the distributions. The oscilloscope was set in a special mode to obtain envelop of 10 ac cycles to get a better representation of PD activity. The oscillo-

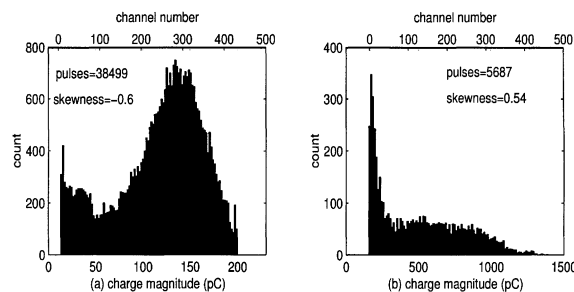


Figure 8. Distributions. a, 200 pC; b, 1400 pC amplifier range.

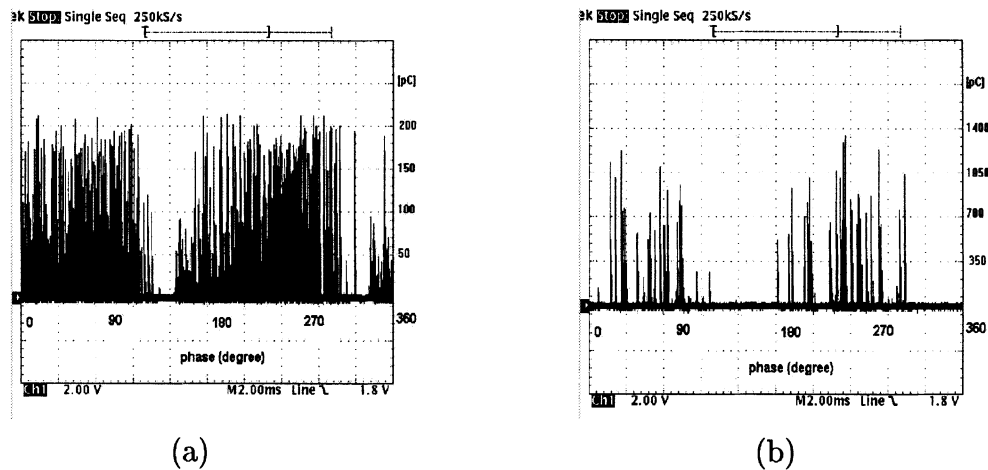


Figure 9. Oscillograms. a, 200 pC; b, 1400 pC amplifier range.

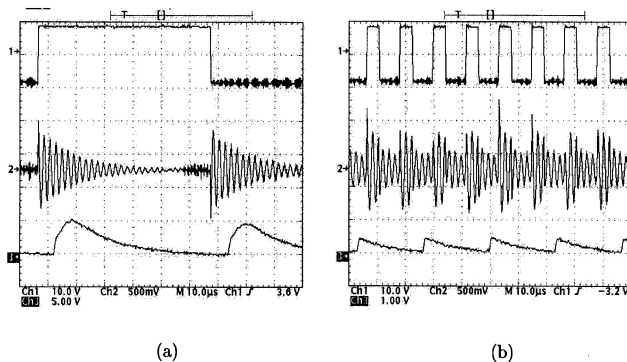


Figure 10. Detector response with square wave calibrator.

grams show difference in PD magnitude and rate of PD activity similar to that seen with PD distributions.

The observed differences arise due to measuring instrument limitations namely the amplifier range (sensitivity-saturation limits), resolution limitation causing no measurement of overlapping pulses (largely seen for small magnitude pulses) and high repetition rate problem. The problem with high repetition rate is explained with results from calibration experiment performed to study pulse response at different repetition rate.

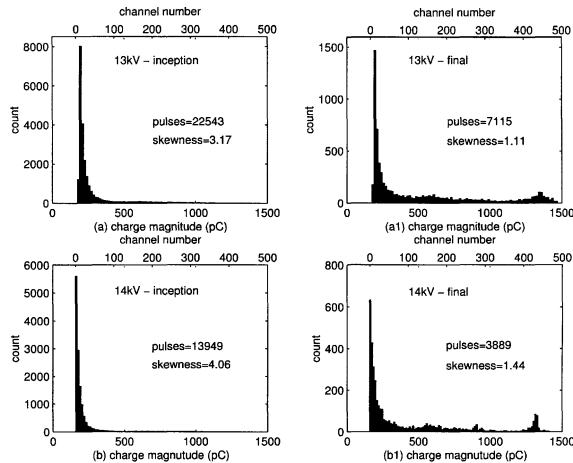
Figures 10a and 10b show square wave pulse (in Ch1) used for calibration, pulse response of the measuring impedance (in Ch2) and the narrowband detector response (in Ch3). Oscillogram (a) in the figure shows two well-resolved pulses of equal magnitude. Overlap in detector response is expected when pulses appear within the detector resolution time. This was observed when duty cycle of input square wave pulse was changed. However, for square wave pulses with very high repetition rate, a different effect other than that expected was observed. Oscillogram (b) in the figure shows pulse response at very high repetition rate. The response in the oscillogram also has reduced magnitude and a reduced settling time compared

to the case in oscillogram (a). The repetition rate of the narrowband response is not the same as the input square wave pulses. The oscilloscope was configured for dc coupling. Note that the magnitude of the input square pulse is kept constant. This effect is perhaps due to envelope detector (lowpass filter) responding with its own time constant to the narrowband amplifier (narrowband filter) response (see Figure 4).

The different effects observed for the measuring system are important for proper interpretation of distributions. The distributions maybe interpreted as follows. At 200 pC range, oscilloscope showed dense PD activity having many small discharge magnitude pulses overlapping with each other. The overlap condition resulted in counting error due to no measurement of overlapping pulses. Therefore, low count of small magnitude pulses is seen in the distribution (Figure 8a). There are suspected errors in magnitude causing left shift in distribution arising for pulses with very high repetition rate (Figure 10). This could be the reason for very few pulses seen in saturation (425th channel, 200 pC) occurring due to reduction in pulse magnitude to less than 8 V. Also, around the saturation region, nonlinearity introduced by the amplifier needs to be considered. At higher range setting (1400 pC), much reduced PD activity is detected due to poor sensitivity. The error because of high repetition rate will also be much reduced and the distributions obtained in this setting can be relied upon. Therefore, PD experiments conducted at 1400 pC range are used for process interpretation.

### 3.3 PD PROCESS REPRESENTATION

PD occurrence affects the state of insulation. One of the prime parameter that controls the rate of this effect is the applied stress. Increase in the applied stress may change PD magnitude and repetition rate. For the same reason the detector-analyzer measurement ability may vary and additionally influence PD process characterization artificially.



**Figure 11.** Distributions at (a,a1) 13kV and (b,b1) 14 kV immediately after application of stress (a,b) and just before failure of the sample (a1,b1).

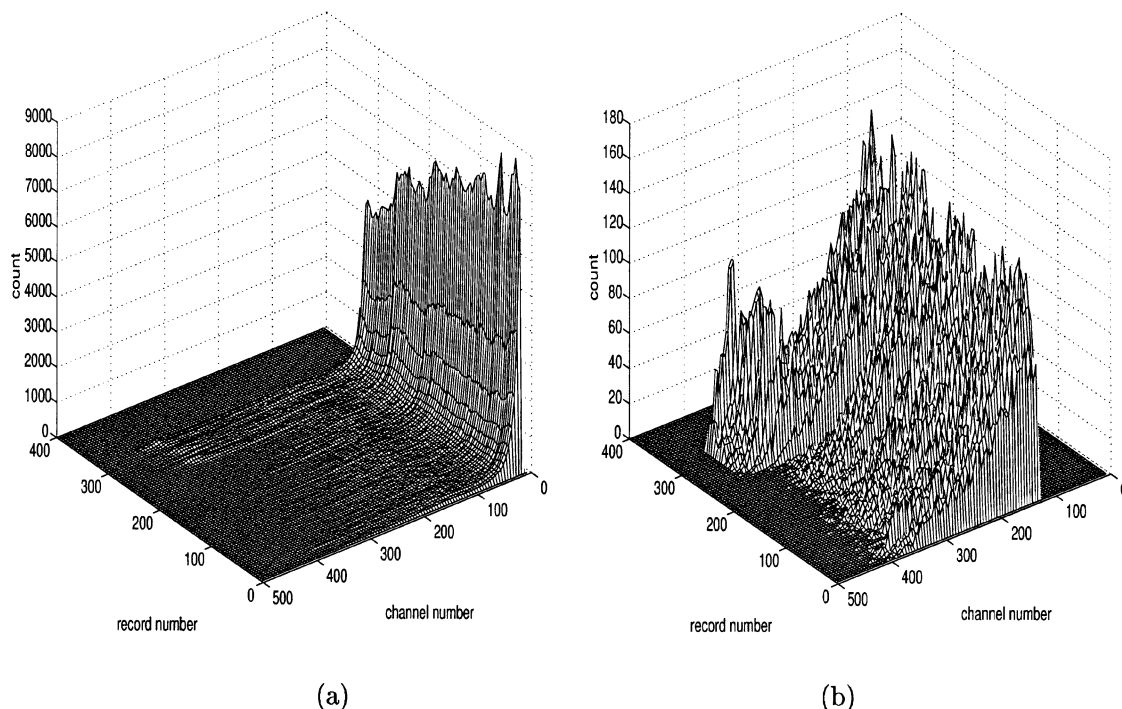
PD process is represented with acquired distributions or with derived parameters obtained from analysis of distributions. Distributions from PD experiments performed at 1400 pC range on oil-impregnated pressboard sample at 13 kV/mm and 14 kV/mm stress levels with the narrow-band-MCA system are used for investigation. Two distributions and oscillograms, one immediately after the start of the experiment and another just before the failure of the sample, are selected in specific to study the fidelity of PD representation.

Figure 11 gives the typical first and final PD distributions at 13 kV/mm (a,a1) and 14 kV/mm (b,b1). Figure 11

depicts the number of pulses measured and the skewness value for each of the distributions. The distributions obtained at 13 kV/mm and 14 kV/mm show pulse count reduction with time. This may be observed visually with the help of peak pulse counts. At 13 kV/mm, the peak pulse count reduced from near 8000 pulses to 1500 pulses while at 14 kV/mm, the pulse count reduced from near 5500 pulses to 600 pulses. An increase in charge magnitude to saturation level (1400 pC) is also seen from the distributions. The distributions typically showed lower pulse counts at 14 kV/mm than at 13 kV/mm.

The detailed variations in distributions at 13kV/mm with time (shown as record number with each record representing 10 second data) are shown in Figure 12. The distribution (b) in Figure 12 depicts change in uncalibrated PD distributions exclusively for the large magnitude pulses obtained by putting a threshold on the distribution (a) to highlight the discharge activity involving large magnitude pulses. It can be noticed from the figure that the pulse count of small discharge magnitude pulses decreases with time and the pulse magnitude (see the maximum measured value) increases with time to saturate at some instant during the experiment. The saturation effect is seen as pulse accumulation around 425th channel in the figure.

Figure 13 gives the oscillograms (13a, initial stage and 13b, final stage) obtained at 13 kV/mm for one ac cycle. From the oscillograms increase in pulse count and phase range of discharge pulses with time is seen. During the measurement, the oscillograms recorded were zoomed and scanned to obtain a rough estimate of pulse count. The



**Figure 12.** Distributions with time. a, Overall distribution; b, exclusive larger discharge magnitude distribution obtained with threshold.

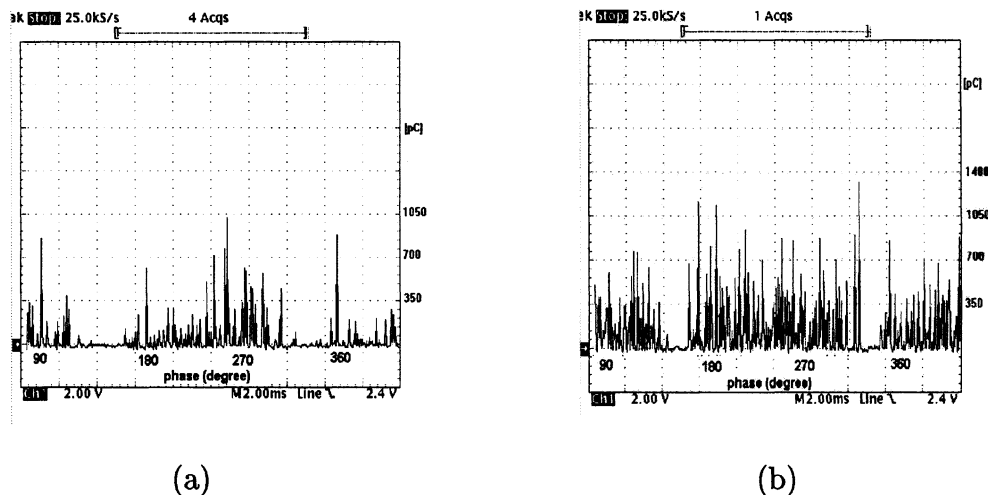


Figure 13. Oscillograms. a, initial stage; b, final stage at 13 kV/mm.

magnitudes of captured pulses on the oscilloscope were also examined to validate pulse magnitudes seen in distributions.

Observations from the oscilloscope were found inconsistent with distribution only on account of pulse count of small magnitude pulses. Investigation with oscilloscope revealed overlapping of many small magnitude pulses (Figure 14a) resulting in no measurement of overlapping pulses causing reduced pulse count for small magnitude pulses in distributions. At 14 kV/mm this effect was very pronounced. Figure 14b shows oscilloscopic record of pulses in one ac cycle with overlapping pulses contributing to a dc shift obtained just before failure of the sample. It can be noticed that PD pulse magnitude in the mid range (marked as “B” in the oscillogram) of active phase region show reduced pulse magnitude, an effect possibly due to high repetition rate.

For PD process interpretation, these effects need to be taken into account to arrive at true PD characteristics.

#### 4 CONCLUSION

THE paper treats a general problem of how a measurement system design and settings influence measurement and interpretation. The importance and use of knowledge about detector and analyzer characteristics (resolution time, detector gain setting and analyzer pulse conditioning technique) for true PD characterization is illustrated with examples from PD experiments on oil pressboard insulation.

As seen from the various examples, high representation fidelity regions in PD distribution depend on the dynamics of the PD process under study and appropriateness of the instrument setting for the given task. Artifacts in acquired PD patterns produced by setting of detectors and measuring system may mask or even change statistical distributions used for automatic PD pattern recognition. This

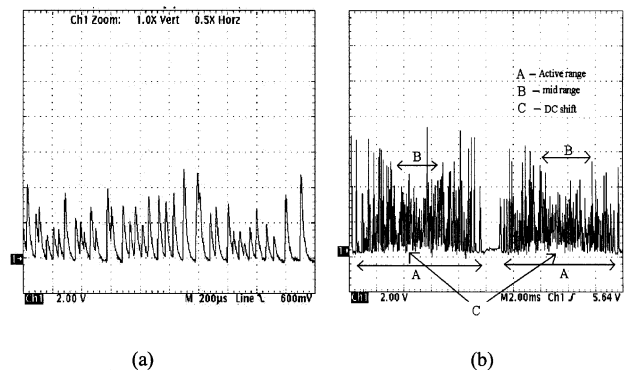


Figure 14. Overlaps in PD pulses. a, pulses in a part of an ac cycle; b, dc shift in pulses in an ac cycle.

may clearly lead to wrong conclusions. The study of measuring system is even more important for insulation systems where high repetition rate discharges may occur.

The instrument used for measurement therefore, needs to be carefully set to obtain best possible representation. Also, detailed documentation of measuring setup and control needs to be provided along with the acquired patterns for interpretation.

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