DISCUSSION PAPER

# Comment and Discussion on Digital Processing of PD Pulses

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## ABSTRACT

**Some of the more salient aspects of the digital processing technology of PD signals are examined. Most of the efforts in this field are concentrated on the application of digital analyzers for pulse height analysis, pattern recognition and identification of the physical phenomena. It is demonstrated that errors in the signal processing unit can lead to dominant mistakes in the interpretation of the test results.**

## 1. INTRODUCTION

THE general availability of the computer based technology makes possible detailed analysis of partial discharge (PD) behavior in HV insulation. Impelled by the virtually boundless novel possibilities of digital processing, new PD measuring instruments that employ various digital techniques have appeared on the market. A detailed overview of the published solutions in the area of digital measurement up to 1992 is given in [1] and other additional papers reflect a rising trend of activity in this field [2–7]. Unfortunately in the course of these rapid developments, some important questions were not posed, and many areas of concern in digitally controlled PD measurement procedures must, therefore, be re-examined. Most of the published results were acquired from measurements on small specimens; only seldom were large test objects considered. The intent of this paper and discussion is to pose key questions on digital processing of PD pulses and to provide some answers, as well elicit further comments from the readers.

## 2. GOAL OF THE ANALYSIS

The first question to be asked is whether we should confine our analysis to the time (frequency) behavior of the discrete PD pulses or also take into account the statistical behavior of the set of pulses. In reply to this question, let us consider Figure 1, which depicts a simplified PD measurement circuit. We can detect only seldom the true shape of the fast [8] PD current $i_{pd}$ under which certain discharge conditions, may approach the form depicted in Figure 2(a). In practice we speak about the apparent charge [15–16] which is related to the current flowing in the measuring circuit, $i_c$ shown in Figure 2(b). In a real situation only $i_c$ is measurable, whose shape is determined to an appreciable extent by the measuring circuit (elements $C_t$, $C_k$ and $Z$ in Figure 1). Analyzing the time or spectral structure of this decoupled current, we can acquire only restricted information on the true time relations of the internal PD process.

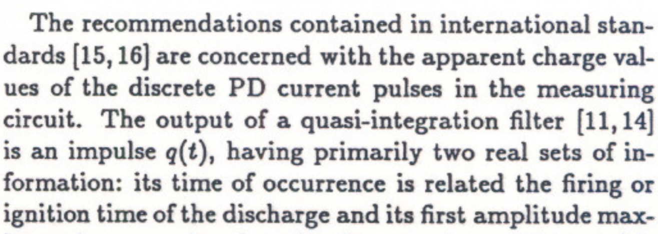


Figure 1. PD detection circuit.

The recommendations contained in international standards [15, 16] are concerned with the apparent charge values of the discrete PD current pulses in the measuring circuit. The output of a quasi-integration filter [11, 14] is an impulse $q(t)$, having primarily two real sets of information: its time of occurrence is related the firing or ignition time of the discharge and its first amplitude maximum is proportional to the charge value $q$, Figure 2(c). The shape of the detected current pulse is considerably modified from the original shape of the discharge impulse

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$i_{pd}$ in the cavity. It is apparent that a digital PD analyzer will simply process the time and amplitude behavior of the output of the quasi-integration filter.

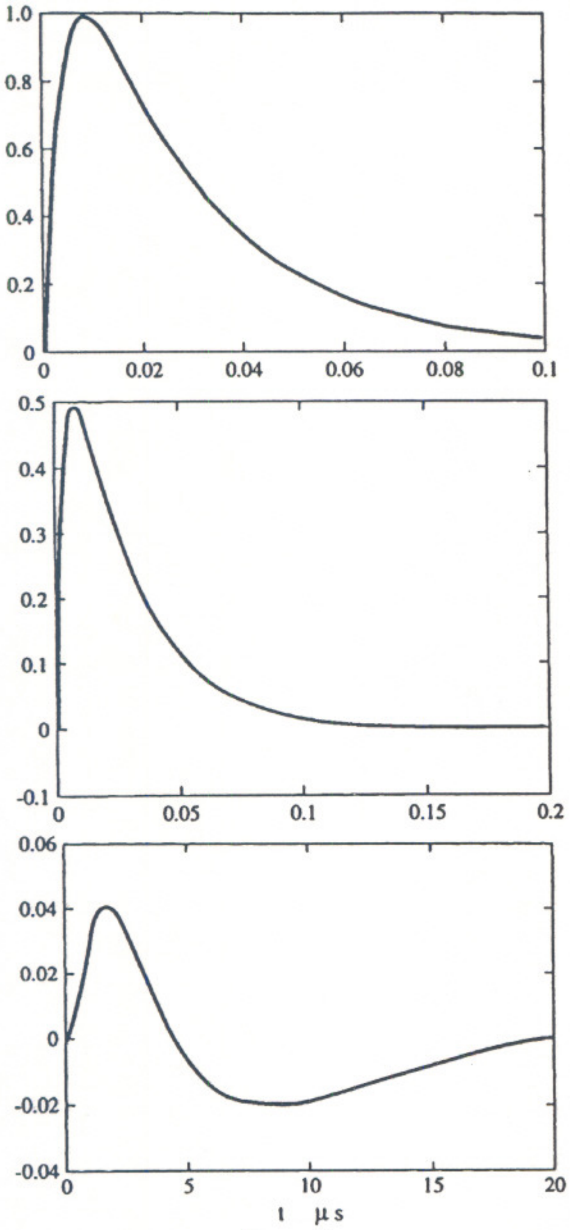


Figure 2.

Pulse forms of partial discharge: (a) current $i_{pd}$ at discharge site, (b) current $i_c$ in the measuring circuit, and (c) quasi-integrated voltage pulse (vertical scale in arbitrary units).

## 3. DESCRIPTION OF THE SIGNAL

The second question concerns the character of the PD signals at the output of the quasi-integration filter. The PD pulse sequence represents a stochastic point process, having two measurable quantities of information: the discharge pulse amplitude which is proportional to the apparent charge (it is not a countable set of values) and the time of appearance or discharge pulse epoch (which is a countable set of values). This stochastic process is not Markovian, because a PD quantity at a given time point or discharge epoch is influenced by other PD quantities that precede the time points before the given point or discharge epoch [2, 7, 11]. The statistical parameters of the stochastic process of the PD pulses also are influenced by the amplitude and shape of the test voltage, since the latter initiates and sustains the PD sequence.

## 4. CRITERIA OF PROCESSING

One may ask the question whether digital processing of PD signals is only a matter of correct sampling and quantification. In designing a digital signal processor, the methods of sampling theory [12] and quantification theory [12] can be used. Unfortunately, in case of the given point process, only one amplitude and one time parameter can be extracted from a given output pulse of the quasi-integration filter. The correct sampling of the output signal results in an enormous redundancy of information and great technical difficulties in the realization. For example, to sample a 400 kHz bandwidth pulse requires a 800 kHz sampler. If we sample a process having a duration of 10 min, we obtain a $8{\times}10^5\times 60\times 10 = 480$ MB data record; moreover this large volume of information may pertain only to a single PD pulse.

A logical solution of this problem is to utilize the technique of triggered processing. In this case a threshold level is set, and the processing is started only if the signal passes this preset level [2, 3, 5, 21]. The processing unit controls the sampling of the signal, and it must identify the time point and the (positive or negative) peak value. In solving this processing problem some difficulties usually arise. For instance, if the length of the pulse to be processed is 10 $\mu$s, and the data acquisition is stopped during this time, we may either lose important information during this time period or obtain wrong information. Figure 3 illustrates such a case: if the processing of the 10 pC pulse $q_1$ inhibits the acquisition step for a period of 10 $\mu$s, the arrival of a 100 pC impulse $q_2$ is not recognized. After this 10 $\mu$s interval the processing$_i$ is completed and a new acquisition (processing$_{i+1}$) step can be initiated. It is clear that the negative queue of the 100 pC pulse $q_3$ will be processed: hence we obtain $-70$ pC as the detected apparent charge. A digital acquisition system with such type of error will yield the pattern shown in Figure 4. It can be discerned, that within the same area there occur both positive and negative values, which constitutes a physical impossibility (the test object was a small polyester capacitor). The very similar pattern of the two opposite polarities demonstrates clearly that there is a problem in polarity processing. It is simple to test a commercial instrument for polarity processing: first we provide a series of simulated positive pulses of 1000 pC at repetition frequency of 300 Hz from a pulse generator. With the threshold limit adjusted at 50 pC, 6 positive impulses will appear clearly on the display. If now another series of pulses with a peak value of 100 pC having a frequency of 10 kHz are added or mixed in, then the system will be seen to experience difficulty with polarity processing; the larger positive pulses will tend to 'flip' intermittently to a negative polarity. From the foregoing simplified consideration it is evident that when the discharge sequence involves discrete pulses separated by short time intervals, the general methods of the digital signal processing may be quite inadequate. Hence the development of special PD pulse processors in the area of discharge measurement is of utmost necessity.

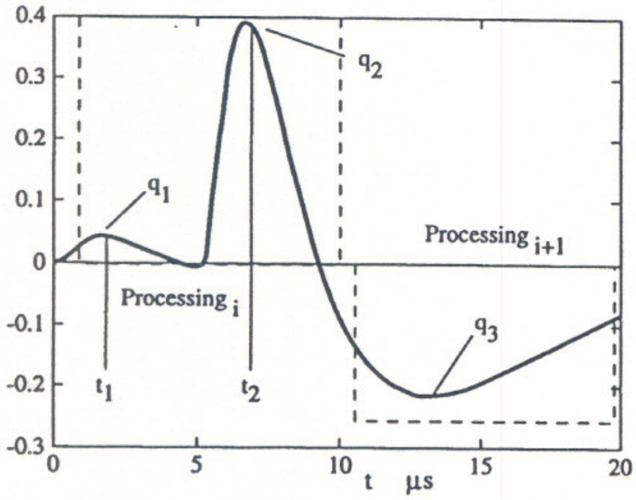


Figure 3.

PD signal processing with an inhibition period of 10 $\mu$s; vertical scale is in arbitrary units.

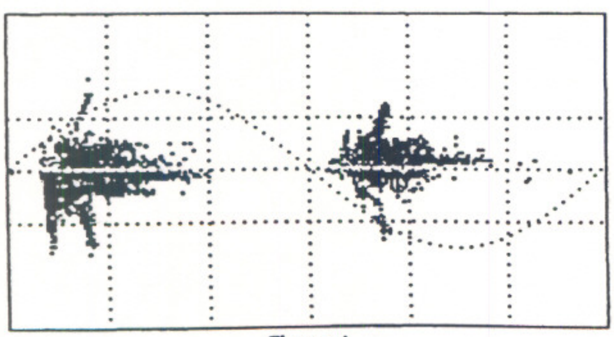

Figure 4.

Incorrectly processed PD pattern, exhibiting polarity errors.

## 5. PURPOSE OF DIGITAL PD ANALYZER

The obvious question to be asked is why a digital PD analyzer ought to be used? In order to gain more information on the life expectancy dependence of insulating systems upon PD onset, it is necessary to obtain as much data as feasible on the intricacies of the PD behavior as a function of time. This involves collection, recording and analysis of vast amounts of PD test data. Since an optimal data acquisition system must be capable of collecting all pertinent information during the test time period [9], this inevitably leads to the use of digital systems.

It is important to point out the difference between certain areas of PD measurements: in the detection and processing of PD pulses emanating from small test objects such as cavities, point-plane electrode systems, *etc.*, the bandwidth of the signals and amplifiers employed is very large (from 1 MHz to $\sim$ 2 GHz), so that the PD current can be processed. The true value of the charge transferred in pC is considered not to be important, and the main information is derived from the pulse discharge patterns. Most of the published work appears to be confined to this area of endeavor. Detection and processing of PD pulses associated with large specimens such as transformers, capacitors and cables, involves the use of reduced bandwidth amplifiers (from 30 kHz to 10 MHz); here the value of the apparent charge is of paramount importance, because the existing standards recommend acceptance limits based on the apparent charge values. Earlier specifications required as well some degree of reproducibility in the apparent charge measurements [10]. With practical measurements on power apparatus and cable specimens, the presence of many different types of discharge sources would confound the pattern recognition task due to the above discussed problem of 'mixed' signals; only a limited amount of work has been carried out in this area [3,4]. In the practice of commissioning of power apparatus and cables on the basis of PD measurements, there remains considerable reticence towards a standardization of a 'purely computerized' type of PD measurement. Thus the display of the maximal apparent charge value by an analog or digital meter remains entrenched as a practical requirement.

## 6. PROBLEMS OF REALIZATION

A correct digital PD analyzer must be capable of recording the following data: the time of occurrence or the discharge epoch of the PD pulses, the first (or second) maximum of the PD pulses (or the integral of the first positive oscillation); the instantaneous value of the test voltage at all discharge epochs and the phase position of the pulses in relation to the test voltage period (*e.g.* with respect to the sinusoidal voltage zero crossing). The prediction of the life expectancy of the specimens must be based not only on the statistical pattern of the PD process at a given voltage, but the on the complete time-voltage statistics of the PD patterns [9]. The latter pattern is a 2-dimensionally approximated probability density function, which is a function of the deterministic process of the applied voltage.

## 7. A PROPOSAL FOR A DATA ACQUISITION PROCEDURE

Based on Figure 3, some pertinent requirements on the processing of a quasi integrated PD pulse may be stipulated: (a) if there is only one pulse in the processing window of 10 $\mu$s ($q_1$), it would seem correct to stop the data acquisition after the signals reach their maxima (and if negative the minima) values; (b) if a second pulse of a higher absolute value arrives during the 10 $\mu$s long processing time, as in Figure 3, the data acquisition can not be stopped and this second pulse must also be processed. Consequently, for the second pulse a principal decision must be taken: a higher PD peak represents more important information than a lower magnitude pulse; hence in our example the $q_1$ impulse must be rejected, and the higher $q_2$ impulse must be processed; (c) to process the second higher PD pulse ($q_2$) two operations must be performed: the maximum (or minimum) of the pulse must be detected, and the incorrectly processed tail end of $q_3$ must be inhibited. If these three conditions are fulfilled, the processing of the PD pulses will provide the necessary resolution and no loss of the relevant charge and polarity information will take place.

## 8. TECHNICAL REALIZATION

The digital acquisition of the pulses in the processing windows does not require the use of the theories of sampling and quantification of stochastic signals, because the discrete pulse on the output of the quasi-integration is a deterministic signal. The statistical parameters consist of the time point discharge epochs and amplitudes of these deterministic pulses. For a fully digital processing system, the sampling criteria are relatively simple: the recommendations of the IEC Standard 270 [14] or IEEE 454–1973 [15] (10% measuring inaccuracy) may be followed and the 1 $\mu$s long rise time edge of the pulses may be sampled at the rate of 100 ns.

Between two sampling steps the processor must adhere to the following steps: When the value of the signal reaches the pre-adjusted threshold level, a trigger signal is generated. If a timer is started at the beginning of the test, the signal content must be now stored (Step 1). In the same interval, the sampling of the signal is started and after 100 ns the value of the signal is stored in an intermediary buffer (Step 2). The next sampled value must be also stored (Step 3) and then compared with the preceding value (Step 4). In case of a positive pulse, a sampled value lower then the preceding one indicates that the maximum is reached and its value must then be stored in the record file (Step 5). If the new value is higher than the preceding one, the procedure must be continued. A 4–5 processor instruction cycle of 100 ns is required; therefore, the instruction cycle must be faster than 20 ns. Special instruments and techniques such as the hybrid analog-digital controlled peak detector, asynchrony logic, *etc.* [3, 5, 7] may constitute additional improvements, but principally the prime requirement of the slow quasi-integrated signal PD signal is that of a fast processing system.

The correct processing of slow integrated PD pulses (length from 5 to 10 $\mu$s) requires fast processing procedures and a carefully designed processing algorithm.

## Contributed Discussions on the Paper.

## 9. DISCUSSION

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To measure PD in an insulation structure adequately stressed requires complex procedures that can be influenced by several factors. The discharge phenomenon itself, occurring inside cavities or gas bubbles or along insulating surfaces, is in some way random, dependent on the statistics of discharge formation, on the insulation memory of past events, on field distortion due to free charges *etc.*

The electric signal produced by a PD is first transferred from its internal source to the terminals of the test object; then it reaches the measuring system where quantitative information is obtained and displayed as a final reading. All these transforms may be considered as different steps of signal processing, that will be examined separately when considering the requirements and the results of a PD test.

In the last decade an evolution has occurred, particularly in Europe, involving at the same time primary metrology and industrial testing. The presence of a large unique market of industrialized countries required the assurance of the product quality, to accredit test laboratories, and to certify measuring instruments. At the moment when a new international standard is being prepared, it may be useful to inquire about the possible consequences of this philosophy on both PD measurements and related tests. Of course it is not meant for international standards to prescribe certifications, but they should make it possible and easy.

*(1) The three stages of processing.*

The basic PD phenomenon always involves the formation of electron avalanches that produce a current pulse. This pulse modifies the voltage across a partial capacitance inside the insulation system and propagates along this system. It can then be detected as a voltage pulse, across the terminals of the test object $C_t$ in Figure 1. A first transfer function may therefore be defined, between the current source of the PD and the corresponding pulse at the input of the measuring system. This transfer function, generally unknown, is sometimes very complex, particularly when the pulse propagates along windings or cables; in any case it depends on the discharge location. It generally produces a stretching on pulse durations and an attenuation of their amplitudes.

At this stage, overlapping may occur between pulses coming within short time intervals from different discharges; pulses may also be affected by noise, mainly due to the test circuit. Signals are successively transmitted along the test circuit, to the measuring impedance in series with the test object and inside the analog part of the measuring system. They are therefore further modified according to the transfer function of this system. Merits and disadvantages of wide-band or narrow-band instrumentation have already been the subject of long discussions that we will not repeat here. It should however be noted that this stage is affected most by disturbances from external sources and by the internal noise of the devices.

The subsequent procedures extract from the pulse signal the most important information it contains, usually its peak amplitude. As is known, this peak amplitude may, under some assumptions, be considered as proportional to the area of the original pulse, through a factor depending only on the parameters of the transfer function of the intermediate systems. The shape of the recorded signal has generally a lower importance, being mainly determined only by the above mentioned transfer function. PD in HV equipment usually is present as a sequence of pulses; therefore, when their amplitudes have been detected and recorded in some analog or digital form, the group of values occurring in a given time period may be analyzed and processed. The most simple analysis was performed in the past by the quasi-peak voltmeters, recording the highest signal amplitudes by means of a circuit with suitable time constants. Oscilloscope presentation techniques later were developed, enabling us to detect the highest repetitive pulse along the period of the applied voltage. On an oscilloscope, PD pulses can also in some cases be distinguished from disturbances, improving the sensitivity.

Using pulse analyzers or adequate software, it is at present possible to build up amplitude distributions for pulses occurring in longer time intervals and to record their modifications in time. The availability of digital systems, with large storage capacity, has recently allowed us to display these amplitude distributions as functions of the time of the pulse occurrence along the period of the applied voltage. This type of processing also reduces or eliminates disturbances with specific characteristics.

*(2) Test requirements.*

For PD tests, some existing standards have already evolved from the 'representation of the worst working conditions' to the requirement of a 'quality of the insulation system'. It was in fact recognized as impossible to correlate the aging effects in a dielectric material to the amplitude of signals detected in a PD test. For acceptance tests of HV apparatus it should be required to have these signals as small as possible under specified stresses, more or less connected to the service conditions. It may be questionable how small the signals should be, in order to be easily detectable and separated from noise. However, this procedure requires a high quality for the design and construction of the insulating structures by controlling their electric field strength at any point.

In terms of the above described scheme, this position gives up any knowledge on the transfer function between an internal PD current pulse and the corresponding voltage pulse at the terminals of the test object. In most of the cases it is in fact impossible to estimate the real dimensions of the PD source and of the cavity where it has been produced. Even more difficult is the evaluation of the chemical or physical deterioration that it will produce during long operating times.

To recognize such difficulties does not however prevent us from researching a better physical knowledge of this stage, particularly in the most simple cases. Theoretical and experimental investigations are therefore necessary and will certainly produce a more confident approach to the PD tests. It should be underlined that the above mentioned position, initially due only to uncertainties in PD measurements, is presently well in line with the most modern views on the quality of HV apparatus. Perhaps in the future new procedures could be proposed, giving the same or better quality assurance, with direct reference to PD intensities.

*(3) Requirements for the measuring system.*

According to the general principle of quality assurance, each measuring device should guarantee the equivalence of its readings with those of similar instruments, within given limits of uncertainty. This is a fundamental condition in order to make comparable the measurements and tests that could be performed on the same test object in different laboratories. This equivalence is generally attained through a traceability to common references (*e.g.* to national standards) and by an estimation of uncertainties based on tests (usually performed on a prototype) in which each influencing quantity is varied over its range of operation.

The present IEC Standard [15] has already indicated a procedure for the calibration of a PD measuring system. It includes the measurement of the ratio between the peak value of the output signal and the area of the input pulse; this ratio has to be determined taking as reference the pulses produced by a suitable calibrator (*e.g.* the charge pulse due to the application of a known direct voltage to a known capacitance). A more detailed calibration procedure is prescribed in the revision of this Standard [16], presently under discussion, which indicates also for the calibrator uncertainty a limit of 3%.

The instrument calibration must be performed for each different test circuit, the result being dependent on the circuit parameters that influence the transfer function between the pulse amplitude at the test object terminals and the instrument reading. To guarantee traceability, the reference pulse generator should then be considered as a secondary standard; its use should follow uniform procedures assuring the prescribed limits of uncertainty as it would be for a calibration performed by an accredited center. Unfortunately, the circuit parameters may influence also the calibration performance.

A rather large uncertainty, of the order of 10 or 20%, may be considered tolerable for instruments used in PD measurements, but it does however require some checking. Usually the above figures, reported in the technical literature, refer only to the repeatability of measurements on the same test object and under the same test conditions so that they can be ascribed more to the behavior of test objects rather than to the characteristics of measuring systems.

*(4) Software validation.*

The above mentioned requirements could be considered as quite obvious, being simple improvements to previous standards, performed in order to attain the requirements of quality assurance. More difficult is the choice of a more or less complete standardization of the third stage of signal processing, which operates on the final series of pulses with different features offered by sophisticated software.

To validate a measurement performed through digital processing, it is not sufficient to calibrate all its computing functions, covering a large range of measuring values and of influencing quantities. It is generally also necessary to test the full software operation in order to recognize its compliance to expectations either by examining its sources and procedures, or by comparing its behavior with that of suitable models.

In any case, these calibrations should remain valid when the instrument configuration or some of the test conditions are modified. They should also assure the absence of possible involuntary or planned misfunctioning in special situations, that could alter a test result. A certification may require the sealing of software to prevent modifications and the presence of a diagnostic program to detect incidental failures. These requirements make a measuring system more complicate and less flexible, reducing its possible uses.

This problem should be examined from different points of view. First of all, the improvements introduced by new techniques on measuring instruments should not be limited by a difficulty in their calibration or in their certification. On the other hand, the present status of this final stage of signal processing produces useful information mainly when a test object presents a large number of pulses with high intensity and when their distribution is changing in time. Experience on different insulation systems shows that these distributions may be used to predict breakdown conditions. This fact makes software very useful for research but less applicable to industrial tests. In this case, also an ability in reducing disturbances through special processing (windows, coincidences *etc.*) may be questionable.

*(4) Conclusions.*

From the previous considerations it appears that different requirements should be recognized to instruments used in research rather than in acceptance tests.

For the manufacturer of a HV apparatus, a test giving only small PD indications cannot be sufficient. He wants to acquire a more complete knowledge of his insulation system, to detect its weak points, to assess its evolution in time. He requires therefore the most sophisticated and complex measuring systems being suitable for identifying and localizing PD. These measuring systems do not require certification, being used for internal research. The reproducibility of measurements can in this case be observed in repeating tests on several similar test objects. Laboratory tests give to the operator a large freedom in changing the test parameters, the test procedure (voltage level, time of application, stress cycles *etc.*) and even the criteria of signal processing. These tests are generally made to breakdown on a special specimen with high stresses arriving often. As these processes may follow different paths, flexibility in the display of results may be highly desirable.

Also the user of an HV apparatus however, when performing field tests on the aging of its insulation, can be interested in complex instrumentation with a complete analysis of test results, taking into account that the working conditions cannot generally be modified. Customers have different interests when performing a PD acceptance test. The measuring system to be used should be simple but adequately certificated by an accredited calibration laboratory; its important features are good sensitivity and low disturbances as the test should demonstrate the practical absence of PD at the voltage levels specified by the standards. The test conditions shall be strictly fixed to assure the reproducibility of the test result. Changes in the display of results should therefore be avoided.

If it would be necessary to consider all these different types of test in future international standards, they should cover separately the different requirements. The definition of successive stages in signal processing, proposed above, is only one way of clarifying these differences.

## 10. DISCUSSION

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Digital signal processing techniques involving the use of high speed analog-to-digital (A/D) converters, as applied to PD pulse-height distribution analysis and pulse counting, have been in use for at least three decades and suitable calibration techniques for digital circuitry have been developed at the time [17–19]. In order to prevent aliasing (inaccurate representation of very rapid rise time discharge pulses), the sampling rates had to be sufficiently high to accommodate all the high frequency components of the incident pulses. Due to the limits in the sampling rates available, the analog data was passed through an analog filter (active) to attenuate the high frequencies. This approach was justifiable since in pulse-height analysis, the principal interest lies in the amplitude of the discharge pulse. [17–19]. The use of microcomputers [20] has facilitated greatly the implementation of pulse height analysis and pulse counting techniques, permitting enormous amounts of PD related information to be obtained with relative ease and little tedium as, for example, in the measurement of the average pulse amplitudes above specific preset levels [21]. However, the use of digital techniques has been confined largely to research work in the area of PD where PD pulse distribution measurements are of principal interest in that they may provide some insight into the insulation degradation process due to discharges and the nature of the discharges themselves [22]. Their application to routine standardized PD tests has been rather limited, because PD detection standards are essentially based on the measurement of the discharge pulse amplitude and its derived quantities of the PD inception (PDIV) and extinction voltages (PDEV) [23, 46]. Since it has not been possible to establish a definite relationship between the discharge intensity and the in-service life of electrical insulating systems employed in cables and power apparatus, the conventional wisdom has always been to insist on the total absence of PD under operating conditions, which in turn favored the establishment and universal acceptance of standardized go/no-go PD tests.

Recent introduction of computerized procedures into commercialized PD detection sets has resulted in equipment that comprises both analog and digital circuitry. For example, the signal to noise ratio of conventional PD detectors may be enhanced by means of suitably designed digital circuitry [1]. Many of the timely questions raised by Osváth in his comments, pertain directly to conventional PD detection circuitry. The pulse forms depicted in Figures 2(c) and 3 presumably represent critically damped and actively filtered outputs from a conventional *RCL* type PD detection circuit. The negative overshoot is difficult to eliminate entirely for all pulses and its presence may result in negative errors should signal integration occur. In practice, positive integration errors are considered to be beneficial in that they augment the apparent sensitivity of the detection circuit, notwithstanding the fact that this may lead to erroneous peak amplitude readings. If digital processing is to be carried out in the case of routine PD measurements, then Osváth is correct in placing the greatest emphasis on the detection of the peak discharge value in that it is this value that is of prime importance in so far as the determination of the PD inception and extinction voltages are concerned for the cable or power apparatus specimens under test.

A frequently overlooked feature of the PD pulse form is its rise time. The response of the PD detectors is contingent upon the rise time of the discharge pulse, which is a function of the overvoltage across the discharge site [24]. When A/D converters are employed for discharge pulse distribution measurements, the response of the pulse detector will be influenced to some degree by the rise time of the incident discharge pulse [25]. Hence, the pulse height analysis system must be calibrated with a pulse having a rise time that falls within the most probable range of values, characterizing the rise time of the actual discharge pulses. Yet most of the published literature on pulse distribution analysis is either remiss in reporting the calibration details, or is not cognizant of their importance.

Osváth justifiably places emphasis on the stochastic nature of the discharge process. The discharge epoch of a given discharge pulse, occurring at a particular discharge site, will be predetermined to some extent by the discharge epoch of the preceding discharge. Any variation in any one of these discharge epochs will thus lead to a precession of the entire discharge sequence, *i.e.* to a migration of the discrete discharge epochs with respect to the sinusoidally applied voltage [26]. Their migration sequence can be accounted for by the stochastic character of the discharge mechanism in that the time of occurrence of each discharge event is governed by the statistical time lag [27]. The stochastic nature of the discharge process leads to unstable discharge patterns (pulse-height or pulse-phase distributions), which pose difficulties when it is attempted to relate these discharge patterns to the type of the discharge sites producing the given patterns. Various expert systems have been utilized in conjunction with digital circuitry in an attempt to relate the observed discharge patterns to actual discharge sources. Statistical preconditioning of the discharge data also has been attempted in order to take into account the stochastic aspect of the discharge process. However, the latter approach may not be entirely free from errors, because a pulse height distribution constitutes essentially a pulse probability density function [28] as Osváth correctly has pointed out.

## 11. DISCUSSION

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Osváth's comment highlights an important issue in the design of digital PD instruments, namely the necessity of using high-speed digital processing to cope with a group of overlapping PD pulses. Such overlapping pulses naturally arise when PD is generated by multiple sources within the device under test and the interpulse spacing is less than the impulse response time of the PD measurement system, *i.e.* is less than resolution time of the instrument as defined in IEC Standard 270.

Osváth correctly views periodic sampling of PD without further processing as inappropriate. He presents an algorithm for processing periodically sampled PD to extract accurately the relevant parameters (*e.g.* PD pulse amplitude and phase of occurrence) from PD pulse measurements such that, should multiple overlapping pulses occur, the amplitude of the largest pulse is recorded correctly. This assumes that the largest pulse causes the most damage to the device under test. Note that, with his approach, the other pulses in the overlapping group will be ignored, causing the measurement of total PD charge to err on the low side. This error will be present in multiple site PD systems regardless of the pulse measurement method used since, statistically, some pulses will always be closer together in time or have amplitude ratios that the measuring algorithm cannot distinguish. Also, depending on the interpulse timing, the amplitude of the succeeding pulses may appear larger or smaller than it actually is, depending if the tail of the earlier pulses adds to or subtracts from the amplitude of the pulse in question. Such an undetectable error also will be present with measurements made of a device with multiple-site PD.

The approach discussed assumes that the PD sensing impedance is 'broad band', *i.e.* has a critically damped impulse response. Many commercial instruments use 'narrow band' sensing impedances (tuned *RLC* circuits exhibiting a damped oscillatory impulse response). If digital PD measurement systems are used with such an impedance, the processing must recover the PD characteristics from the oscillatory waveform. Algorithms for correctly evaluating overlapping PD pulses from such impedances will be considerably more complex than the one proposed by Osváth and may, in fact, not be practical.

Regarding the proposal, based on the PD response shown in Figure 2(c), the 10 $\mu$s processing window used in the example algorithm should probably be 20 or 30 $\mu$s in order to insure that the pulse 'tail' falls below the detection threshold during the processing period. If a 10 $\mu$s window is used, the pulse may be registered as a large positive pulse followed 10 $\mu$s later by a second negative pulse which is actually the tail of the first pulse. Alternatively, 'downstream' processing can be used to reject the second of two pulses separated by exactly the width of the processing window. Note that, should the first pulse exceed the linear range of the A/D converter resulting in a maximum-level reading (all 1's), these later pulses could be used to reconstruct the magnitude of this first over-range pulse if desired.

The algorithm presented in Section 8 does not include such processing windows, even though they are discussed earlier in the paper. The processing window needs to be modified and restart if subsequent pulses are detected within the window so that the tails of succeeding pulses are not erroneously recognized as additional pulses. Also, if the largest pulse is not the first one in the group, the detected phase-of-occurrence will have to be changed to reflect the actual phase of the largest pulse, not that of the first pulse exceeding the threshold.

Further, Osváth's algorithm may run into trouble with PD pulses having wide pulse widths and/or long tails such as can occur under low gas pressures or when the applied voltage is very close to the PD inception voltage [8,29]. The extended pulse tail may be recorded as multiple pulses unless the PD measurement system can be programmed for a longer pulse processing window. Note that the charge contained in such pulses will not be represented accurately by the peak amplitude of the quasi-integrated PD preamplifier since the pulse's frequency spectrum will be contained in the pass band of the preamplifier.

Finally, Osváth appears to assume that his algorithm will be executed in a high-speed microprocessor. For the times he quotes, a hardware implementation using digital registers, comparators, *etc.* under control of a state machine is more economical than a microprocessor. With advanced programmable logic devices, such a custom processing engine could be placed in a single integrated circuit.

*(1) Implications of PD as a Stochastic Phenomenon.*

As Osváth points out, PD is a non-Markovian point process characterized by both short and long term memory with such random variables as PD pulse amplitude, phase or time of occurrence, pulse width, and pulse waveshape [11,29]. As such, complete characterization of the PD source requires a collection of conditional probability distributions relating the random variables describing PD. Depending on the sophistication of the analysis, data from $\sim 5000$ cycles of PD may be needed to generate meaningful results. Generation of such a set of distributions in real time is generally not economical, so practical systems must record the values for the random variables on digital storage media for later off-line stochastic analysis [7,30]. As a minimum, the amplitude and phase-of-occurrence (discharge epoch) of each PD pulse needs to be stored as Osváth notes.

As a stochastic process, PD is inherently subject to random fluctuations in its characteristics, visible in the wide variation in PD pulse amplitudes, pulse-to-pulse spacing, and pulse shapes over time scales ranging from $\sim 1$ s to $\sim 30$ days. Further, many of the sources of PD found in real equipment change or age due to the effects of PD on the dielectrics present. This change results in dramatic changes in the characteristics of PD over time [31–36]. A practical digital PD measurement system has to be able to adapt to such changes automatically while maintaining calibration. This adaptation can include changing the gains of analog preamplifiers and the digitization thresholds in response to changing signal and background noise levels. Self calibration of the measurement system should also be used.

*(2) Other Considerations.*

Externally and internally generated noise that may or may not be synchronized with the power line is a fact of life in testing real systems. Several noise-suppression algorithms have been proposed [37–39]. In a practical system such algorithms must be executed in real time prior to PD pulse measurement and recording.

In many PD measurement situations, the applied test voltage is not necessarily constant, changing either as part of the PD test protocol or due to factors beyond the experimenter's control. Additional information on the test conditions and calibration information can also be stored with the PD data to create a self-documenting data file [40]. For example, the test voltage must be monitored and recorded along with the PD for correlation with changes to the characteristics of the PD. If the test voltage is a clean sinusoid or dc, this monitoring can be limited to periodically recording the root-mean-squared (rms) value of the voltage. For nonsinusoidal voltages, periodic recording of the waveform with intermediate rms value tracking is required.

Measurement time, in most situations, is also a major driving function due to the demands of the production line, maintenance schedules, or the high hourly costs of equipment down time. A historic record of PD status is also desired for equipment performance trend analysis.

Finally, those making the measurements are accustomed to monitoring PD using existing PD test equipment. The users of improved digital PD measurement equipment expect to be presented with familiar measurements in real time in addition to any more sophisticated processing taking place. Given the increasing capacity of moderately priced processors, a preliminary analysis similar to that of current PD measurement systems can be performed on the digitized PD data in real time, and parallel its storage operations.

*(3) Future PD System Implications.*

Digital techniques offer the prospect of providing additional measurement options for the user such as real-time noise suppression and PD location (*e.g.* time domain reflectometry for cable fault location). Future digital PD measurement systems may well employ multiple processors due to the different time scales involved. For example, one can envision a system made up of high speed synchronous logic executing an algorithm such as Osváth suggests for PD pulse acquisition, a high-speed digital signal processor microprocessor for noise reduction and real-time monitoring, a medium-speed microprocessor for system control and for handling the user interface, and a separate medium-speed microprocessor for control of data recording.

## 12. DISCUSSION

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It is known that PD measuring systems used in most HV laboratories may be conveniently supplemented by computer aided systems. Currently most manufacturers of HV test equipment are providing such equipment, though international standards do not give any specific recommendations for such equipment. However, the IEC Publication 270 is presently under revision and digital processing of PD quantities is to form part of the new document. Comparing the international development and trends in the field of digital PD detectors on the one hand and the necessity of new recommendations on the other, the following three sub-division for application of digital PD detectors can be made:

1. The measurement of the apparent charge. To display the test results in a protocol, the recording of specified PD magnitude is necessary. For this purpose the minimum requirements for calibration of the digital detector must be specified.
2. The recording, storage and evaluation of PD quantities. To analyze the PD processes, recording, storage and evaluation of PD pulse related quantities of $q_i$, $u_i$, $t_i$ and $\phi_i$, and their derived quantities and other relevant parameters are necessary. With regard to the foregoing requirements a guide stating the calibration procedures must be developed.
3. Post-processing of the recorded data to evaluate other parameters.

Statistical analysis of the PD activity within the time windows or in the course of time may be used for an in-depth diagnosis of the insulation quality of the test object *etc.* Until the requirements given in (1) and (2) are explicitly stated in the new document, discussion on this topic in terms of procedures or standards is rendered very different. Nevertheless, the particular apparatus committees should be encouraged to treat this subject with relevance to specific test objects.

A digital PD detection is in general based on analog measurement of apparent charge q as treated in the IEC Publication 270. In other words, a digital PD detector is an extension of the analog systems used to record the PD quantities during the tests with ac and dc voltages. As a result, the digital part is used to process analog signals for further evaluation. Depending on the application, distinction can be made between two types of digital detectors, see Figure 5.

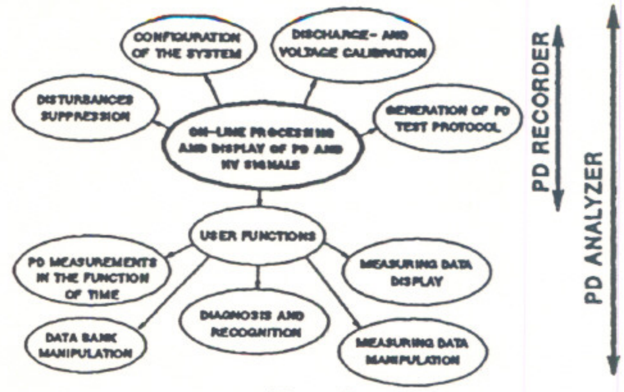


Figure 5.
Schematic structure of a digital PD detector.

*(1) Measurement of the peak value of the PD magnitude.*

Due to the fact that the pulse shape of a discharge is determined by the resonant frequency of the discharge circuit, the digitalization of discharge pulses should not concentrate on the shape of the PD pulse but rather on the peak values of the discharge pulses, see Figure 6.

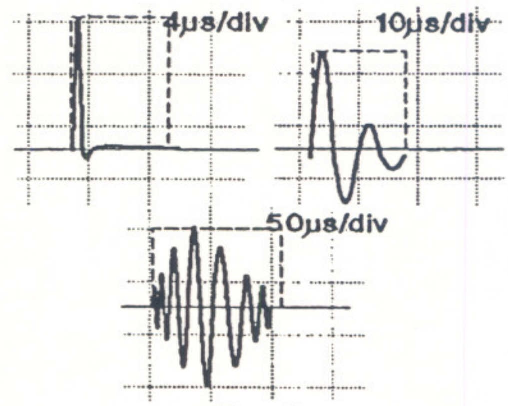


Figure 6.
Output voltage signals for apparent charge in three different PD measuring systems.

The important difference between analog and digital detectors is that digital signals contain no information between individual samples of the measured signal. In consequence, the peak value of the discharge pulse can only be approximated. To obtain the peak value of discharge pulses two measures are recommended. First, after the quasi-integration of the discharge current pulses, using sufficiently high sampling rates $f_s > 10f_2$, the discharge pulses are digitalized and stored as numerical values. To determine the peak value of the discharge pulse these numerical values must be interpolated using mathematical routines to produce a curve similar to the curve recorded by an analog detector. Second, after the quasi-integration of the discharge current pulses and before the digitalization an analog circuit can be used to capture the peak value of the discharge pulse. Using a sample and hold circuit a pulse can be generated with an amplitude proportional to the peak value of the discharge pulse. In this way the resolution time of the digital detector may be adjusted to the pulse resolution of the analog detector only. As an example, it is known that in the case of corona discharges under ac voltage the discharges are symmetrically disposed about the voltage peak, and are of equal magnitude and are equally spaced in time. For a long time this property was a recognized secondary discharge standard.

The importance of correct digitization is emphasized in a forthcoming paper [42]. PD was processed from pulses of a needle-plane electrode system at 40 kV, and various bandwidths and time resolutions. In all cases during 2 minutes, the same well defined point-plane configuration at HV electrode was studied. It is known that this configuration is characterized by stable behavior in PD magnitude and PD intensity. To test the influence of resolution time of digital detector on different PD pulses as detected by different band-pass filter characteristics two bandpass filters were used: wideband of 40 to 400 kHz and narrowband of 70 to 80 kHz. It was found that selecting the correct resolution time of the digital detector for a certain filter characteristic of the PD detector provided correct measurement of the PD magnitudes. On the other hand, a wrong time resolution of the digital detector may falsify the measurement result of discharge magnitude. It follows, from this example, that whole in-depth analysis as is usual by computer-aided processing may be strongly influenced or even falsified by incorrect digitization of PD pulses.

*(2) Display of PD magnitude.*

Similar to recommendations as given for an analog detector, (see IEC Publication 270), a digital detector shall provide the same possibilities to display the individual PD pulses on the screen. Due to the fact, that the actual standards or specifications of different apparatus are assumed on the base of analog PD detection, a digital detector shall continuously quantify the largest PD magnitude in the same way as an analog system. In particular, using digitally-based peak detector the specified PD magnitude should be quantified in accordance to a relationship between reading and the repetition rate for constant pulses.

Principally, after digital processing of a PD sequence a digital PD detector shall be able to display the magnitude of apparent charge as observed during the test. This can be done in the following two ways:

1. by displaying the specified PD magnitude; in this case statistically processed value of PD sequences as observed during the test time will be evaluated. In this case, different numeric procedures can be used to display the PD magnitude, based on the intensity distribution of the PD pulses. In this case the most appropriate statistical parameters have to be selected *e.g.* the mean value of specific percentile quartiles of this distribution, and the mean value of all maximum PD pulses as observed during one second in each power frequency cycle.

2. by continuously displaying the magnitude of a single PD event as observed during the test. Depending on digital processing at least the maximum discharge magnitude is observed during the specified test time. This can be done over a period of one second or over a specified power frequency cycle. It is important, that the manufacturers of digital systems should, however, indicate how the largest repeatedly-occurring PD pulse is displayed.

*(3) Calibration of a digital detector.*

The procedure to calibrate a digital PD detector shall be the same as for an analog system. First, the test object under consideration and the complete test circuit according to IEC Publication 270 shall be set up in which the digital detector is a part of the measuring system. Then, a calibration procedure as valid for analog detectors shall be applied with a calibration pulse magnitude $q_o$. To verify the performance of a digital PD detector, the following procedures would be necessary. Using a single pulse calibrator, the linearity of the measuring ranges for apparent charge must be determined, using a pulse generator with variable rise time, the inequality between the rise time and the upper limit of the filter frequency characteristic must be established.

A digital PD detector should have the same pulse resolution time $T_r$ as an analog system. For a particular test configuration, this time shall be determined as specified in IEC Publication 270. Using a double-impulse or square wave calibrator and a device to measure the time delay $\Delta t$ between two consecutive response pulses, the resolution time of a system can be determined.

As digital PD detector/PD analyzer provides additional capabilities to record many quantities related to PD, the performance of this system should evaluated by additional tests. Such tests should be partly based on the application of stochastic calibrators or calibration procedures as already described in IEC Publication 270. If the digital PD detector/PD analyzer is designed to quantify discharge power $P$, the correct measurement of power frequency voltages should be verified. Furthermore, it is necessary to verify the correct measurement of a number of response pulses, when a specific number of calibration pulses is injected to the system. As a result the following procedures would be necessary to establish the performance characteristics of a PD detector/PD analyzer. Using phase-triggered pulse sequences with a known number of pulses per positive and negative half wave of the power frequency, the response of the PD detector/PD analyzer should be determined. Using a voltage calibrator, the linearity of the measuring range for HV signals could be determined. Using a phase-triggered calibrator, PD pulse phase accuracy with respect to the applied sinusoidal voltage should be determined. And using phase triggered pulse sequence, calibration for derived quantities could be carried out.

In the case of time behavior analysis of PD quantities a compression of registered data can be applied. For this purpose different data reduction methods could be used. Therefore manufacturers of digital systems should, however, indicate the principles used for data compression. Moreover, the correctness of the procedure as used for data reduction has to be tested by an adequate calibration procedure.

## 13. DISCUSSION

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Osváth is to be commended for exploring weaknesses in the techniques currently used for digital PD data acquisition. In particular, he has shown that the use of a simple trigger and acquisition period can produce data artifacts when PD pulse intervals are shorter than the measuring system's pulse resolution time. The cause of the problem is investigated and a solution is proposed. As the author has pointed out, the problem and proposed solution apply principally to pseudo-integrating measurement systems, where the measuring system's bandwidth is the primary factor in determining the system output waveshape.

The following comments and questions relate to these proposals.

A digital PD analyzer should sample the entire test voltage waveform rather than those voltage values at the instant of the discharge. This should not place an undue burden on the acquisition circuitry or memory since the bandwidth of the test voltage is relatively limited. With the proposed technique, valuable information could be lost if the voltage waveform is significantly distorted and discharge is infrequent.

How does the proposed algorithm fare when there is a sequence of more than two pulses that cannot be completely resolved by the measuring system? Apparent charge and pulse count information would be lost if all but the highest pulse were discarded. Would the existing methods not be preferable in these situations?

The proposed algorithm seems to sacrifice pulse count accuracy in favor of apparent charge accuracy. Little justification is given for this selection. Are there cases where a more precise pulse count could be more important and informative than apparent charge information? Is there an algorithm modification that could be made to provide a more accurate estimate of pulse count?

As the author explained, part of the problem with existing digital PD acquisition systems is due to the difficulty in determining precisely the start of a new PD pulse. The low-pass characteristic of pseudo-integrating amplifiers needed for apparent charge measurement places a minimum on the pulse resolution time, and to some extent irreversibly obscures apparent charge values and epochs of pulses which do not meet the resolution time. The author has chosen to place the digital processing circuitry in the signal path after the pseudo-integrating amplifier and this attendant loss of information. Would it not be more appropriate and effective to maintain a relatively broad bandwidth signal path until the digital signal processing circuitry is employed, at which time pulse trigger information could be evaluated better? Assuming that dynamic range limitations could be overcome, the DSP circuitry could perform the pseudo-integration needed for apparent charge measurements.

The advent of fast data acquisition, memory, and digital signal processing circuits has made near real-time analysis of PD signals a possibility. Is the state of current technology such that more robust and effective DSP techniques can be employed to resolve closely spaced pulses, rather than the techniques proposed, based on the well-defined impulse response of the common pseudo-integrating measuring system?

## 14. DISCUSSION

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In Section 8, Osváth states that the theories of sampling and quantification of stochastic signals is not needed because the discrete pulse is deterministic. The author then describes a problem setting in which a stochastic signal is present. The author may not have considered any theories in signal processing, but that does not mean that they do not apply. The following aspects must be considered when defining a signal processing algorithm.

Sampling theory must be considered when making these measurements. In Section 4 it is stated that one needs to sample the PD pulse at a frequency equal to twice its bandwidth. This is not correct. Sampling theory says to sample at a frequency equal to twice the frequency of the highest frequency signal component. This may not always be practical, but the signal must be sampled at a frequency high enough to obtain an accurate result. It is a well known fact that sampling a pulse at a frequency equal to its 3 dB upper cutoff yields unsatisfactory results. Sampling frequencies used in practice are, at minimum, 4× the 3 dB upper cutoff and more often as high as 10× the upper 3 dB cutoff.

The author is measuring a random amplitude of a PD pulse. This certainly is not deterministic in a sense. One might argue that the pulse shape is deterministic. However, when studied in detail, the pulse shape also must be modeled in a stochastic manner. In fact, an instrument used for on-line PD measurements in generators exploits this fact. Evidently the author has not considered the presence of noise in his algorithm. This adds yet another stochastic element. To describe the PD pulse as deterministic is totally incorrect.

Two closely spaced PD pulses are described as deterministic. This must mean that one knows when they will occur. In Section 3 the author states that PD is a stochastic point process; this is true. I find it curious why this description is abandoned and the assumption made that the process is no longer stochastic. There exists signal processing algorithms that can distinguish two closely spaced PD pulses, measure both amplitudes and the time between them. However, the design of these algorithms requires making statistical assumptions (obtained through measurement) about the nature of the signals.

The author suggests an ad hoc signal processing algorithm to measure PD. While this algorithm might loosely be named a signal processing algorithm, it is not based on any signal characteristics. A suitable algorithm is the following [42]. Pass the digitized signal through a filter with the following characteristic

$$H(\omega) = \frac{\beta\overline{a^2}S^*(\omega)}{\overline{a^2}\lambda|S(\omega)|^2 + N(\omega)} \qquad (1)$$

The amplitudes and epochs are determined by the amplitude of the peaks and time between the peaks. This filter has the following effects. It deconvolves closely spaced PD that are randomly spaced. It gives a LMMSE of the amplitude and time separation. The filter also mitigates noise present in the measurement. This algorithm could be readily implemented in real time using some of the more advanced signal processors available such as an FIR processor; a general purpose DSP chip would not be suitable because it could not handle the throughput.

# 15. DISCUSSION

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The comments raise some questions about the digital acquisition of PD pulses which seem to be pertinent to PD measurement bandwidths of $\gtrsim$ 3 MHz. The authors may be interested to know that their concerns have been addressed over the past 20 y with regard to PD measurement in generators and gas insulated switchgear. In these applications, it is now customary to use ultra-wide bandwidth (UWB) PD detection, with a 100 to 1000 MHz bandwidth. The primary reason for the UWB technique is to improve signal-to-noise ratio, and/or to locate where the PD is occurring in the apparatus [43,44]. However, there is an added advantage in that the signal measured with the UWB technique typically has relatively little ringing, and the pulse duration (including ringing) is much shorter (from 100 ns to 1 $\mu$s) than from conventional PD detectors. Thus the probability of PD pulse superposition, *i.e.* two PD pulses occurring within the same 1 $\mu$s interval, is very much lower.

In the UWB instruments for PD pulse detection which we have been designing since 1980, we have taken great care to ensure that only the first peak of the pulse is recorded, and that there are cross-inhibits to prevent, for example, positive pulses being characterized as negative pulses because of ringing [45]. The on-line PD test now is used routinely on many thousands of motors and generators around the world to detect stator winding insulation problems. Although there are some disadvantages in UWB measurements, in particular from pulse attenuation and calibration difficulties, using UWB eliminates many of the problems outlined above.

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