A Simple Metric for Assessing the Severity of Partial Discharge Activity Based on Time-Sequence-Analysis-Discharge Level Patterns

Brian G Stewart[a] and Lily Yang
School of Engineering, Science and Design, Glasgow Caledonian University,
Cowcaddens Road, Glasgow G4 0BA, UK

Martin D Judd, Alistair Reid, and Richard A Fouracre
Department of Electronic and Electrical Engineering, Royal College Building
204 George Street, Glasgow G1 1XW, UK

[a]E-mail : b.stewart@gcal.ac.uk

(Received December 12 2006, Accepted December 17 2006)

This paper introduces a partial discharge (PD) severity metric, *S*, based on the evaluation of time-sequence PD data capture and resulting Time-Sequence-Analysis Discharge (TSAD) level distributions. Basically based on an IEC60270 measurement technique, each PD event is time stamped and the discharge level noted. By evaluating the time differences between a previous and subsequent discharge, a 3D plot of time-sequence activity and discharge levels can be produced. From these parameters a measurement of severity, which takes into account dynamic or instantaneous variations in both the time of occurrence and the level of discharge, rather than using standard repetition rate techniques, can be formulated. The idea is to provide a measure of the severity of PD activity for potentially measuring the state of insulation within an item of plant. This severity measure is evaluated for a simple point-plane geometry in SF_6 as a function of gap distance and applied high voltage. The results show that as the partial discharge activity increases, the severity measure also increases. The importance of future investigations, quantifications and evaluations of the robustness, sensitivity and importance of such a severity measurement, as well as comparing it with typical repetition rate assessment techniques, and other monitoring techniques, are also very briefly discussed.

Keywords : Partial discharges, Data processing, EHV insulation

1. INTRODUCTION

Partial discharge (PD) monitoring of insulation systems and power plant has now become a key condition monitoring tool for many power utilities and power customers. Normally, for AC systems, the assessment of ϕ-q–n PD patterns for evaluating the condition and integrity of insulation provides insight into the type and nature of the potential fault conditions (see for example[1-4]). As outlined in the IEC60270 PD standard[5], normally, the peak discharge levels (usually in pC) and an assessment of PD repetition rates can provide an experienced engineer with a means of evaluating the severity and potential consequences of the discharges on the insulation. As an example such techniques have been used in high voltage DC systems by Morshuis and Smit[6], where a cumulative PD product ($pCmin^{-1}$) is defined from the PD repetition rate and the discharge levels. A decision of the state of the insulation is then taken if this value exceeds a certain threshold limit. Obviously, this can also be applied to AC measurements of PD.

Clearly in HV AC systems, ϕ-q–n patterns fail to include a measure of the time repetition rate of the PD pulses from cycle-to-cycle. Repetition rate is an important diagnostic indicator in terms of evaluating discharge severity in any insulation system. It is therefore important that preferably simple quantitative means of including repetition rate along with discharge magnitudes in the diagnostic representation of PD should be further explored. However, use of such a metric appears to have received little attention. In particular, the concept that the time differences between individual PD pulses and the actual size of the PD pulses should be used within a metric to determine a more informative assessment of plant condition than that provided by independent repetition rates and discharge level values. The fact that new metrics which measure the combined discharge level and repetition rate have not received attention may be due to the fact that sequential capture of fast PD events often requires expensive equipment, can be limited by the data capture techniques employed or the limited sampling rate available. This however is continually changing as data capture technology is advancing at rapid rates.

This paper attempts to introduce a novel, yet simple, means of quantifying the severity of AC PD events through evaluating a simple "*severity metric*", S (measured in pCs^{-1}), associated with the quantification of time – sequence – analysis - discharge level representations of the PD activity. It should be noted that Pulse Sequence Analysis (PSA) techniques have been well known in PD measurement and assessment for some time e.g.[7]. Using concepts based on PSA this severity metric effectively measures the rate of discharge, but takes into account explicitly the time differences between successive PD events and the discharge magnitude as well. It is therefore not the same as a cumulative product measurement. This new quantifiable metric S is an integrated or convoluted measure of the discharge levels and their repetition rates, and may provide a better or more accurate quantifiable value to assess the severity of any insulation system under stress. The metric was applied to a simple point-plane discharge geometry with a variable point-plane distance and shows that the value S increases in an expected manner as the PD activity increases.

The structure of the paper is as follows. Section II introduces the concept of time-sequence-analysis discharge plots and the experimental set up used for the investigations. Section III defines the new severity metric S, section IV presents the metric results for simple point-plane gap variations in SF_6, section V discuss the potential future work in relation to the metric, whilst section VI is summaries the main results of the paper.

2. TIME-SEQUENCE-ANALYSIS-DISCHARGE-PLOTS AND EXPERIMENTAL SET-UP

A conventional PD product of repetition rate and PD discharge magnitude level is often used to quantify PD severity. Unfortunately these measures do not include accurately a precise relationship between the actual time difference between successive PD pulse events and the charge associated with the PD. Basically repetition rate measures provide a simple time-averaged rate of discharge. In many cases this may be suitable for some practitioners. To include individual time differences between successive PD events, and therefore a more inclusive and more accurate measure of frequency repetition the concept of a new severity metric is developed as follows.

Intuitively, the time delay between each PD event is associated with the repetition of the PD. Therefore, the smaller the time difference between successive PD events, the more severe the ensuing damage or degradation of the insulation. Similarly, the larger the PD magnitude, the larger or more severe the damage of and the greater the likely rate of the degradation. If these factors can be combined explicitly into a simple metric then a more accurate means of quantifying PD product or severity may be possible. Fundamentally, such a metric will implicitly take into consideration repetition rate.

To achieve this the first thing is to take a sequential series of time stamped PD events (t_n, Q_n), where t_n is the time of the PD event and Q_n is the measured apparent charge. Consider three sequential PD events occurring at times t_{n-1}, t_n, and t_{n+1}. Two time delays are calculated for the value of t_n, namely the time difference between the n^{th} PD and its predecessor $n-1$ i.e. $\Delta T_{n-1} = t_n - t_{n-1}$ and also between the successor $n+1$ and the n^{th} PD i.e. $\Delta T_n = t_{n+1} - t_n$. A three dimensional time-sequence plot is then evaluated for every PD event based on the coordinates $(\Delta T_n, \Delta T_{n-1}, Q_n)$, where as above Q_n is the PD magnitude of the event at time t_n.

In order to produce PD data for analysis, a point-plane PD geometry in SF_6 was used. Figure 1 shows the test cell arrangement used in the experiments. The experimental set-up is shown in Fig. 2. The PDs were measured using an IEC60270 system which was connected to a LeCroy Wavepro 7300 digital oscilloscope. The scope was controlled using custom LabView software, which allowed triggered, multi-record continuous time-stamped PD data to be captured and downloaded to a laptop computer for data processing.

As an example of the results, Fig. 3 shows a typical time-sequence-analysis-discharge (TSAD) distribution plot, i.e. a distribution of points $(\Delta T_n, \Delta T_{n-1}, Q_n)$, associated with the point-plane PD geometry in SF_6.

The plot in Fig. 3 allows a graphical understanding of the distribution of the magnitude of individual PDs and their time relationship between preceding and successive PD events. This figure shows that over all 50 Hz capture cycles there are many cycles where PD pulses occur within the same cycle period i.e. < 20 ms, and also many PD pulses occur with a time difference around 20 ms i.e. repeatable pulses separated approximately by the cycle period. However there are many pulses which have occurred at time differences greater than the cycle period, indeed there are instances where there are no discharges for times of up to 4 cycles of the 50 Hz supply voltage.

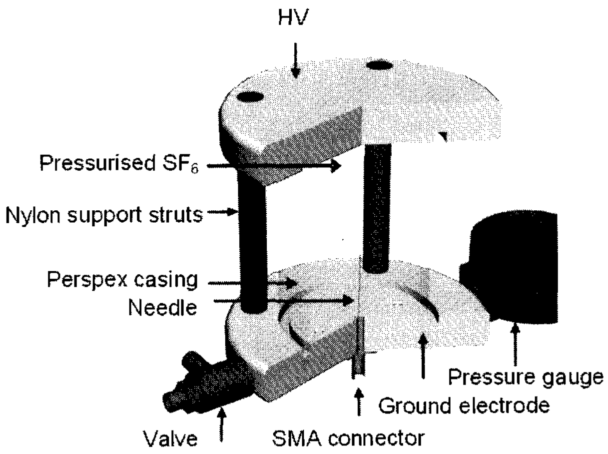

Fig. 1. Profile of SF_6 test cell arrangement.

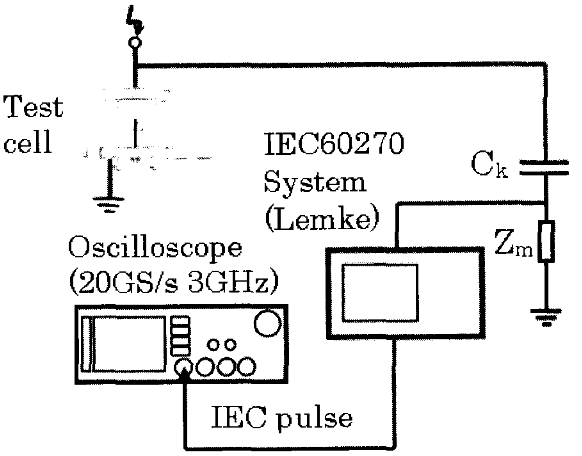

Fig. 2. Experimental test set-up.

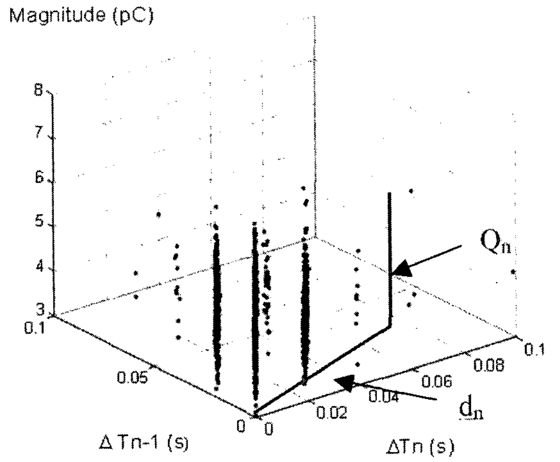

Fig. 3. Example of a TSAD plot for a point-plane gap in SF_6. The parameters which are used for defining the severity metric for each discharge are also displayed.

Obviously, as the applied high voltage is increased the TSAD patterns will change and it will be expected that much more PD activity will occur within individual power cycles over the sequential data capture period. This will result in more clustering points with values of ΔT_n and ΔT_{n-1} less than 20ms. Clearly, over time, such an increased activity will have a more "severe" or detrimental effect on insulation.

3. DEFINITION OF A SEVERITY MEASUREMENT *S*

With reference to Fig. 3, it is possible to define a severity measure *S*, which takes into consideration the PD charge magnitude and also, implicitly, a measure of the time-frequency rate associated with each single PD event. In this paper *S* is defined as:

$$S = \frac{\sum_{n=1}^{N} \left(\frac{Q_n}{d_n} \right)}{C} \tag{1}$$

In equation (1), Q_n, is as before, the apparent charge of each measured PD, N = number of consecutive PDs measured, C = number sequential cycles of the power supply over which PDs are measured, and d_n is defined through

$$d_n = \sqrt{(\Delta T_n^{\ 2} + \Delta T_{n-1}^{\ 2})} \tag{2}$$

S therefore has dimensions of pCs^{-1} and is effectively a measure of the discharging "current" causing damaging and/or arising as a consequence of damage within the insulation system. The quantity d_n is a measure of the time magnitude associated with each PD event as evaluated in the TSAD diagram. One could of course define d_n differently, i.e. $d_n = (\Delta T_n + \Delta T_{n-1})$ or $(\Delta T_n + \Delta T_{n-1})/2$. However, the reason for choosing equation (2) is based purely on the time and charge magnitudes arising from the 3D plot distributions. In this respect, d_n is a non-linear "weighted" time-pulse-sequence value based on the time differences between previous and successive PD pulse events. It is also important to realise that if d_n is to be defined in one of the alternative ways, it would not change the general tenet that an increase or decrease of ΔT_n and/or ΔT_{n-1} would influence *S* in similar ways. If Q_n is small or large and d_n is small, i.e. PDs which occur close together in time within a cycle, then these points will contribute in a more significant way to increasing the value of *S*. Conversely, if Q_n is small or large but d_n is large then these points will contribute less to the overall value of *S*. Therefore, in essence, *S* is a normalised measure over the measurement cycles of the effective discharge rate associated with repetitive PD activity.

3. APPLICATION OF *S* TO SIMPLE POINT_PLANE GEOMETRIES

TSAD plots and evaluations of *S* were made for three different point-plane gap sizes in SF_6 under different applied high voltages. Gap sizes of 2.5 cm, 3.5 cm and 4.5 cm were selected for the experiments. Figures 4-6 display a number of the measured TSAD distribution plots for the gap sizes and for a variety of applied voltages.

These graphs show that as the voltage increases, then as expected, the rate of PD activity and the magnitude of the PDs increases. Table 1 shows the calculated value of the severity metric *S* for a number of different applied voltages.

Table 1. Measurement of S as a function of gap size and applied voltage.

Gap Size (cm)	Applied Voltage (kV)	Severity Measure *S* (pCs^{-1})
2.5	11.4	1081.1
2.5	12.4	9272.1
3.5	12.4	253.1
3.5	13.5	5984.7
3.5	15.5	16618.0
4.5	16.4	848.9
4.5	17.3	1231.2
4.5	19.5	5333.5

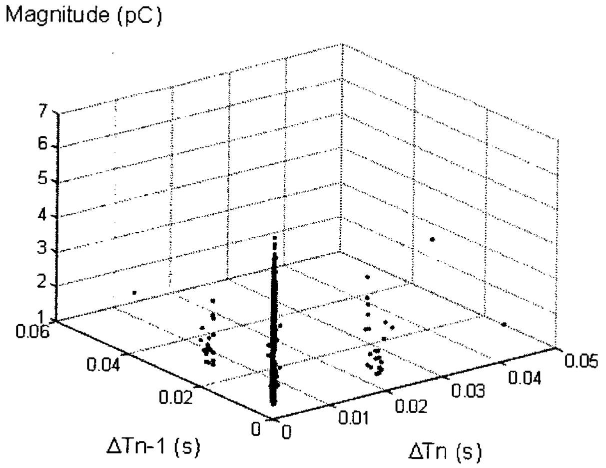

Fig. 4a. TSAD plot for gap =2.5 cm at 11.4 kV.

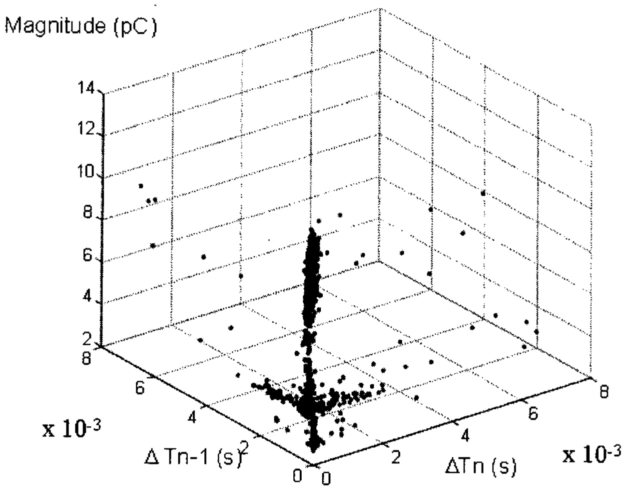

Fig. 4b. TSAD plot for gap = 2.5 cm at 12.4 kV.

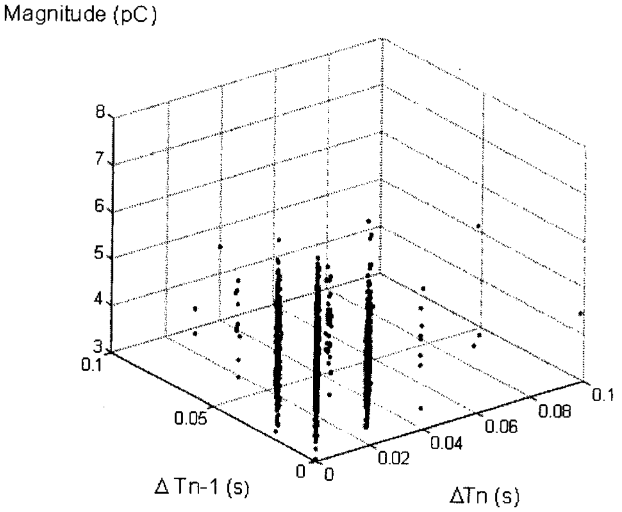

Fig. 5a. TSAD plot for gap = 3.5 cm at 12.4 kV.

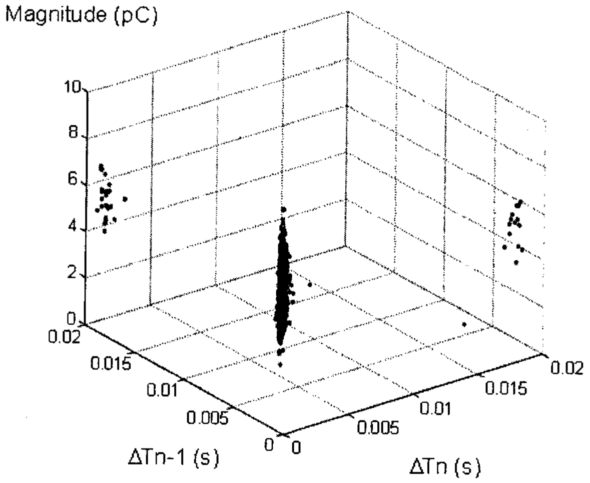

Fig. 5b. Typical TSAD plot for gap = 3.5cm at 13.5 kV.

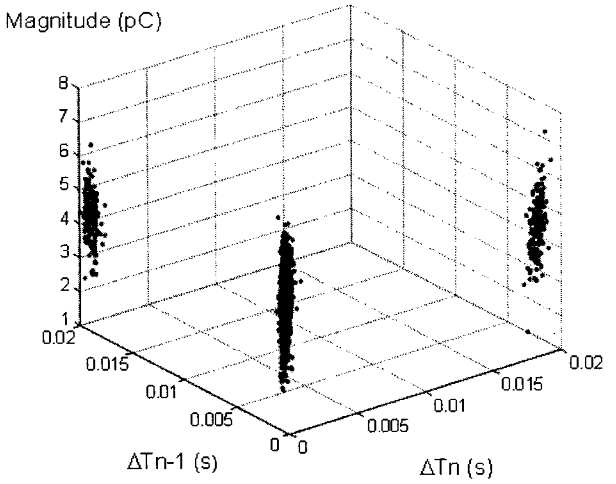

Fig. 6a. TSAD plot for gap = 4.5 cm at 16.4 kV.

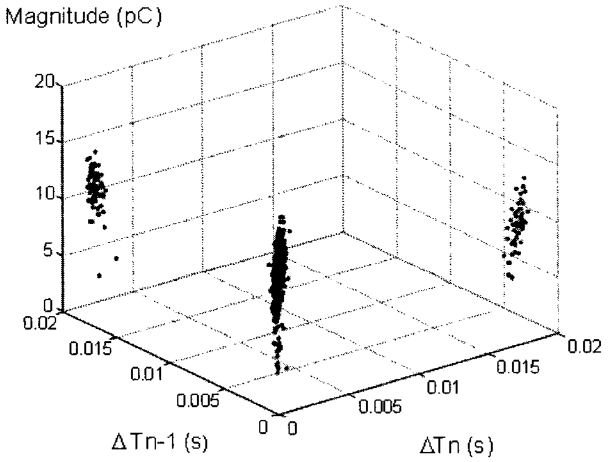

Fig. 6b. TSAD plots for gap = 4.5cm at 19.5 kV.

It is clear that the severity measure S increases as the voltage increases and this is consistent with increased PD activity. There will be a relationship between gap size, voltage and S, but it can be seen that S does appear to be a representative quantitative measure of the activity seen on the TSAD plot. This may be particularly important to high voltage plant monitoring where voltage and gap size (i.e. the local E field) is not known. Table 1 indicates that the severity correlates well with increased electric stress at the defect.

5. DISCUSSION

Though S behaves in way that is anticipated, it requires deeper analysis and investigation in terms of its importance in assessing the quality of insulation degradation, particularly in relation to determining "good" or "bad" insulation. Clearly it does appear to correlate with the electrical stress, which is the key driver in relation to insulation degradation processes. In addition, the use of the TSAD plots themselves as a diagrammatic and additional tool for PD diagnostics requires further attention. Certainly, the plot provides a measure of PD activity and potentially, the distribution of time-sequence-analysis discharge points/clusters may be indicative of particular insulation faults or fault characteristics over time. Whether S, or its variants, provide a better quantification of the underlying physical and chemical mechanisms associated with PD is worthy of consideration. However, the relationship between S and the large number of variable parameters requires to be determined. Similarly, a comparison between S and standard repetition rate discharge level products is required in order to ascertain the differences, distinctions and nuances that may exist in their quantification and assessment of degradation. Such an investigation would determine whether a more complex time-sequence analysis evaluation of severity is indeed different from a time averaged repetition rate severity technique. In addition the relationship between -q-n pattern variability, the type of insulation fault characteristic, and the actual visible or electrical insulation damage occurring requires to be quantified as a function of S. The ultimate goal is to provide a measurement S, similar to a repetition rate discharge level product, which indicates the quality and/or lifetime expectancy of the insulation or plant item under test. However, as there are potentially so many variables to contend with in the measurement of partial discharge activity, this is undoubtedly **not** a simple task!

6. CONCLUSIONS

This paper has presented the concept of a severity measurement S based on time-sequence-analysis-discharge level plots of PD activity. This metric attempts to include the frequency of occurrence of PDs and the PD magnitude at the individual pulse-timing levels rather than the normal use of repetition rate and apparent charge product considerations. Though alternative definitions may be considered, it does appear that S behaves in an expected fashion in relation to increased PD activity and also increased high voltage. As discussed above, further evaluation of S, its comparison as a metric in relation to other PD techniques, and also its variability in relation to effective condition monitoring assessment and diagnostics of insulation is part of future work.

ACKNOWLEDGEMENT

The authors wish to acknowledge the funding provided for this research work by the Engineering and

Physical Science Research Council (EPSRC), Grants GR/S/86747 (UoS) and GR/S/86760 (GCU).

REFERENCES

[1] F. H. Kreuger, E. Gulski, and A. Krivda, "Classification of partial discharges", IEEE Trans. Electrical Insulation, Vol. 28, No. 6, p. 917, 1993.

[2] E. Gulski and A. Krivda, ''Neural networks as a tool for recognition of partial discharges'', IEEE Trans. Electica Insulation, Vol. 28, No. 6, p. 984, 1993.

[3] E. Gulski, "Discharge pattern recognition in high voltage equipment", IEE Proc. Sci., Meas. & Tech., Vol. 142, No. 1, p. 51, 1995.

[4] N. C. Sahoo, M. M. A. Salama, and R. Bartnikas, "Trends in partial discharge pattern classification: A survey", IEEE Trans. Dielectrics and Electrical Insulation, Vol. 12, No. 2, p. 248, 2005.

[5] IEC International Standard 60270, "High voltage test techniques – partial discharge measurements", International Electrotechnical Commission (IEC), Geneva, Switzerland, 3rd Edition, 2000.

[6] P. H. F. Morshuis and J. J. Smit, "Partial discharges at dc Voltage: Their mechanism, detection and analysis", IEEE Trans. Dielectrics. & Elecrical Insulation., Vol. 12, No. 2, p. 328, 2005.

[7] M. Hoof and R. Patsch, "Pulse sequence analysis: a new method for investigating the physics of PD-induced ageing", IEE Proc. Sci. Meas. & Tech., Vol. 142, No. 1, p. 95, 1995.