Statistical Analysis of Partial Discharge Phenomena—Time of Occurrence Distributions

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Abstract

This paper presents time-of-occurrence (phase) distributions of individual pulsating partial discharges (PDs) which occur in a point-dielectric gap in air for ac voltage conditions. It is determined that the pulse phase distribution is adequately modeled by a normal (Gaussian) distribution. Based on such best-fit normal distributions, estimated mean values of the phase and the standard deviations are given for the individual PD pulse distributions. For the alternating voltage case, the spread of time-of-occurrence distributions of succeeding pulses are universally broader than that of preceding pulses. PD pulse separations are non-uniform in phase. Further, if one assumes the usual sinusoidal waveform, then the voltage separation of PD pulses are also seen to be non-uniform.

Introduction

Partial discharge (PD) measurements serve as an important tool for improving the reliability of HV-insulation systems. The assessment of insulation failure of HV equipment using PD measurements requires the interpretation of the PD measurements themselves. The statistical characterization of pulsating PD signals has been shown[1-3] to play an important role in understanding PD phenomena. The development of diagnostic systems which utilize statistical PD data for pattern recognition is important for the identification of types of defects in electrical insulation. As PDs comprise a large variety of physical phenomena, one of the most difficult aspects of the interpretation of the PD phenomena is the randomness of the time-resolved PD pulses. This paper attempts to analyze the PD signals from the point of view of characterization via probabilistic distributions. As a result of a newly-developed PD recording system which continuously records all PD pulses that occur, high-resolution distribution data of the time-of-occurrence of individual PDs are obtained for analysis. Because of the extended recording period of this new system, such distribution data are smooth in appearance, and individual pulse components are identifiable. The distribution data of the pulsating PDs when ac voltage is applied to point-dielectric gaps in air are given and compared. The individual pulse phase distribution data is characterized by a normal distribution. Optimal estimates of the mean phase and standard deviation are derived.

Experimental Conditions

The schematic diagram of the experimental setup is shown in Fig. 1. A zero-crossing detector is utilized to obtain the phase of occurrences of the PDs, and digitized data are collected by a computer. The PD was generated between the point and the dielectric epoxy by applying a continuous sinusoidal alternating voltage at 60 Hz to a stainless steel point electrode. The tip radius is about 50 μm and the gap distance is 0.5 mm ±0.01 mm. The insulating gas is air at a pressure of 100 kPa. The surface of the epoxy resin with Al_2O_3 filler rests on top of the stainless steel disk plane. The RC time constant of the integrator is about 20 μs (C=100 pF, R=200 kΩ). The integrated PD waveform is summed together with 20 μs wide time marks from a zero-crossing detector. The PD digitizing system uses a multifunction data acquisition board to continuously acquire the waveform which carries both PD and time mark information at a sample rate of 1 million samples per second with a resolution of 12 bits.

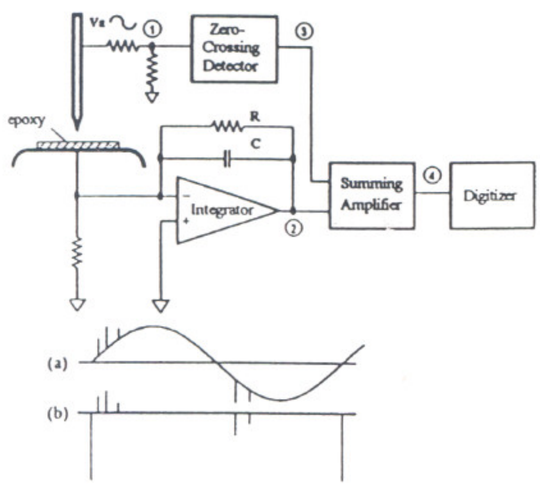


Fig. 1. Experimental arrangement for the study of PD characteristics and the measurement of the time-resolved pulse amplitudes. (a) A typical waveform showing superposition of the voltages from test point ① and ②. (b) A waveform seen at test point ④ which is the sum of the voltages from test point ② and ③.

Time-of-Occurrence (Phase) Distributions

Figure 2 shows the time of occurrence (phase) distributions of individual PD pulses for the gap voltages of 1.79 kV, 1.95 kV, 2.15 kV, 2.40 kV, 2.70 kV, 3.00 kV.[4] The data at each voltage level were collected consecutively for approximately 5 minutes. Both the number of positive and negative PD pulse distributions per ac cycle increase as the voltage increases, but, at a different rate.[5] The number of positive PD pulse distributions per cycle increases from one (1.79 kV) to six (3.00 kV), while, the number of negative PD pulse distributions per cycle increases from seven to seventy. The number of positive and negative pulse distributions are dependent on the supply of the initiatory 'first' electrons which control the statistical characteristics of the PD activity such as time of occurrence with respect to the phase of the applied ac voltage[6].

Normal Distribution Modeling

The PD pulse distribution data were analyzed to determine the function which gave the best fit of the data. The best fit was determined to be that provided by a normal (Gaussian) distribution. The normal distribution has a probability density function $f(y,\mu,\sigma)$ given

by $$f(y,\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{1}{2}(\frac{y-\mu}{\sigma})^2}$$

where μ and σ are the mean value (of the phase) and the standard deviation, respectively. In probabilistic terms, the normal distribution is classified as a symmetric, moderate-tailed distribution.

Because of its universality and optimal statistical properties, the method chosen and used herein for normal distributional model fitting was that of least squares fitting. From a strictly functional point-of-view, the equation for $f(y,\mu,\sigma)$ above is a non-linear function in two variables, μ and σ. The least squares methodology provides estimates for μ and σ which have the property of

minimizing $$\sum_{i=1}^{n}(y_i-f(y_i,\mu,\sigma))^2$$

where y_i is the raw data and n is the number of points y_i. Thus the estimates that result will yield that normal distribution which provides the closest fit—in an equi-weighted least square sense—relative to the raw pulse data traces.

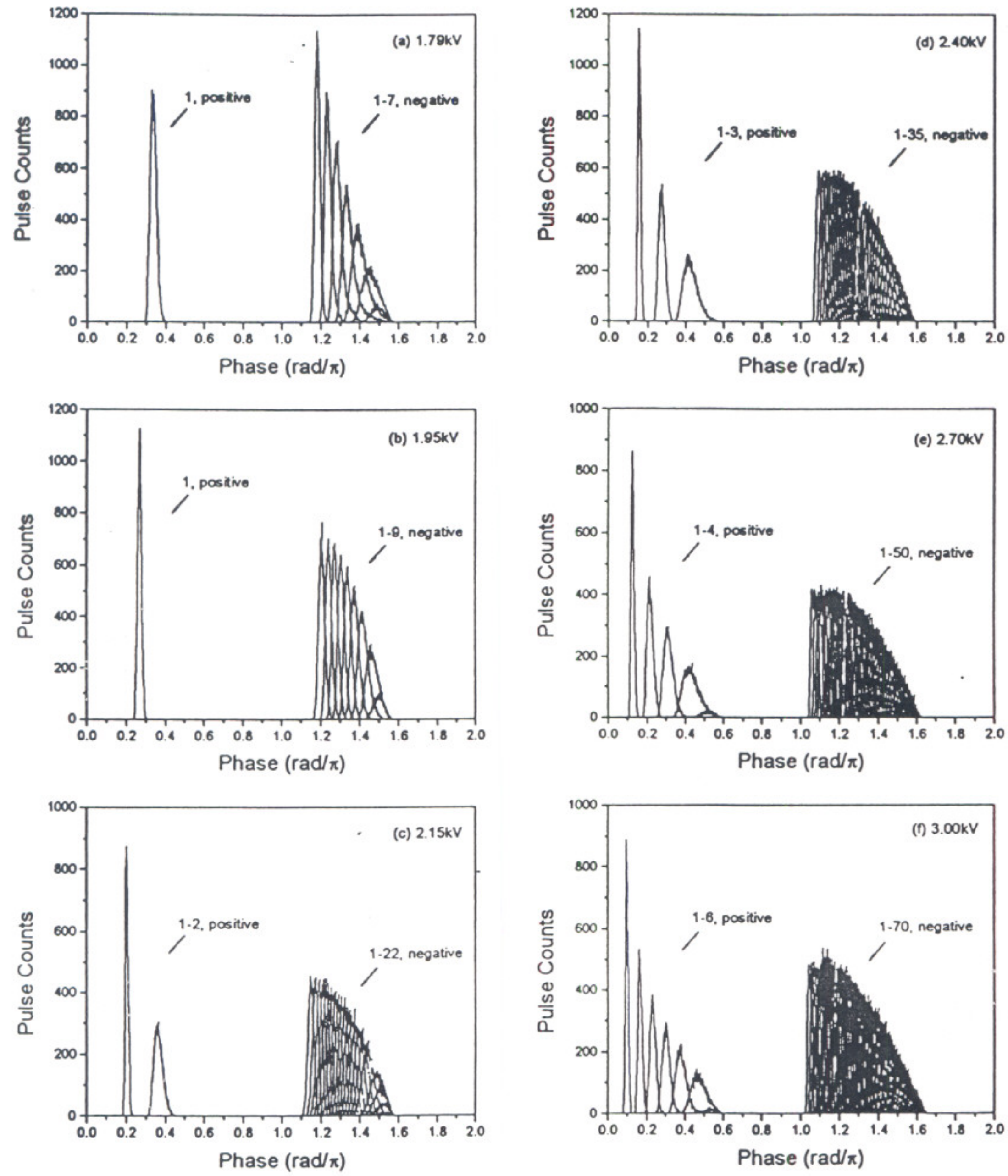


Fig. 2. Individual PD phase distributions in air (gap distance = 0.5 mm ±0.01 mm, frequency = 60 Hz). Gap voltage: (a) 1.79 kV; (b) 1.95 kV; (c) 2.15 kV; (d) 2.40 kV; (e) 2.70 kV; (f) 3.00 kV. The numbers (*1, 2, 3, …*) identify the individual pulse distributions within the positive half cycle or negative half cycle of the sinusoidal alternating voltage.

Such non-linear fits were carried out for individual PD pulse traces under each of the 6 voltage conditions—210 fits in all. The results of the fits for the negative PD pulse traces for the 1.95 kV voltage condition is presented in Fig. 3. Although there are individual traces which exhibit mild skewness and hence provide opportunities for improved fits (the subject of a future paper), by and large, it is clear from Fig. 3 that in general the PD pulses are adequately modeled by the normal distribution.

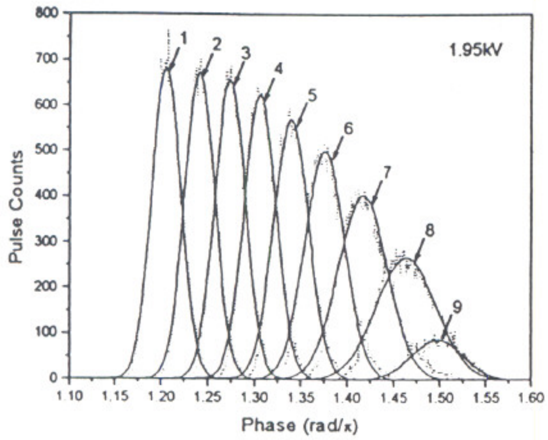


Fig. 3 Best-fit normal distributions (solid lines) of negative pulses in Fig. 2 (b). Dotted lines are experiment data.

Mean Phase Value and Standard Deviation Analyses

Mean phase values and standard deviations obtained from the normal curves fitted to the data in Fig. 2 are shown in Fig. 4 (a) and Fig. 4(b). Fig. 4 (a) shows the pulse distribution identification numbers versus their mean values. The non-linear character of the plots in Fig. 4 (a) indicate that the mean phase values are not increasing uniformly with pulse distribution sequence; that is, the separation between the mean phase values are seen to be larger for the initial and final values in the distribution sequence compared to the intermediate values. Fig. 4 (b) shows the standard deviations versus the mean phase values of the individual PD pulse distributions. Note from Fig. 4 (b) that the standard deviations increase with the increase in mean phase values. This increase can be attributed, in part, to the cumulative influence of the preceding pulses on the succeeding pulses through charge deposition on the insulating surface and creation of the residual space charge in the gap. The non-linear character of the standard deviation depends critically on the nature of the distribution of the pulse separation which will be addressed in a future paper.

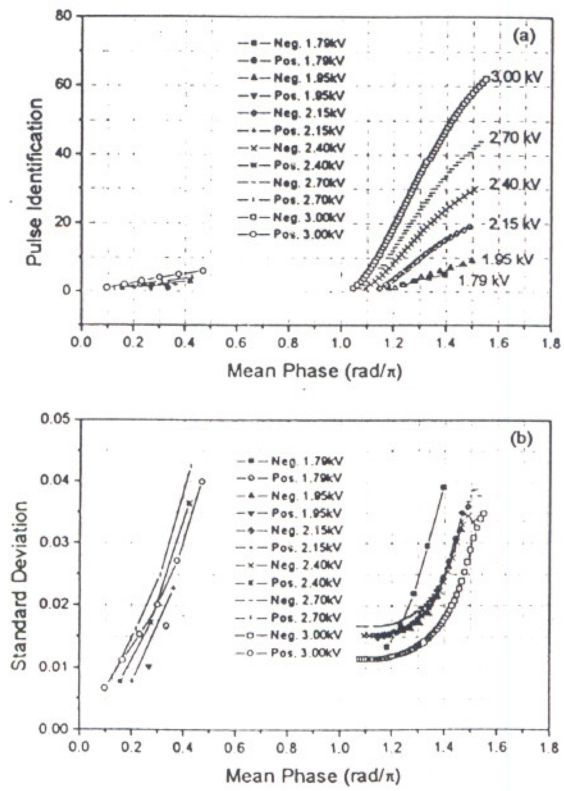
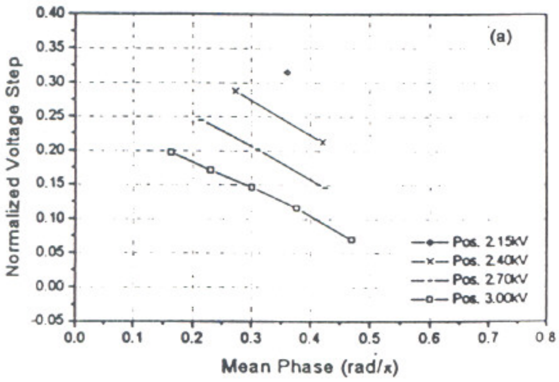


Fig. 4 (a) Pulse identification numbers of the individual pulse distributions versus mean phase values. (b) Standard deviations of the individual pulse distributions versus mean phase values.

Figures 5 (a) and 5 (b) show the voltage separations (voltage steps) on the normalized sinusoidal waveform (i.e. voltage amplitudes normalized to unity) between the mean phase values of adjacent Gaussian pulse distributions. The step sizes show a non-linear decrease with the pulse sequence. When the mean phase value is close to 1.5 (rad/π), the voltage steps approach zero. The results presented in Fig. 5 are particularly significant because they show that in this case the mean phase values do not universally follow the simple model of a constant voltage step size which theoretical considerations infer.



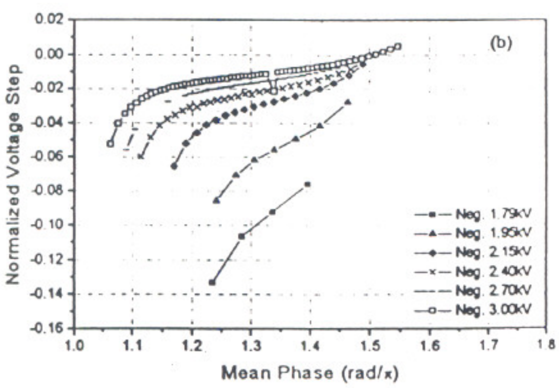


Fig. 5 Voltage steps on the normalized sinusoidal waveform between the mean phase values of adjacent Gaussian pulse distributions: (a) positive half cycle, (b) negative half cycle.

Conclusions

With some exceptions due to mild skewness, time-of-occurrence (phase) distributions of pulsating PDs when ac is applied to point-dielectric gaps in air tend to follow a normal distribution. Based on estimates derived from best-fit normal distributions, it is seen that PD pulse separations are non-uniform in phase. Further, if one assumes the usual sinusoidal waveform, then the voltage separation of PD pulses are also seen to be non-uniform for the experimental conditions of point-dielectric gaps under ac voltage.

For the alternating voltage case, the spread of time-of-occurrence distributions of succeeding pulses are universally broader than the preceding pulses; that is, the standard deviations of the individual PD pulse distributions increase with increasing mean phase value. This spread increase can be attributed, in part, to the cumulative influence of the preceding pulses on the succeeding pulses through charge deposition on the insulating surface and creation of the residual space charge in the gap.

References

1. Richard J. Van Brunt, "Stochastic properties of partial-discharge phenomena," *IEEE Transactions on Electrical Insulation*, vol. 26, pp. 902, 1991.
2. Richard J. Van Brunt, P. von Glahn, and T. Las, "Non-stationary Behavior of Partial Discharge During Discharge Induced Aging of Dielectrics," *IEE Proceedings of Science Measurement Technology*, vol. 142, pp. 37, 1995.
3. Richard J. Van Brunt, Peter von Glahn, and Tadeusz Las, "Anomalous stochastic behavior of partial discharge on aluminum oxide surface," *Journals of Applied Physics*, vol. 81, pp. 840, 1997.
4. Yicheng Wang, Xiaolian Han, Richard J. Van Brunt, and etc., "Digital Recording and Analysis of Partial Discharges in Point-dielectric Gaps," presented at 1998 IEEE International Symposium on Electrical Insulation, Arlington, Virginia, 1998.
5. Xiaolian Han, Yicheng Wang, Loucas G. Christophorou, and Richard J. Van Brunt, "Characteristics of Partial Discharges on a Dielectric Surface in SF_6-N_2 Mixtures," presented at Eighth International Symposium on Gaseous Dielectrics, Virginia Beach, Virginia, 1998.
6. Lutz. Niemeyer, "A generalized approach to partial discharge modeling," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 2, pp. 510, 1995.

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