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Recent Developments at NIST on Optical Current Sensors and Partial Discharge Diagnostics

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Introduction

This is a summary of a presentation given at the 1992 Workshop on Advanced Substation Equipment Diagnostics sponsored by the Electric Power Research Institute (EPRI) in Palo Alto, California. Research activities at the National Institute of Standards and Technology (NIST) on development of advanced optical current sensors and partial-discharge diagnostics are briefly described. More detailed information about the research underway in these areas at NIST can be obtained from the publications cited here in the list of references. The purpose of this presentation is to draw attention to the NIST projects and discuss their relevance to the improvement of measurements applied to electric-power systems, especially those used in substations.

The first activity discussed here is concerned with the use of optical fiber techniques to measure current. The second is concerned with a new approach to analyzing partial-discharge (PD) data that should prove useful in improving the reliability of pattern recognition schemes that are under development to identify the characteristics of defect sites in the insulation where the discharges occur.

Optical Current Sensors

Considerable interest appears to have emerged on the use of optical sensors for various electric-power applications as evident, for example, from two recently held workshops on "Optical Sensing in Utility Applications" sponsored by EPRI. Two groups have been formed within the IEEE Power Engineering Society to develop standards for optical current transducers (OCTs).

The operation of these sensors is based on the Faraday effect and has been discussed thoroughly in a review by Day and Rose [1]. The principle of operation is indicated in Figure 1. When linearly polarized light is passed through an optically active (Faraday) material immersed in a magnetic field $\vec{B}$, the plane of polarization will be rotated by an angle θ given by

$$\theta = \int_L V\vec{B}.d\vec{l}, \tag{1}$$

after traveling a distance L. Here the factor V is usually a constant material parameter known as the Verdet constant. Since the integral on the right hand side of Equation (1) is proportional to the current that generates the magnetic field in cases where the path L is a loop around the conductor, θ is also proportional to current. Thus an optical measurement of θ is also indirectly a measurement of the current. An example of a system that uses this concept to measure current is shown in Figure 2. In this case, the optically active material is actually a fiber with N turns.

The utilities are motivated to develop and implement use of the optical sensors for several reasons. First of all, optical measurement procedures are relatively immune to electromagnetic interference and are thus well suited to cases where measurement of electrical quantities must be made in an electrically noisy environment. In comparison with conventional current measurement methods that employ transformers on high-voltage lines, optical sensors that use the magneto-optic effect tend to be more compact and explosion-proof. Many of the problems associated with insulating the instrument under high-voltage conditions are avoided. The output from an opto-electronic measurement system is also usually directly compatible with standard digital recording instrumentation. Moreover, it may be possible to use a single OCT for both revenue metering and overcurrent protection, thereby eliminating the two optimized current transformers presently used for these applications.

The use of optical current sensors in substation equipment is still being tested. Both Tennessee Valley Authority (TVA) and Asea Brown Boveri (ABB) have shown that, for revenue metering, the OCTs that they have developed yield results that compare favorably with those obtained from current transformers [2]. Several manufacturers such as (ABB), Square D, and 3M are now marketing, or have plans to market OCTs based upon bulk glass sensors that are suitable for utility applications. The optical current and temperature sensors are the most advanced of the optical sensors. Optical voltage sensors are still largely experimental and tend to have limited dynamic range. The use of OCTs to detect overcurrent transients still has problems and will require more testing.

There are technical challenges that remain before wide-spread use of optical sensors will become acceptable to the utilities. For example, optical techniques tend to be more susceptible than transformers to certain environmental influences. In particular, effects of vibration and temperature variation can produce errors exceeding limits specified by the standards for instrument transformers. Although some manufacturers claim to have overcome these problems, it appears that further testing is required to verify the measurement system stability under conditions of practical interest. The advantages and disadvantages of optical current transducers are summarized in Table I. Presently, OCTs used for power-system monitoring are not stand-alone units, i.e., they are part of redundant configurations that employ more than one measurement method. Reliability must be unequivocally demonstrated in order to gain acceptability. For revenue metering, traceability to NIST is required. This necessitates the development of new calibration methods.

In the case of optical voltage sensors, there are many problems that need to be overcome. The voltage sensors currently used are very sensitive to temperature and can only be used at relatively low voltages. Use of these sensors for high-voltage measurements can, therefore, only be considered in conjunction with voltage scaling. Those voltage sensors that can withstand full voltage, such as Kerr cells, have problems with the development of internal space charge under ac and dc conditions, and are presently limited to measurement of impulse voltages.

Through the research conducted at NSIT, significant advances have been made to improve the sensitivity and stability of optical sensors, and efforts are underway to transfer these techniques to industry. At this time, NIST has a joint project with (TVA) to develop OCT characterization tests and calibration techniques. The possibility is also under consideration for formation of a cooperative research and development agreement with Square D, (ABB), and 3M, for characterization of commercial OCTs. There is interest within NIST to develop new high precision OCTs and optical voltage sensors and to improve the methods for testing and calibrating these devices. Future work should include investigations into the relevant properties of various newly discovered electro-optical and magneto-optical materials. There appears to be promise for achieving sufficient sensitivity with some bulk-type sensors to allow detection of relatively weak transient currents associated with partial-discharge activity in power systems. More information about the ongoing NIST work on optical current sensors can be obtained by contacting:

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Partial-discharge Diagnostics

Low-level pulsating partial-discharge (PD) phenomena are known to occur at defect sites and weak points in high-voltage insulating systems. The occurrence of PD is often the prelude to insulation failure resulting in electrical breakdown. Additionally, PD can be a source of undesirable electromagnetic noise and can lead to formation of corrosive and toxic chemical by-products.

Although standards for PD measurement have been in existence for many years (IEC Publication 270, 1968), these standards pertain mainly to certification of high-voltage equipment at the time of installation. Existing standard measurement procedures have questionable applicability to the periodic or continuous monitoring of substation equipment during operation, e.g., bushings, transformers, busline, and breakers.

As evident from the large number of publications, conferences, and workshops that have recently appeared on this subject, there appears to be a world-wide interest in improving partial-discharge measurements that are applied to a variety of systems both for factory testing and online monitoring. There is considerable effort underway now, especially in Japan [3–6] and Europe [7–9], to develop "smart" PD measurement systems that use data on the statistical properties of PD to identify the type of defect in an insulating system responsible for the observed discharge activity. Statistical data on PD pulse-height and phase distributions can be used to define "patterns" that are fed into computers which employ neural networks or other schemes that are designed to recognize patterns. Thus far, the reliability of pattern-recognition methods has been hampered by the use of relatively crude, unresolved statistical data and a failure to understand the factors that control the observed complex stochastic behavior of PD.

The problems associated with PD measurements can be broken down into three stages as indicated in Table II; namely detection, signal processing, and stochastic analysis. Although there has been research activity at NIST on all three stages [9], the present discussion is focused on new developments related to the third stage.

Recent research conducted at NIST [10–14] has shown that PD phenomena are, in general, complex stochastic phenomena that not only exhibit significant statistical variability in amplitude and phase, but are also characterized by nonstationary behavior and effects of pulse-to-pulse or phase-to-phase memory propagation. Under many conditions, the PD phenomenon is sufficiently random or chaotic that it would appear to be impossible to define PD pulse patterns that can be correlated meaningfully with particular physical or chemical characteristics of the discharge site.

Recognizing this problem, scientists at NIST have recently developed new methods for quantifying the stochastic behavior of chaotic pulsating phenomena like PD that show promise for providing "patterns" needed for meaningful and reliable PD pattern recognition [14–15]. The methods involve determinations of sets of *conditional* pulse amplitude, phase-of-occurrence, and integrated charge distributions together with related correlation coefficients and expectation values. The results from this type of analysis can reveal memory effects that are uniquely characteristic of PD phenomena. By this approach, it is also possible to assess nonstationary behavior that is associated with discharge-induced "aging." Conditional distributions can also be more readily predicted in terms of physical mechanisms than the unconditional distributions determined by the traditional multichannel analysis methods. This has been demonstrated by recent Monte-Carlo simulations of the phenomenon [16–17].

A diagnostic representation of an ac-generated PD phenomenon is shown in Figure 3. Shown in this figure are the applied ac voltage (assumed to be sinusoidal), PD pulses with indicated amplitudes and phases, and local electric-field strength at the site where the discharge occurs. Positive and negative discharge pulses can occur whenever the field strength exceeds the threshold values E_I^+ and E_I^- respectively. When a discharge pulse occurs, it deposits charge at the site which then reduces the field below the threshold value. A significant fraction of the charge deposited by a

PD event will, under most conditions, remain at the site to affect the initiation and growth of subsequent discharge events. It can thus be seen that memory effects play an important role in controlling the stochastic behavior of PD. These memory effects are unique to PD phenomena and can, in fact, be used to distinguish PD from other types of electrical noise.

Memory effects are revealed from a determination of various conditional probability distributions functions. The distributions are conditional in the sense that the properties of a PD event, e.g., its amplitude, phase, or pulse shape, are recorded only if earlier events are known to satisfy specific conditions. Examples of conditional and unconditional phase distributions for individual negative PD pulses are shown in Figures 4 and 5. Figure 4 shows the results from a measurement of PD generated by applying an ac voltage to a point-dielectric discharge gap. Normalized unconditional (dashed line) and conditional (points) phase distributions are shown for the first, eight and sixteenth pulses. The conditional distributions correspond to the indicated restricted ranges of values for Q^+ which is the total charge associated with all PD events that occurred during the previous positive half-cycle. Consistent with the expectations implied by the diagram in Figure 3, it is seen that the larger the value of Q^+, the sooner in phase will be the occurrence of PD events on the next half-cycle. Similar results from a computer simulation of the PD phenomenon are given in Figure 5.

The types of distributions shown in Figures 4 and 5 can be used to define a multidimensional pattern that can be used for identification purposes. Conditional distributions should improve the reliability of pattern recognition because they inherently contain information on pulse correlations that is absent in the phase-resolved PD data obtained by the more conventional methods.

Up to the present time, stochastic characterizations of PD phenomena by the NIST method have only been carried out under reasonably well-defined conditions in the laboratory. The main obstacle to applying this method to analysis of PD data acquired in the field is simply that of acquiring the necessary data. A reliable stochastic analysis generally requires a continuous record of data from many cycles of the applied voltage, typically more than 10^4. Moreover, the data need to be digitized in proper format during the recording process for subsequent analysis by computer. Devices presently used to record PD data, e.g., digital storage scopes and multichannel analyzers, neither acquire enough data nor store it in the proper manner required for stochastic analysis. Before stochastic analysis can be applied, it will be necessary to prerecord PD data or transfer it online to a computer for storage and subsequent analysis. The instrumentation for doing this is under development and not yet available commercially.

Given a sufficiently long data record of PD amplitude and phase, a complete stochastic evaluation of the data can be performed using algorithms developed at NIST. This evaluation involves sorting of the PD data into "bins" as it is read sequentially into the computer. Each bin corresponds to a particular conditional or unconditional distribution in phase, integrated charge, or amplitude. The distributions are then examined to determine possible nonstationary behavior, i.e., time dependent changes in the stochastic properties such as might result from discharge-induced changes in the physical and chemical characteristics of the site. In general, the distributions determined by this method are not independent. An appropriate consistency analysis can be performed to determine that they satisfy the expected mutual relationships. The conditional distributions can also be used to compute correlation coefficients that quantify the degree of correlation among successive PD events.

In order to use the results of stochastic analysis for possible site identification, it is necessary to define and generate "patterns" based on the conditional distribution data and related correlation coefficients. It is also necessary to identify these patterns with particular types of defects or aging mechanisms in the insulating system. The pattern recognition analysis itself requires development of a data base of stochastic patterns for PD that apply to specific types of equipment, e.g., cable connectors, transformers, bushings, etc. In the "learning phase," stochastic patterns together with corresponding defect identifications must be fed into a neural network or other identification system. The reliability of the pattern recognition scheme must be tested using data from an "unknown" source, e.g., generated by computer simulations or from laboratory measurements.

In evaluating the effectiveness of pattern recognition schemes, a number of fundamental questions will need to be addressed. For example, can changes in stochastic behavior of PD be related to known changes at a defect site? How unique are the PD patterns generated from determination of conditional distributions? How does the probability for correct defect recognition increase with increasing refinement of the stochastic characterization? Finally, once the method is proven, there will be questions about its cost effectiveness when applied as a diagnostic for practical systems encountered in substations. Are there savings to be realized by doing PD measurements that involve stochastic analysis and pattern recognitions?

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Table I. Advantages and Disadvantages of Optical Current Transducers

Advantages:

- intrinsically safe – all solid dielectric construction
- complete optical isolation
- no hysteresis or saturation effects
- wide dynamic range
- lightweight
- outputs compatible with digital signal levels

Disadvantages:

- sensitive to environment: temperature & pressure (vibration)
- lack of standards
- expensive

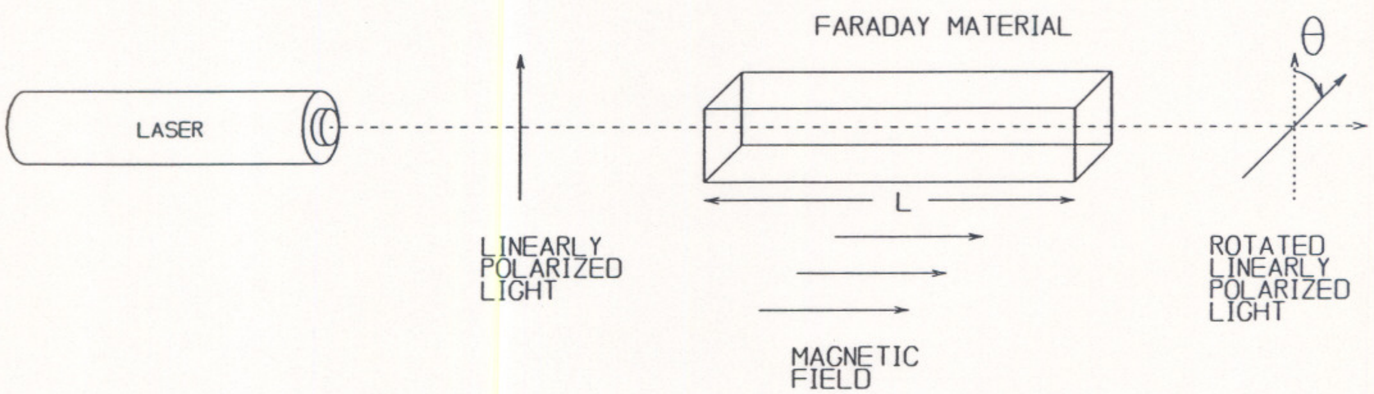
Table II. Different Stages of PD Measurement

1. Detection
   - Electrical
   - Optical
   - Acoustic
   - RF Emissions

2. Signal Processing
   - Noise filtering
   - Phase correlations
   - Pulse amplitude determination
   - Time-domain reflectometry

3. Stochastic Analysis (Pattern Recognition)
   - Unraveling memory effects
   - Assessment of nonstationary behavior
   - Generation of multidimensional "patterns"
   - Neural network

THE FARADAY EFFECT



$$\theta = \int_L V\vec{B} \cdot d\vec{l}$$

Figure 1 – The Faraday effect. When linearly polarized light from a laser passes through an optically active material of length L parallel to the direction of an applied magnetic field, the plane of polarization of the light will be rotated by an angle θ as shown.

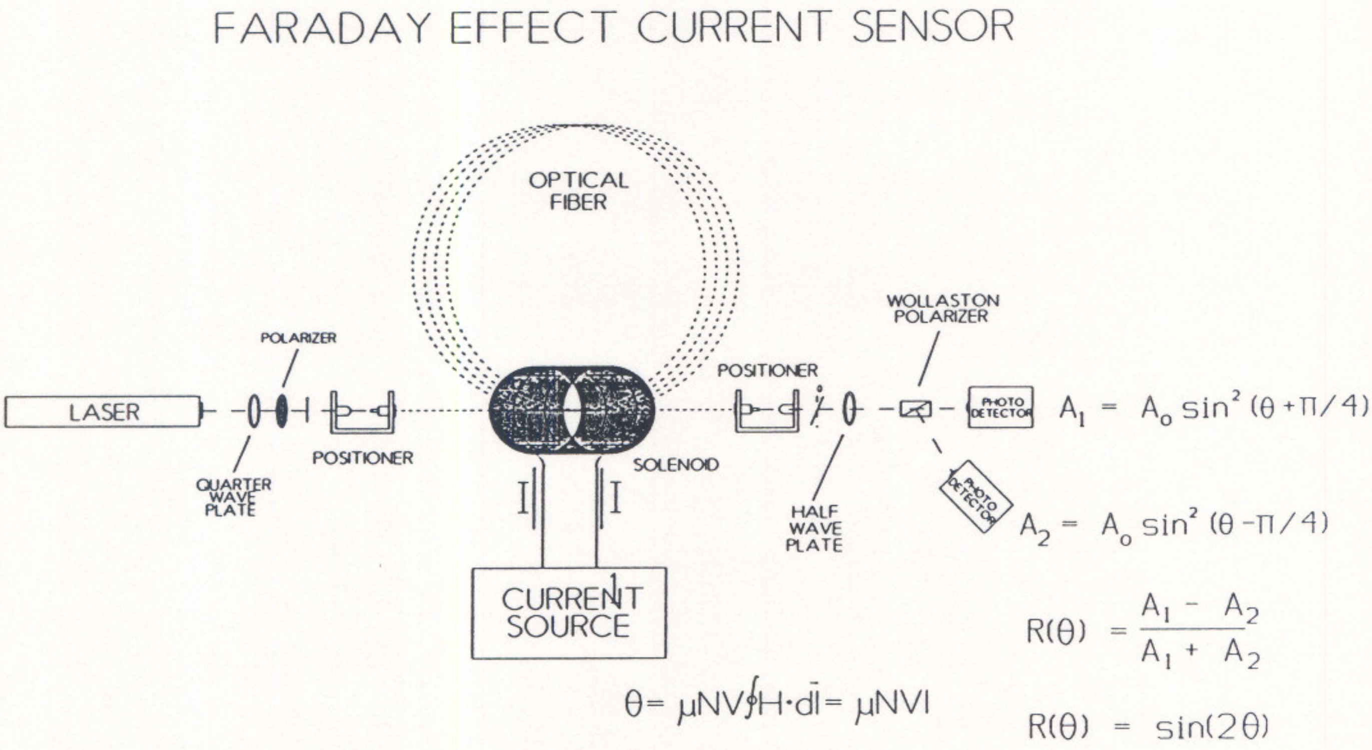


Figure 2 – Example of a system in which the Faraday effect is used to measure current.

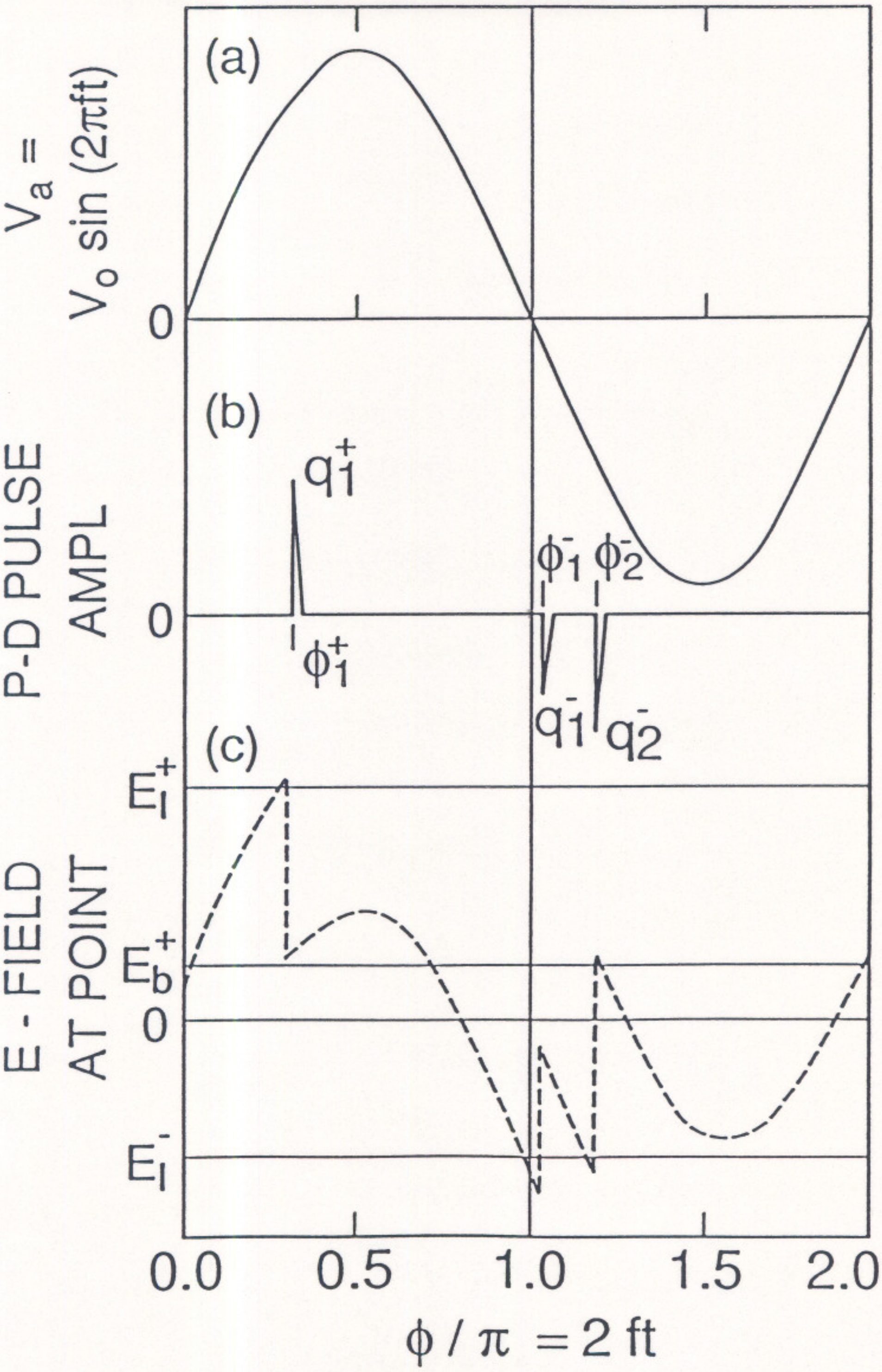


Figure 3 – Diagrammatic representation of an ac-generated PD process. Shown is the applied voltage (V_a), the local electric field strength at the discharge site (E), and the amplitudes ($q_i^{\pm}$) and phases ($\phi_i^{\pm}$) of the individual PD pulses. Onset levels ($E_I^{\mp}$) and a possible constant bias level (E_b^+) are also shown.

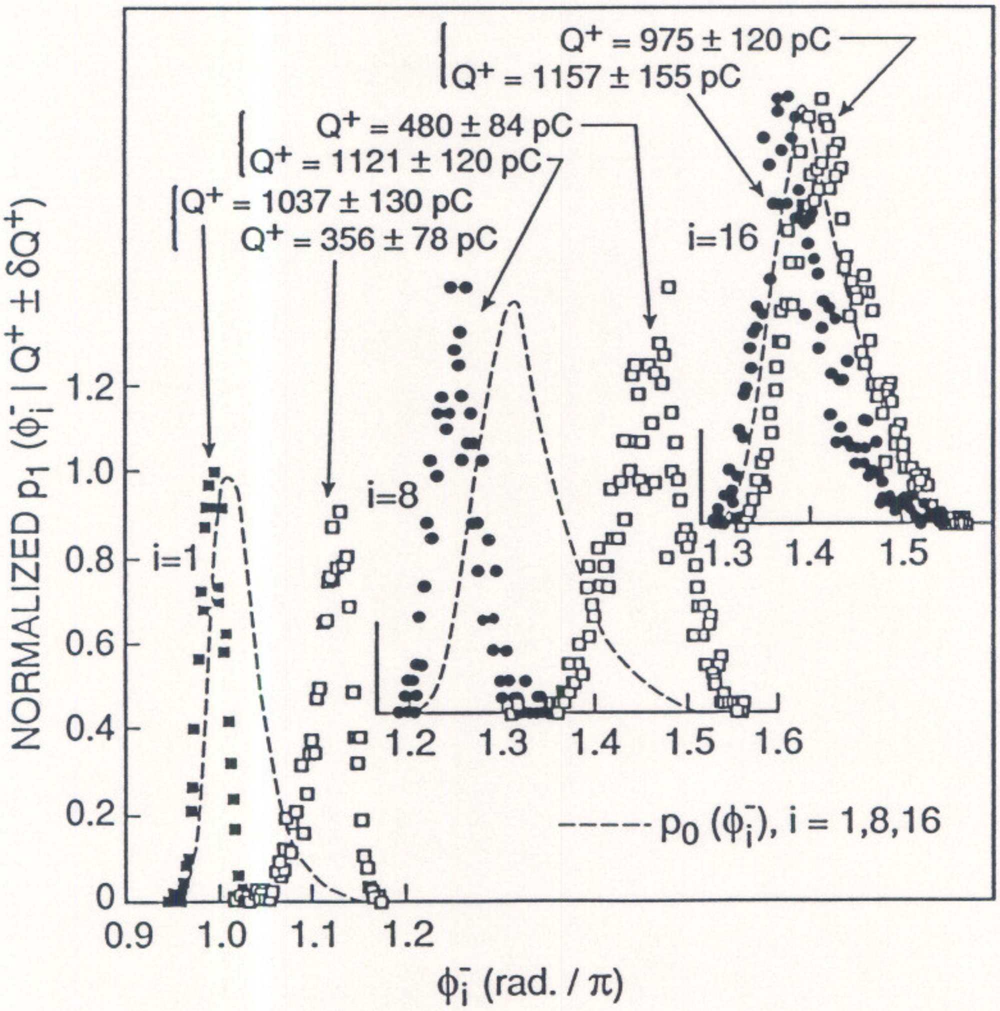


Figure 4 – Normalized conditional and corresponding unconditional phase-of-occurrence distributions for the first, eighth, and sixteenth PD pulses to appear on the negative half-cycle. Indicated are the ranges of values for the total charge (Q^+) from all positive PD events that occurred on the previous half-cycle which were used to specify the conditional distributions. These results were obtained from measurements of PD generated in a point-to-solid dielectric discharge gap.

CALCULATED PHASE-OF-OCCURRENCE

DISTRIBUTION FROM MONTE-CARLO SIMULATION.

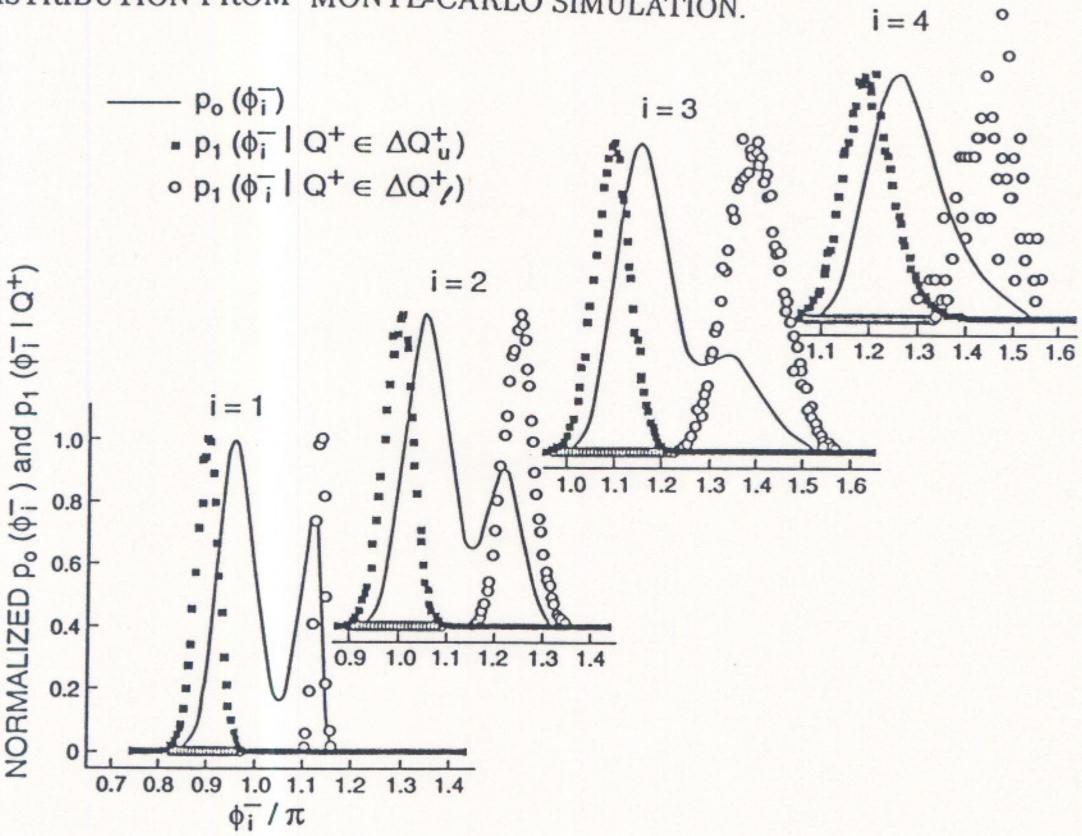


Figure 5 – Normalized conditional and corresponding unconditional phase-of-occurrence distributions for the first four negative PD pulses from a Monte-Carlo simulation of a ac-generated PD process based on a physical model described elsewhere [16].