Fundamentals of Partial Discharge in the Context of Field Cable Testing

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In the past, the details of partial discharge (PD) phenomena have been relevant primarily to specialists in apparatus development and testing. Most users typically specified appropriate standard tests in purchasing documents and did not require a detailed understanding of PD phenomena. The PD limits specified in standard tests are based on noise considerations in the measuring circuit and not on limits that damage the insulation. With the advent of widespread field PD testing of distribution cable, PD-related phenomena have become relevant to a much broader cross section of apparatus operators. The purpose of this article is to provide background on fundamentals of PD, especially as related to field PD testing of cable systems.

With the advent of extensive field PD testing of distribution cables and accessories, the fundamentals of PD have become relevant to a larger audience.

What Is PD?

Breakdown

The term "partial discharge" is defined by IEC 60270 (Partial Discharge Measurements) as a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor. A PD is confined in some way that does not permit complete failure of the system, i.e., collapse of the voltage between the energized electrodes such as the cable conductor and neutral wires. PD can result from breakdown of gas in a cavity, breakdown of gas in an electrical tree channel, breakdown along an interface, breakdown between an energized electrode and a floating conductor, etc.

Signal Generation and Detection

Such a discharge generates a voltage PD signal between the system conductors as a result of the change in the electric field configuration, which takes place when the discharge occurs. For example, we can consider a cavity in the dielectric of a cable. As we raise the voltage, the field in the cavity increases and is greater than the field in the surrounding dielectric as a result of the lower dielectric constant of the gas in the cavity. The magnitude of the field also depends on the shape and location of the cavity. When the field becomes sufficiently high in the cavity, the gas can break down, in the process of which it goes from nonconducting to conducting, and the field in the cavity goes from very high to nearly zero immediately after the discharge (Fig. 1). The measured PD signal is the result of the change in the image charge on the electrodes as a result of the transient change in the electric field distribution caused by the discharge.

A less precise but more intuitive way to look at this phenomenon is to consider the transient change in capacitance between the conductor and ground shield of the cable when the cavity goes from nonconducting to conducting. Obviously, the capacitance increases when the cavity is conducting, which means that a current must flow down the cable to charge the additional capacitance and maintain constant voltage on the cable. This current flows through the impedance of the cable and generates a voltage pulse, which propagates down the cable.

The voltage in the cavity collapses in at most a few nanoseconds (10^{-9} s) so that the resulting voltage pulse which propagates in both directions away from the PD source has an initial pulse width in the ns range. The voltage pulses arising from PD at interfaces may be of some tens of nanoseconds in duration. However, all shielded power cables have substantial high frequency attenuation as a result of losses in the semiconducting shields (XLPE) [1,2] and dielectric (PILC, EPR) [3]. Such high-frequency attenuation increases the pulse width and decreases the pulse amplitude as a function of distance propagated, which also limits the optimum signal detection bandwidth [4-6] to the range of 10 MHz for XLPE cable and to as little as 300 kHz for PILC cable. The appropriate bandwidth for EPR cable varies among manufacturers with some relatively close to the XLPE case and others closer to PILC.

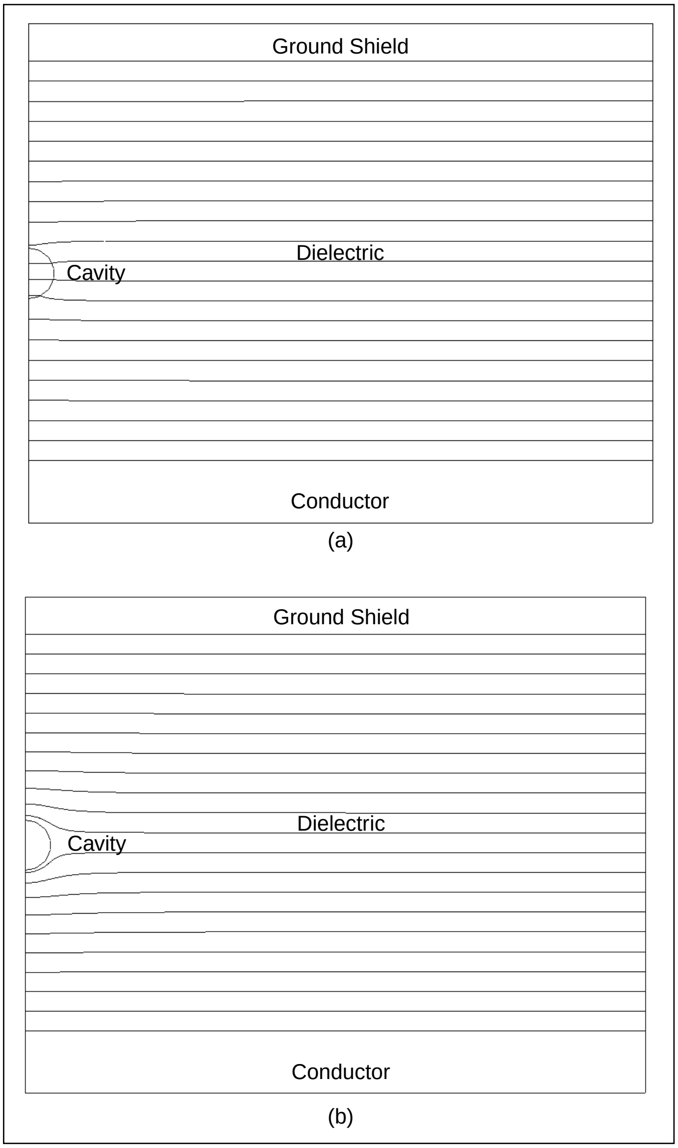

Fig. 1 Equipotential plots for an 0.8 mm diameter cavity in an XLPE cable with 6.4 mm (0.25") thick dielectric. In each case, the model is axisymmetric about the left boundary of the figure. The left figure shows the case for the cavity filled with air, and right, the case for the cavity when conducting during discharge. Using finite element analysis, we can compute the change energy stored in the electric field and equate this to ½ $\Delta C \cdot V^2$. On this basis, the change is capacitance is 2.4 × 10^{-16} F. However, if this change in capacitance takes place at 2 pu peak voltage for a 15 kV cable (about 24 kV), the PD magnitude would be roughly $V\Delta C$ or 6 pC.

In ultrawideband PD detection, as usually practiced in field PD testing of distribution cable, the PD voltage pulse is detected directly through capacitive coupling to the cable with a bandwidth ranging from a few hundred kHz to a few tens of MHz, depending on the type of cable being tested. In conventional PD detection as practiced in the laboratory, PD signals are usually detected with a bandwidth of 100 kHz or less, so that the detector acts as a low pass filter or integrator. For complex test objects, the high frequency stimulus of the PD pulse inevitably causes substantial ringing in the voltage pulse. The low pass characteristics of a conventional PD detector integrate this ringing to an effective charge which can be measured in picocoulombs, hence the convention of measuring PD in picocoulombs.

Calibration

The purpose of "calibration" in the context of PD detection is only to assure that if two different systems are used to measure the same sample, they get the same answer. However, no direct connection can be made between the measured PD magnitude and what is going on in the test sample. For example, if we take exactly the same cavity and place it at the same relative position in a 15 and 35 kV cable, one of which has twice the insulation thickness as the other, the PD magnitude measured for the 35 kV cable will be half that for the 15 kV cable, basically as a result of the reduced capacitive coupling to the electrodes. Obviously the physical phenomena that occur in and around the cavity depend only on the local field at the time of the discharge, and this must be about the same for both cases to cause discharge within the gas of the cavity. Thus, the physical phenomena and damage to the dielectric are essentially the same in both cases; however, the signal is twice as large in one case as the other. This points to a fundamental limitation of PD testing-the measured PD magnitude depends on the geometry of the sample and the location of the cavity or defect within the sample. Based on PD magnitude alone, we can say little about the cause of the discharge. Given an assumed defect and sample geometry, we can estimate the PD characteristics with reasonable accuracy using finite element computations (Figs. 2 and 3) [7].

PD-Related Failure

PD can occur without immediate failure. Indeed, some sources of PD can continue for years without causing failure. This includes discharge to a floating metallic component, PD between the neutral wires and insulation shield of a cable [8], various sources of corona, etc. For a PD source to cause failure of a solid dielectric it must cause tracking along an interface or create an electrical tree, which will grow through the dielectric and bridge the conductors. Electrical trees can be caused by:

1. PD within a cavity, which gradually erodes and pits the surface. (Some PD can increase the conductivity of the cavity wall and "short circuit" the cavity, thereby causing extinction of the PD);

2. Conversion of a water tree by a lightning or switching impulse;

3. Conversion of a large water tree by high ac voltage; and/or

4. Charge injection from a stress enhancement such as a metallic contaminant in the dielectric, a protrusion at the semicon-dielectric interface, etc.

Interfacial pressure and cleanliness of interfaces is essential to long-term, high-voltage endurance. Tracking along interfaces of distribution accessories is a major source of PD-induced failure, often caused by poor workmanship or lack of cleanliness during assembly.

Materials differ greatly in their resistance to degradation by PD, from low resistance to degradation for unfilled polyolefins such as XLPE, to much greater resistance for filled polymers, such as EPR cable and accessory insulation, to nearly total resistance to PD for specially formulated EPR-based insulations. Thus the severity of a PD source must be judged not only in the context of the PD activity but also in the context of the material in which that PD is taking place. However, PD (tracking) along an interface can cause failure even if the solid dielectric is totally immune to the PD-induced electrical tree initiation.

Distinguishing PD Sources

Given that a source of PD can be inevitably fatal or totally harmless to the long-term reliability of a cable system, distinguishing the nature of a PD source becomes very important. A great deal of work has been published on methods of classifying PD sources. Such classification systems can be based on any combination of PD statistics, such as the phase distribution, amplitude distribution, repetition rate, correlation of PD pulses in time, pulse shapes, etc.

One clear lesson from this body of work is that such classification systems must be developed for the specific equipment under test. No universally applicable "PD classification engine" is likely to be developed any time soon. Thus, PD classification must be undertaken in the context of the system under test. In the case of a cable system, this means that the PD classification system must take into account the specific type of cable under test-e.g., XLPE, EPR (and sometimes the specific type of EPR), or PILC-and the specific types of accessories on that cable (i.e., specific splice type and termination type). Most of the field PD test techniques presently being applied can locate individual PD sources along the cable and have the potential to analyze the PD characteristics of each PD source. However, to interpret the PD data, details of the insulation at the PD site should be known at the time of testing or at least be available once PD sites are known, e.g., cable insulation type, and the specific model of each splice along the cable. Further, PD classification systems need to be developed for each type of cable, splice and termination so that "dangerous" PD can be distinguished from "harmless" PD.

PD Magnitudes and Defect Sizes

As seen from Fig. 2, PD from "microcavities" is not going to be detected in the field. In general, a cavity must be in the millimeter range to generate about 10 pC, which is typically the minimum PD magnitude that can be detected under best-case field conditions using time domain PD detection techniques. An electrical tree must be of similar length in the direction of the field to generate a similar PD magnitude. Characteristics of PD in electrical trees differ from those in spherical voids. The pulse shapes, rise and fall times, width, and amplitude depend on the applied field in the insulation. At fields in the range of 2 kV/mm, which is typical for distribution cables, the electrical trees are branchlike, and the PDs proceed in steps along a branch rather than by a single discharge from the tree-inducing defect to the end of the tree branch. As a result, up to several tens of small discharges pulses occur per half cycle, and these are too small to be observed in the field [9]. Electrical tree initiation phenomena, which occur before channel formation and PD, give rise to electrical activity in the fC range (10 -15 C), and will not be detected under field conditions.

Risk

Off-line PD testing is usually carried out at between two to three times the normal operating voltage. The primary reason for such a test condition is that the PD inception voltage is substantially greater than the PD extinction voltage-a factor of up to 2 in theory and more like 1.5 to 1.7 in practice. Thus, to assure that PD, once stimulated by a surge on the system, will not persist at normal operating voltage, the system must be tested to the range of twice normal operating voltage. Of course, not every surge will produce PD in a void. PD will occur only when an electron is

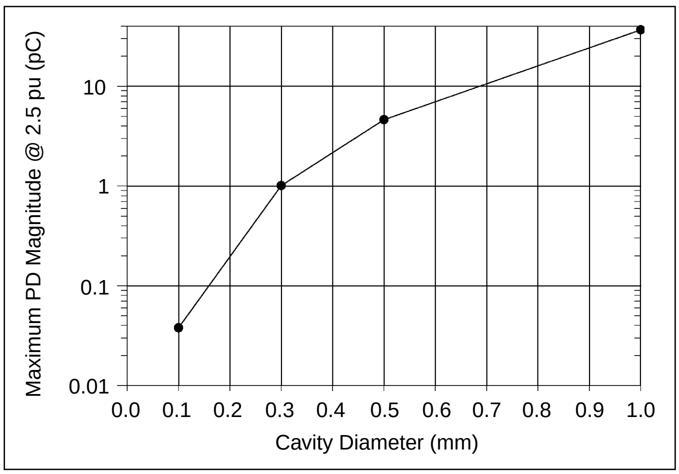

Fig. 2 PD magnitude as a function of spherical cavity size for 15 kV, EPR cable geometry assuming that the cavity discharges at the peak of a 2.5 pu excitation (30 kV). The PD magnitude is proportional to the cavity volume. To produce 10 pC PD magnitude, which is about the best sensitivity claimed for field PD detection using time domain techniques, a cavity diameter of about 0.7 mm is required, which is a rather large cavity. The required cavity size for XLPE cable dielectric for the same PD magnitude would be even larger. Similar computations were undertaken for an electrical tree channel with the result that a 1 mm channel resulted in about 6 pC PD magnitude.

present in the void and the voltage due to the surge is above the inception value.

Testing at elevated voltage carries an appreciable risk as the phenomena that cause electrical tree initiation increase exponentially above a threshold field. Below this threshold field, essentially no damage is done, and above this threshold field damage becomes increasingly rapid with increasing voltage. A cable in good condition is capable of operating at 2 pu or even 3 pu for short periods with no problem. However, the cables being PD tested in the field are often old and not in very good condition. For such cables, the chances of causing failure of a cable that otherwise would operate reliably for an extended period of time increases with increasing test voltage. Based on the above, the rationale for testing above 2 pu is not obvious.

Off-Line vs. In-Service Testing

Another approach is to test in-service, which means at normal operating voltage. The assumption in this case is that the cable has been at operating voltage continuously for a long time so that if a surge could have put it into discharge it would have done so. Note that if the cable is taken off voltage, then all PD stops and will not start again when the cable is energized until the voltage is raised above the inception, which can be up to twice the voltage at which PD extinction occurs.

In-service testing has the obvious advantage that the cable is not put at any additional risk from the PD test. The problem is that utility operating procedures often preclude direct access to the high-voltage conductor. This can be overcome through the use of inductive coupling [10]. As well, frequency domain PD detection has been applied, which provides increased PD detection sensitivity relative to time domain techniques at the cost of less accurate prediction of PD location. However, tests can be undertaken at numerous locations as the time required for setup and testing is very short since no outages are required.

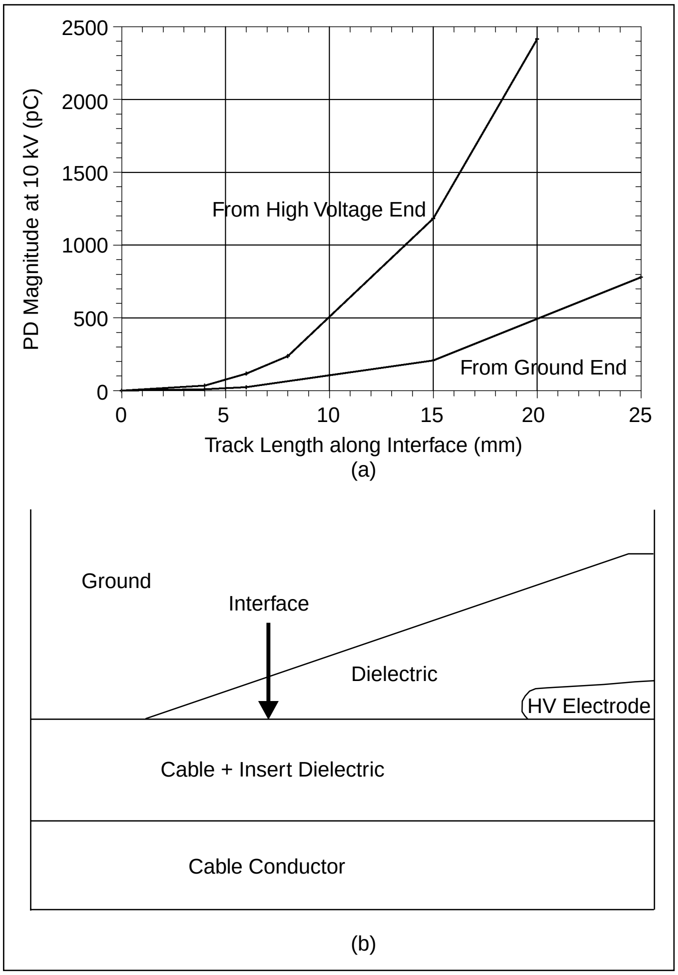

Fig. 3 Estimate of PD magnitude as a function of track length along the interface in a distribution joint. This is really a 3-D geometry, and various approximations were made to reduce the problem to 2-D. Consequently, these data must be considered approximate, but reasonably indicative.

Noise Reduction and Dynamic Range

The PD signal is generally very small, and environmental noise under field conditions can be very large. Several approaches to improving detection sensitivity have been implemented. All such approaches are based either on knowledge of the nature of the PD pulse or on detection of environmental noise. Presently available digital signal processing (DSP) is not sufficiently fast for implementation of on-line noise reduction through wavelet transforms, correlation techniques, etc. As a result, all present time domain approaches to PD detection require that the system be triggered by a PD pulse that is above the noise. Once this pulse has been detected, data can be recorded and DSP techniques can be used to search for the second, smaller PD pulse, which is reflected from the far end of the cable and is required for PD location. If DSP could be implemented continuously on the PD signal data stream, the PD detection sensitivity could probably be improved by an order of magnitude, from about 10 to 100 pC to the range of 1 to 10 pC under field conditions. [11,12]

Closed-loop noise reduction approaches detect environmental noise and attempt to subtract it from the PD signal stream. This can be done with various levels of sophistication, and again, present DSP is not adequate to implement the most sophisticated approaches in real time [11,12].

Detecting the small PD signal in large noise also raises a dynamic range issue. Fast (50 MHz) A/D converters as required to implement a 20 MHz bandwidth PD detector usually have a dynamic range of 8 bits. If the PD signal falls below the first bit, nothing can be detected. This problem can be overcome in two ways. First, through the use of companding prior to digitization (or through the use of a nonlinear digitizer) [10,11]; and/or through the use of sampling at 8 bits but at a much higher frequency and subsequent use of decimation (down-sampling/filtering) to improve the effective dynamic range of the A/D conversion process.

Summary

The above discussion makes clear that many aspects of PD detection in the context of field testing are not mature, including:

1. The ability to estimate the probability of cable system failure on the basis for measured PD signals;
2. The ability to detect small PD signals in large amounts of environmental noise;
3. The relative efficacy of in-service vs. off-line PD testing.

Water Treeing and PD

As is well known, water treeing is the primary degradation mechanism for large amounts of older, XLPE-based cable. Water treeing can be described as a dendritic pattern of electro-oxidation, which converts the hydrophobic polymer to hydrophilic and results in the condensation of water into the electro-oxidized region, which in turn results in self-propagation of the electro-oxidized tracks or channels. In the growth region, these electro-oxidized tracks are too small to observe (probably in the range of 10 nm in diameter) [13, 14]. Water trees are visible because of the large number of water-filled microcavities along the electro-oxidized tracks.

The detection of water trees has been an important issue for a long time, and various attempts have been made to detect electrical or optical signals from growing water trees. Densley, et al. [15] searched for optical signals from growing water trees. Such signals could come from electroluminescence or from PD. Since PD results from gas breakdown, strong light emission is inevitable and can often be detected with much greater sensitivity than the electrical signal. However, in spite of substantial effort, no optical signals were observed, which means no PD from the growing water trees.

Dorris, et al. [16] spent a good deal of effort looking for electrical signals from water trees under EPRI sponsorship. They worked with water trees grown under high field conditions for which the electromechanical forces are substantial so that the polymer can yield without extensive electro-oxidative degradation of the polymer to reduce its yield strength. Dorris, et al. did find very small electrical signals from growing water trees, but these were clearly not the result of PD. An analysis of the data published by Dorris et al. indicates that the signals they observed could be explained by sudden extensions of a water tree channel by between 10 and 100 nm.

In spite of extensive efforts to find PD signals from growing water trees, none has been found. Thus, one must conclude that growing water trees do not generate PD signals, unless they give rise to an electrical tree. Therefore, detection of water trees during field PD testing implies generation of electrical trees from the water trees, and from the above analysis, these electrical trees must be in the range of 1 mm long.

Water trees can "convert" to electrical trees as a result of a lightning impulse [17,18] or as a result of ac voltage [19]. The likelihood of causing a pre-existing water tree to convert to an electrical tree during a field PD test obviously increases with the test voltage and the test duration. In general, electrical trees are more difficult to initiate than to grow, so that an electrical tree, once initiated, tends to grow to failure. Certainly the industry has extensive experience with increased failure rates of old, water treed, XLPE dielectric cable after lightning storms, and this is ascribed to conversion of water trees to electrical trees by lightning impulses and subsequent growth of the electrical tree to failure at normal operating voltage.

Conclusions

PD behavior in extruded cable systems is complex, and the state of our present knowledge precludes an accurate assessment of remaining life of cables that have PD.

The source of PD, e.g., void, interface or electrical tree, will affect PD characteristics such as magnitude and repetition rate. The PD discharge magnitudes decrease with increasing insulation thickness.

For any particular cable system, time to failure cannot be predicted on the basis of discharge magnitude. For example, electrical trees can grow rapidly during periods of small discharge magnitude, while large magnitude discharges, depending on their location, may be completely innocuous. The future of field cable PD testing will depend on developing PD classification engines for specific cable types and accessories which allow dangerous PD to be distinguished from harmless PD.

Steven Boggs received his Ph.D. and MBA degrees from the University of Toronto in 1972 and 1987, respectively. He spent 12 years with the Research Division of Ontario Hydro and six years as Director of Engineering and Research for Underground Systems, Inc. Steve is presently Director of the Electrical Insulation Research Center of the University of Connecticut and Research Professor of Materials Science, Physics, and Electrical Engineering. He is also an Adjunct Professor of Electrical Engineering at the University of Toronto. He has published widely in the areas of PD measurement, high frequency phenomena in power apparatus, high field degradation of solid dielectrics, and SF_6 insulated systems. He was elected a Fellow of the IEEE for his contributions to the field of SF_6 insulated systems.

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References

1. S.A. Boggs, A. Pathak, and P. Walker, "Partial Discharge XXII: High Frequency Attenuation in Shielded Solid Dielectric Power Cable and Implications Thereof for PD Location," *IEEE Electrical Insulation Magazine,* Vol. 12, January/February 1996, pp. 9-16.
2. G.C. Stone and S.A. Boggs, "Propagation of Partial Discharge Pulses in Shielded Power Cable," 1982 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena National Academy of Sciences, Washington, DC, p. 275-280.
3. L.M. Zhou and S.A. Boggs, "Effect of Shielded Distribution Cable on Very Fast Transients," Accepted for publication in *IEEE Trans. PD*.
4. S.A. Boggs and G.C. Stone, "Fundamental Limitations to the Measurement of Corona and Partial Discharge," 1981 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena and reprinted in the *IEEE Trans. EI-17*, April, 1982, p. 143.
5. S.A. Boggs, D.D. Pecena, S. Rizzetto, and G.C. Stone, "Limits to Partial Discharge Detection-Effects of Sample and Defect Geometry," *Gaseous Dielectrics*, V, L. Christophorou, ed. Pergamon Press, 1987, p. 629.
6. F.H. Kreuger, M.G. Wezelenburg, A.G. Wiener, and W.A. Sonneveld, "Partial Discharge Part XVIII: Errors in the Location of Partial Discharges in High Voltage Solid Dielectric Cable," *IEEE Electrical Insulation Magazine*, Vol. 9, No. 6, Nov/Dec 1993, pp. 15-23.
7. S.A. Boggs, "Partial Discharge-Part III: Cavity-Induced PD in Solid Dielectrics," *IEEE Electrical Insulation Magazine*, Vol. 6, No. 6, November/December 1990, pp. 11-20.
8. J. Densley, "The Effect of Aggressive Chemicals on Extruded Insulation Shields," Appendix A1D(5-30)3, *Minutes of 105th IEEE PES Insulated Conductors Committee Meeting*, Spring 1999, pp. 44-49.
9. J. Densley, T. Kalicki, and Z. Nadolny. "Characteristics of Partial Discharge Pulses in Electrical Trees and along Interfaces in Extruded Cable Systems." Accepted for the February 2001 issue of the *Transactions on Dielectrics and Electrical Insulation*.
10. N. Ahmed and N. Srinivas, "Partial Discharge Measurements in Distribution Class Extruded Cables," *Proceedings of the IEEE Transmission and Distribution Conference*, Vol. 1, 1999, pp. 46-51.
11. I. Shim, J.J. Soragham, and W.H. Siew, "Digital Signal Processing Applied to the Detection of Partial Discharge: An Overview," *IEEE Electrical Insulation Magazine*, Vol. 16, No. 3, May/June 2000, pp. 6-12.
12. I. Shim, J.J. Soragham, and W.H. Siew, "Application of Digital Signal Processing to the Detection of Partial Discharge-Optimization of A/D Conversion," *IEEE Electrical Insulation Magazine*, Vol. 16, No. 4, July/August 2000.
13. H.R. Zeller, "Noninsulation Properties of Insulation Materials," *1991 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena*, pp. 19-47.
14. E. Moreau, C. Mayoux, C. Laurent, and A. Boudet, "The Structure Characteristics of Water Trees in Power Cables and Laboratory Specimens," *IEEE Trans EI-28*, No. 1, 1993, pp. 54-64.
15. S.S. Bamji, A.T. Bulinski, R.J. Densley, A. Garton, and N. Shimizu, "Water Treeing in Polymeric Insulation," *CIGRE Paper 15-07*, 1984, pp. 7.
16. D.L. Dorris, M.O. Pace, T.V. Blaleck, and I. Alexeff, "Current Pulses during Water Treeing, Procedures and Results," *IEEE Trans. DEI-3*, No. 4, August 1986, pp. 523-528.
17. R.H. Hopkinson, "Better Surge Protection Extends Cable Life," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, pp. 2827-34.
18. S.A. Boggs, R.J. Densley, and J. Kuang, "Mechanism for Conversion of Water Trees to Electrical Trees under Impulse Conditions," *IEEE Trans. PD-13*, No. 2, April 1998, pp. 310-315.
19. A.T. Bulinski and R.J. Densley, "Final Breakdown Mechanism of Water Treeing," *1991 Annual Report of CEIDP*, 1991, pp. 298-305.