Partial Discharges in Low-Voltage Cables

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Significance

Part 4 – Propagation and coupling of surges

This paper is only indirectly related to the topic of surge propagation in the context of surge-protective devices, but is included here as it might be a gateway to further information on pulse propagation – the basic technique used in the investigation summarized by this paper

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PARTIAL DISCHARGES IN LOW-VOLTAGE CABLES

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ABSTRACT-Testing of high voltage apparatus for partial discharges has long been recognized as an important part of quality control for these devices. Recently, interest has been focused on methods for testing low voltage cables to determine their integrity under adverse operating conditions such as a loss of coolant accident. A new method, utilizing partial discharges, is presented which has the potential for locating breaches in the insulation of in situ, low voltage, multi-conductor cables.

INTRODUCTION

Cables used in power plants are selected on the basis of qualification tests [1] which provide a sufficient degree of confidence in the ability of the cables to maintain operational readiness for a well-defined "life" duration. As the cables age under the various environmental stresses prevailing in a power plant, nuclear plants in particular, the question arises of how much "residual life" exists in the cables as they approach their rated, qualified life. There is considerable interest in assessing this readiness, and a number of investigators have proposed various test methods [2]. In particular, a method that could allow nondestructive, in situ assessment would be extremely valuable. The detection of partial discharges at identifiable sites along a cable offers a method for assessing the likelihood of a fault to occur during a loss of coolant accident on a cable containing an incipient defect. Such an incipient defect might be a breach of the insulation that would remain undetected under normal operating conditions.

Low-voltage cables, in contrast with cables designed for high-voltage service, are not provided with an insulation structure aimed at making them free from partial discharges under moderate overvoltage conditions such as the application of a test voltage. Therefore, the occurrence of a partial discharge at an incipient defect site has to be differentiated from the background of the expected partial discharges that will occur over the length of the cable in the absence of any significant defect. The test method described in this paper offers the opportunity to make this differentiation and locate the discharge sites associated with insulation breaches. Three representative types of cables in which artificial defects had been created were subjected to the test; every defect was successfully located.

PRINCIPLE OF THE METHOD

Partial discharges will occur along the entire length of a cable when voltages greater than the partial discharge inception voltage are applied. To develop a strategy for analyzing experimental data from a cable that also contains defects resulting in partial discharges at specific sites, several assumptions need to be made.

The first is that there are no preferred partial discharge sites in the cable under test. Therefore, it would be expected that, ideally and in the absence of any defect, the partial discharges would be uniformly distributed along the length of the cable.

The second assumption is that, in the absence of a defect, the partial discharge pulses occur as random events in time, i.e., the observed process is a marked random point process [3]. Using these assumptions causes the observed partial discharge process to resemble, asymptotically, a Poisson shot noise process [3,4], with pulses emanating from all positions along the cable. If a sample of data were analyzed by calculating a histogram of the positions from which each pulse in the sample emanated, then, using this model, the histogram would correspond to a uniform distribution.

The third assumption is that amplitudes of the pulses, expressed in units of charge at each partial discharge site, are gamma-distributed [4] with the parameters of the probability density being independently and identically distributed. The observed probability density of the charge will then have the form

$$\mathrm{p}(q) = \int_{z,w} \mathrm{p}(q|z,w)\,\mathrm{p}(z)\,\mathrm{p}(w)dz\,dw \qquad (1)$$

where $\mathrm{p}(q)$ is the probability density of the observed charge in the entire cable, $\mathrm{p}(q|z,w)$ is a conditional probability density of the charge at a single site, $\mathrm{p}(z)$ is the probability density of the locations of the partial discharge sites along the cable and $\mathrm{p}(w)$ is the probability density of the parameter w, such as the degree of imperfection in the insulation (local field enhancements) that control the most probable discharge amplitude q at that site. By assumption, there is no preferred site and experimental evidence indicates that the physical behavior at each site is similar. This suggests that the superposition of these infinitesimal processes will yield a seemingly well behaved, predominantly unimodal probability density for the charge and this has been observed experimentally.

Now consider the model for a defect. The goal of this measurement technique is to detect an insulation flaw which is defined, for these purposes, as a complete crack through the insulation to the conductor. Partial discharge in electrode arrangements that consist of a conductor-conductor interface or conductor-dielectric interface is often more active than when the electrodes are a dielectric-dielectric interface. The implication is that the partial-discharge sites at the flaws will be more active than the sites in the rest of the cable and consequently cause significant deviations from the ideal model.

The basic idea of the measurement technique is to identify whether the data significantly deviate from the behavior defined by equation (1). In this case, equation (1) is modified by adding a term in which $\mathrm{p}(w)$ is replaced by $\mathrm{p}(w|z)$

$$\begin{aligned}\mathrm{p}(q) &= \int_{z,w} \mathrm{p}(q|z,w)\mathrm{p}(z)\mathrm{p}(w)dz\,dw \\ &\quad + \Sigma_i \int_{z,w} \mathrm{p}(q|z,w)\mathrm{p}(w|z_i)\mathrm{p}(z)dz \qquad (2)\end{aligned}$$

where w depends on z and is highly localized to particular points z_i. Admittedly, the model is a gross idealization of the expected

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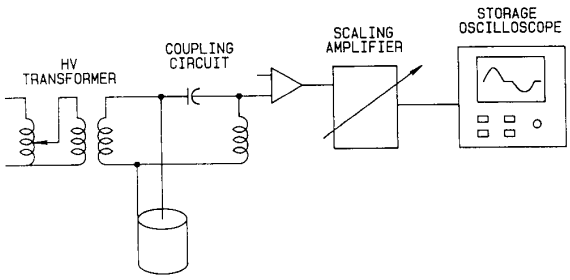


Figure 1. Block diagram of partial discharge detection and recording.

behavior, however, the general concept has merit if the defects do behave differently from the normal background partial discharge in the cable. In practice, there will be naturally occurring, preferred partial discharge sites that are not flaws but cause variations in the expected background count rates. In fact two such preferred locations have already been identified, the ends of the cable.

EXPERIMENTAL APPARATUS

The experimental apparatus implemented is a general purpose system designed for acquiring broadband partial discharge waveforms and processing the acquired signals as shown in the block diagram of Figure 1. The key elements are the high-voltage system, the coupling circuit and the data acquisition and analysis system. The high-voltage system used to apply the necessary voltages to the cables under test consists of a 60 Hz high-voltage transformer with appropriate noise filtering. Measurements on the cables are made at voltage levels exceeding the partial discharge inception voltage by 10, 20, and 40 percent. The inception level is defined as that voltage which causes at least one partial discharge pulse above a specified charge level q per second.

The partial discharge signals are coupled from the cable under test to the measurement system through a coaxially mounted, 1 nF capacitor. The capacitor is the first element in a high-pass filter having a lower cutoff frequency of 30 kHz and a 1000 Ω input impedance. Initial testing with sensitivities ranging down to 0.05 pC did not produce useful results because the partial discharge magnitudes at inception are in excess of 10 pC. Since the predominant partial discharge levels are greater than 10 pC, an attenuator and input protection are included in the circuit which limits the input sensitivity to 1 pC. The capacitance of the input protection limits the bandwidth of the system to approximately 10 MHz. This input bandwidth is adequate for these experiments since the cables under test are lossy and limit the usable bandwidth to within this range. A variable attenuator is included between the input preamplifier and the gain block of the system to provide amplitude scaling which prevents saturation of the amplifier for larger partial discharge amplitudes.

Partial discharge pulses are recorded using a LeCroy 9400A[1] digital oscilloscope which has an 8-bit digitizer that can sample 32 000 points at a 100 MHz rate. The advantage of using this oscilloscope is its ability to segment its 32 kB acquisition memory so that it can acquire up to 250 separate waveforms at its maximum sampling rate before having to transfer them to a computer over an IEEE 488 interface. The computer is a PC-AT class computer. The ASYST[1] scientific software package is used for acquisition control and data analysis. Up to 20 000 waveforms can be collected before the available disk space limits the computer's ability to process the data; typically 5000 waveforms are collected. Active data collection occurrs only during a few seconds of the voltage application to the cable under test, however, voltage is typically applied for 8 minutes since the high voltage system is not under control of the computer and time is needed to archive the data. Since the system uses a computer with only moderate computational ability, all processing has to be performed off line.

[1]The identification of commercial materials and their sources is made to describe the experiment adequately. In no case does this identification imply recommendation by the National Institute of Standards and Technology, nor does it imply that the instrument is the best available.

MEASUREMENTS

Two fundamental estimates are made from each recorded waveform: an estimate of the charge, and an estimate of the location of the partial discharge site in the cable. It would be desirable to calculate estimates for all detectable pulses; however, since the measurement system is general purpose, trade-offs for cost, speed, and data handling capabilities have been made. With these constraints, only a limited number of waveforms can be collected and analyzed.

The method used to calculate the charge in the partial discharge waveform is the same as that used in [4] and has been shown to be more accurate than the usual measurement of the peak value of the pulse. The technique uses the pulse energy derived from the waveform to develop an estimate of the charge and assumes that the measured partial discharge waveform is similar to calibration pulses injected into the cable. The calibration pulses are generated by applying a fast-rise step of known amplitude through a known capacitance into the cable under test. Further corrections in the estimates to account for the cable attenuation were not deemed necessary.

If the flaw is detectable, then the histogram of the charge will no longer be unimodal. Using this fact, the measurement can be enhanced by setting a lower discrimination level so that the instrument measures only those partial discharges which appear to be anomalous. The lower discrimination level is also referred to as the trigger level, the level which the partial discharge pulse must exceed to initiate the recording cycle of the digital oscilloscope.

The basic principle used to determine the location of the partial discharge can be understood by referring to Figure 2. When a partial discharge pulse originates at some point interior to a cable it splits evenly into two pulses which travel in opposite directions. One pulse, referred to as the direct pulse, proceeds toward the detector end arriving at time t_1. The other pulse proceeds toward the open end of the cable and is reflected from the open circuit back toward the detector end, arriving at the detector at time t_2. Knowing the velocity of propagation, v, for the cable, the location, ℓ, is given by

$$\ell = \frac{v(t_2 - t_1)}{2}$$

where the location is referenced from the open circuit end of the cable.

To save time in processing, a simple but accurate method is used to calculate the locations. The technique applies an approximate matched filter to the recorded pulses whose shape resembles a

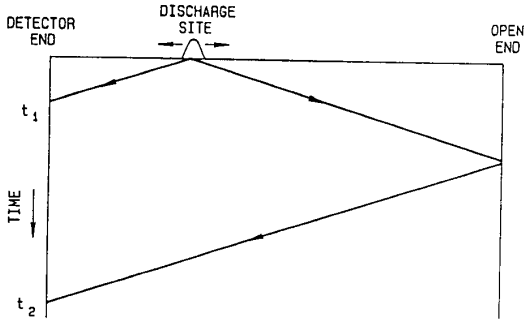


Figure 2. Position versus time diagram of direct pulse and reflected pulse propagation.

partial discharge pulse. In effect, this assumed pulse is cross-correlated with the pulses in the measured data. The time delay between the two largest pulses in the waveform is determined and converted into a location using a measured propagation velocity. More accurate delay estimators are not justified since the increased computational effort does not provide enough increase in accuracy. When the two largest pulses in the data record are from two distinct discharge sites, the estimate is referred to as a phantom delay. The probability of calculating a phantom delay is small at the voltage levels used, with less than 1 percent of the estimates being phantoms. These phantoms are not a problem since the time delay between the pulses is random and does not lead to a count rate that favors any particular site. A limitation of this technique is the existence of a measurement blind spot in the cable: when the arrival times of the direct pulse and reflected pulse are nearly the same, it becomes difficult to differentiate between a single pulse and two closely spaced pulses. Without special, computationally intensive processing, these sites all appear to be at a distance range near the end of the cable, in effect creating a blind spot.

TEST RESULTS

In this case, the measurement technique is intended for use in situ on 600 V class nuclear power plant cables and so representative cable types were used in the experiments. These cables can be grouped into three categories: shielded cables, unshielded multiconductor cables, and unshielded single conductor cables. The following samples were used in a series of experiments:

- An unaged, unshielded, two conductor, #14 AWG, 600 V class, neoprene jacketed cable of the same type used for control cabling in nuclear power plants.
- An unaged, 50 ohm, coaxial cable of the same type used for instrumentation cabling in nuclear power plants.
- An aged, unshielded, 15 conductor, #18 AWG cable of the same type used for instrumentation cabling in nuclear power plants.

No experiments were conducted on unshielded single conductor cables since the techniques to be discussed require that the cable have some transmission line properties; a single conductor, in the absence of ground plane, does not.

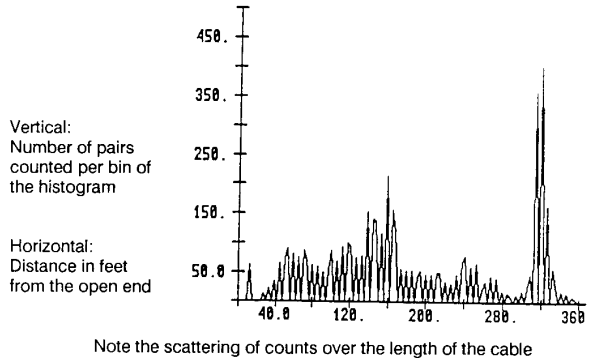


Figure 3. Histogram of delay times between the two major pulses in each event of a 5000-element record containing true pairs and random pairs.

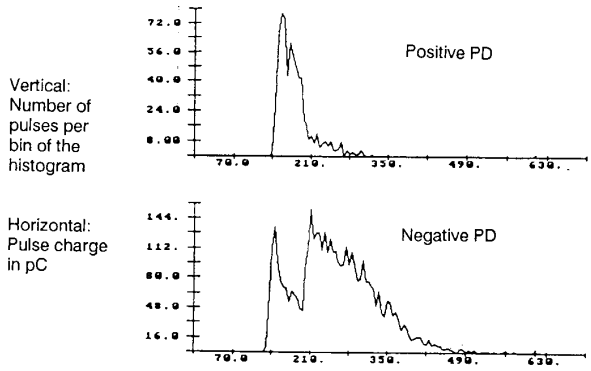
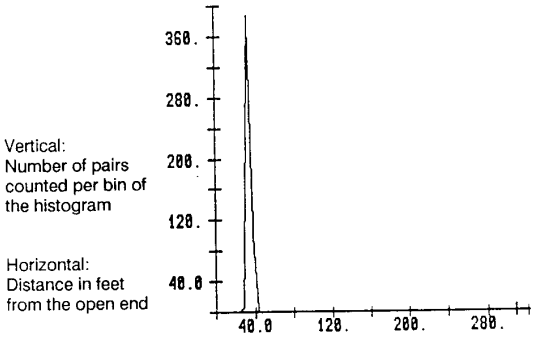


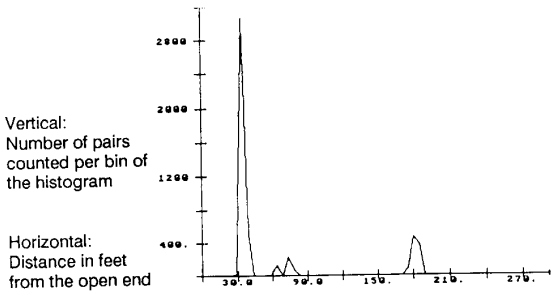
Figure 4. Histogram of the distribution of partial discharge pulses (PD) as a function of their charge transfer magnitude ("pulse height").

Tests were performed on 100-m (330 ft) length of unaged, two-conductor cable with artificial defects introduced at three locations. A small portion of the jacket was removed at three locations and the insulation was carefully pierced through to the conductor using a #60 twist drill in two of the locations; a small razor knife was used to slit the wire insulation in the third. In neither case was any of the insulation removed; only a break was created from the conductor surface to the surrounding atmosphere. The partial discharge inception voltage of the cable was 4500 V and measurements were made at voltages levels 10, 20, and 40 percent above inception. With a small lower discrimination level, the low-level background partial discharges have dominant count rates indicating that the partial discharges are distributed along the length of the cable as shown in Figure 3. If the lower discrimination level is increased, then the count rates of the partial discharges from the defect sites dominate the background count rate as indicated by the charge histograms of figure 4; note that the histograms are not unimodal. The locations of the individual damage sites were found using those delay values which corresponded to data near the peaks of the charge histograms. Each of the damage sites was correctly identified as can be seen in figures 5, 6 and 7. Other measurements were made on a 20 m (66 ft) length of coaxial cable with artificial damage inflicted by slightly abrading the shield. The partial discharge inception voltage was 5200 V. In this case, the defect was immediately



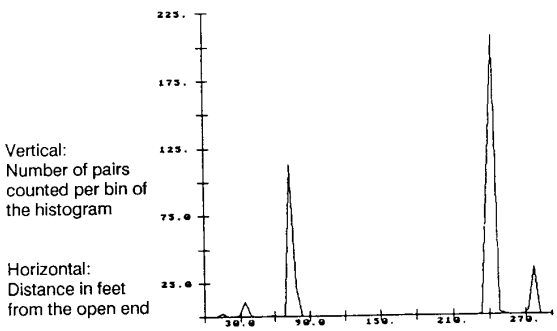
Note the emergence of a defect signal at 70.2 feet, location of an actual defect.

Figure 5. Histogram of time delays for 5000 V and pruned data.



Note the emergence of a defect signal at 34 feet (actual defect), with minor indications at 70 feet (already detected in Figure 5), and at 178 feet (no known defect at that point).

Figure 6. Histogram of time delays at 5200 V and pruned data.



Note the emergence of a defect signal at 240 feet (actual defect), with substantial signal at 70 feet (already detected in Figure 6), small signal at 34 feet (as in Figure 5), and new signal at 280 feet.

Figure 7. Histogram of time delays at 6000 V and pruned data.

identified because the partial discharge activity at the damage site was much greater than the background partial discharges. Similar results were also obtained while measuring a 12-m (40 ft) length of aged multiconductor cable containing an artificial defect. The artificial defect was created by piercing the insulation on one of the 15 conductors with a small razor knife, similar to the slit described above. The partial discharge inception voltage was 2300 V. Similar to the previous case, the partial discharge activity at the damage site was greater than the background of the rest of the cable allowing easy identification of the flaw.

CONCLUSIONS

The test method based on partial discharge detection using signal processing makes possible the identification and location of insulation breaches, undetectable under normal service conditions, that may become a fault under additional environmental stresses, or may progress into a fault under further aging.

Tests performed on three representative types of low-voltage cables have demonstrated that the method can differentiate between signals emanating at incipient defect sites and the background of partial discharges occurring over the length of the cable.

In order to induce partial discharges, the test voltage must clearly be raised above the inception voltage. Depending on the cable structure, this test voltage will be on the order of a few thousand volts, a subject of possible concern, but not a fatal limitation for a test method offering the reward of definite identification of defects that could become fault locations.

The demonstration was obtained with a general-purpose PC-type computer, using a commercial software package augmented by moderately complex custom-designed software. In a more dedicated system, with further software enhancement, additional benefits are possible, such as the detection of incipient defects with only brief exposure of the insulation to the test voltage, automated scanning of the data for most significant content, and optimization of the test procedure into an expert system approach.

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REFERENCES

[1] IEEE Std 383-1974 Standard for Type Test of Class 1E Electrical Cables, Field Splices, and Connection for Nuclear Power Generating Stations.

[2] Proceedings: Workshop on Power Plant Cable Condition Monitoring EPRI EL/NP/CS-5914-5R, July 1988.

[3] Snyder, D.L., *Random Point Processes*, John Wiley and Sons, New York NY, 1975.

[4] Steiner, J.P. "Digital Measurement of Partial Discharge", Ph.D. Thesis, Purdue University, W. Lafayette IN, May 1988.

[5] Steiner, J.P., Weeks, W.L. and Furgason, E.S., "Digital Estimation of Partial Discharge", 1987 Annual Report, Conference on Electrical Insulation and Dielectric Phenomena, Gaithersburg MD, October 1987.