Medium Voltage Cable Defects Revealed by Off-Line Partial Discharge Testing at Power Frequency

Key Words: cables, impurities, defects, electrical trees, medium voltage, partial discharge, testing, water trees.

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An effective, off-line partial discharge diagnostic test method for cables that identifies defects such as electrical trees associated with water trees and insulation contaminants, delamination, and physical damage caused by rough handling is briefly described.

Introduction

Medium voltage cables insulated with extruded dielectric materials, especially crosslinked polyethylene (XLPE), are extensively used throughout the world. Large scale commercialization of XLPE insulated cables began in the 1960s. In North America, the early cables were not jacketed. The requirement for jacketing, started in the early 1970s, did not become widespread until some time in the mid to late 1980s. As early as 1970, cable users became aware of early deterioration and premature failure of these cables. Among the causes cited were water treeing, impurities, delamination of semiconducting screens, and protrusions. As the early XLPE cable population is aging, its impaired reliability is becoming cause for serious concern. Several different testing technologies are attempting to help identify those cables that need repair, rehabilitation, or replacement [1]. The authors' company has been engaged since 1996 in performing cable diagnostic tests by means of an off-line, partial discharge (PD) location technology, using a 50/60 Hz excitation voltage.

This article describes typical cable defects uncovered while testing over 9,000 km of medium voltage XLPE insulated cables. After a brief review of the testing method, the procedure that led to the identification, localization, and characterization of typical defects found in operating cables will be described. Water trees often are considered as a major issue leading to premature cable degradation [2]. Partial discharge activity has not been reported within water trees (WT) during their growth [3]–[5]. However, "conversion" of WTs to electrical trees (ET), which are associated with PD activity, have been discussed [6], [7] in the context of laboratory research. The formation of ETs has been considered as a final breakdown mechanism leading to cable failure within a relatively short time. This paper, based on actual service performance of cables, will show several cases in which ETs associated with WTs have not led to cable failure even after several years of service in very harsh operating environments. It will, as well, describe several other defects, such as inclusions, rough semiconducting screen surfaces, screen delamination, and damages caused by rough handling during installation. Partial discharge characteristics typically associated with some of these defects will be shown. Examples of PD detected in a cable rehabilitated with silicone-based fluid injection will be illustrated.

Off-line 50/60 Hz PD Testing Method

The cable under test is disconnected from the system, and the following testing steps are implemented [8]:

- a low-voltage time-domain reflectometry operation intended to locate cable joints (splices) and other irregularities, such as corroded neutrals;
- a sensitivity assessment test;
- a PD magnitude calibration test;
- a PD detection and location test under voltage stress conditions;
- data analysis and reporting; and
- a "matching" test to locate the exact physical PD site in a buried cable.

Each of these steps, except the first—which has no direct relevance to the subject of this paper—will be briefly described.

A. Sensitivity Assessment

The purpose of this step is to determine the value in picoCoulomb (pC) of the smallest PD signal detectable under the test conditions. The setup is illustrated in Figure 1.

A calibrated pulse, such as 5 pC, is injected at the near end. The PD estimator detects and records the response. If the reflected signal cannot be seen above the filtered noise level, a larger signal, such as 10 pC, is injected. This process is repeated until the reflected signal is observable. This determines the smallest PD signal that can be resolved under the test conditions.

B. PD Magnitude Calibration

The calibrated pulse generator is connected to the cable remote end. A large signal, such as 50 pC or 100 pC, is injected. The corresponding signal recorded at the near end is evaluated by integrating it with respect to time ($q = k\int vdt$). The constant k is adjusted until the PD magnitude read is 50 pC or 100 pC. The instrument is now calibrated for measuring the apparent charge, q, of the PD.

C. PD Testing under Voltage Stress

In Figure 1, the pulse generator is replaced by a 50/60 Hz resonant transformer. The voltage is rapidly raised to the cable-operating level (1.0 p.u.) at which it is maintained for several minutes as a conditioning step. The voltage is ramped to its maximum value (such as 2.0 p.u. or 2.5 p.u.). It then is returned to zero as quickly as possible. During this stress cycle, several sets of data are captured, as shown in Figure 2, each set encompasses an entire 50/60 Hz period. The rising and falling parts of the voltage help determine the PD inception voltage (PDIV) and extinction voltage (PDEV), respectively.

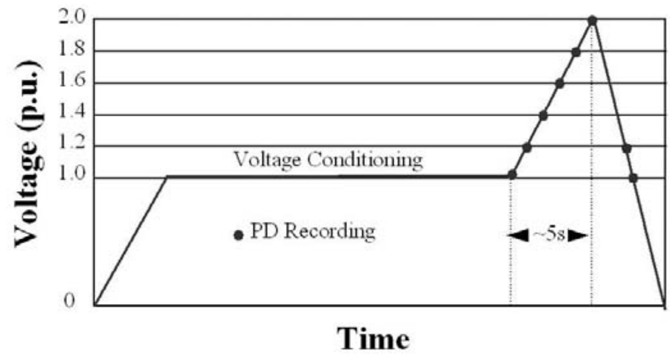

Figure 2. Time profile of the excitation voltage applied during a partial discharge (PD) test.

D. Data Analysis and Reporting

Figure 3 illustrates a typical data set. Prior to analysis, noise mitigation filters are applied. A cursor moving from left to right stops at each signal whose magnitude exceeds a preset value dictated by the remaining background noise, and displays the signal in a time-expanded frame. The PD magnitude, the phase angle at which it occurred, and its location estimated by reflectometry are determined and stored. Figure 4 is a histogram showing the frequency of PD occurrence per cycle versus the PD location at each voltage level. For each PD, a phase-resolved display is prepared at each test voltage level, as will be shown later.

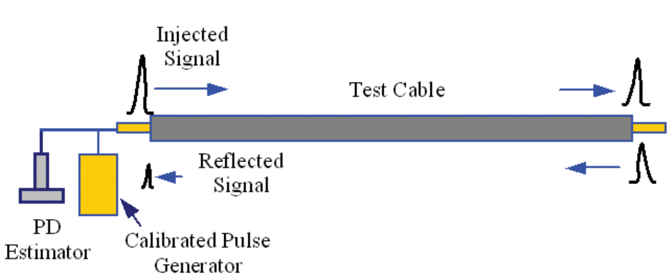

Figure 1. Setup to assess the threshold of sensitivity during a field test.

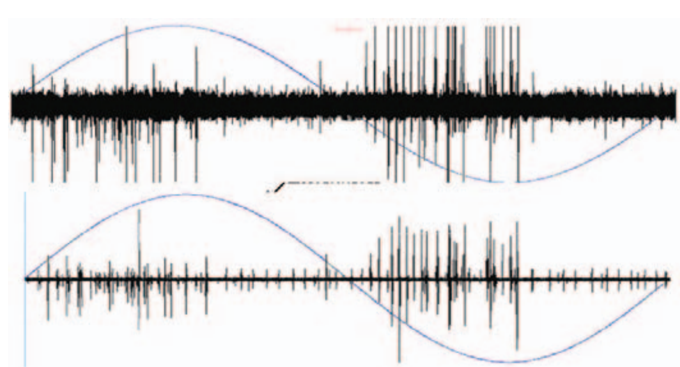

Figure 3. Unprocessed partial discharge (PD) data (above) recorded during one voltage cycle and data after noise mitigation (below).

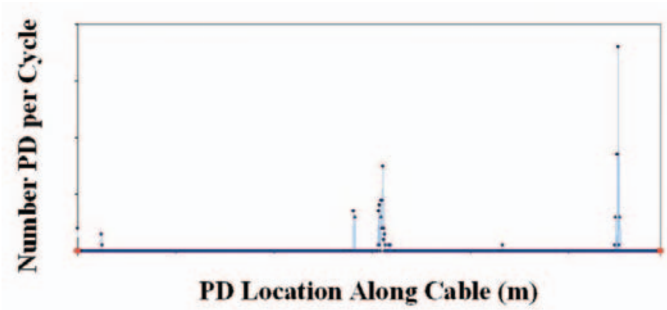

Figure 4. PD histogram showing, at each location, the number of partial discharge (PD) per cycle.

E. "Matching" Operation

The purpose of this operation is to match the estimated PD site to its actual physical location along a buried cable. The estimated distance from the near end is measured with a measuring wheel. A small test hole is dug until the cable is reached. A voltage pulse simulating a PD is injected electromagnetically into the cable. The location in which this pulse was injected is estimated by the PD-measuring equipment installed at the near cable end. This provides the distance by which to move in order to get to the correct PD location.

Characterization of Cable Defects

A. Procedure

In order to identify the PD causing defect, a cable section of a minimum 7 m length—containing the "matched" PD site—is removed from the field and subjected to a laboratory investigation where a final PD location is carefully performed from both cable ends, using the regular reflectometry method or an accurate "time-of-arrival" method. A large number of measurements have confirmed that the PD site located in the field and that found in the laboratory are generally within ±0.6 m of each other. The cable is sectioned into 0.3 m long specimens; one contains the measured PD site and the rest cover 0.9 m length on either side of the PD site. The protective jacket, the concentric neutrals (or metal shields), and the insulation screen are removed. A thorough visual examination of the insulation surface can often reveal the exact location of the PD site. The specimens are immersed in a bath of silicone oil heated to approximately 110°C, until the XLPE insulation becomes transparent. Visual examination of the insulation reveals the defect, which is properly marked. After cooling, the insulation is machined into a 0.25 mm –0.50 mm thick spiral (slinky) for microscopic examination. Generally, the examination is done without applying a dye. However, dyeing with a solution of methylene blue is an option that is sometimes exercised to confirm the existence of a WT.

B. Electrical Trees Associated with Water Trees

Water treeing manifests itself as strings of water-filled microcavities. Relative to dry XLPE, the insulation containing WTs has a higher permittivity (dielectric constant) and a higher conductivity. Whether the WT is of the vented (growing out of one of the screens) or bowtie (growing from the insulation volume radially toward both screens) variety, its share of the total voltage applied across the insulation is very small compared to the dry insulation surrounding it. As a result, ETs tend to form in the dry areas adjacent to WTs whenever defective sites with enhanced electric stress exist in these areas. Discernible PD may not be sustained within the WT, but it does occur at the surrounding ET sites. Several examples follow.

Electrical Tree Growing from Screen toward Vented WT: Figure 5 illustrates a large, vented WT emanating from a conductor screen and an ET emanating from the insulation screen. The ET is growing radially toward the top of the WT. This site was first detected in the field in 2002. The PDIV remained constant at 2.5 p.u. for two additional years in service without failure.

Electrical Tree Emanating from Conductor Screen under a WT: Figure 6 illustrates the case of several ETs emanating from the same screen (conductor screen) and growing in the "shadow" of a large, vented WT. Note that each ET in Figures 5 and 6 is

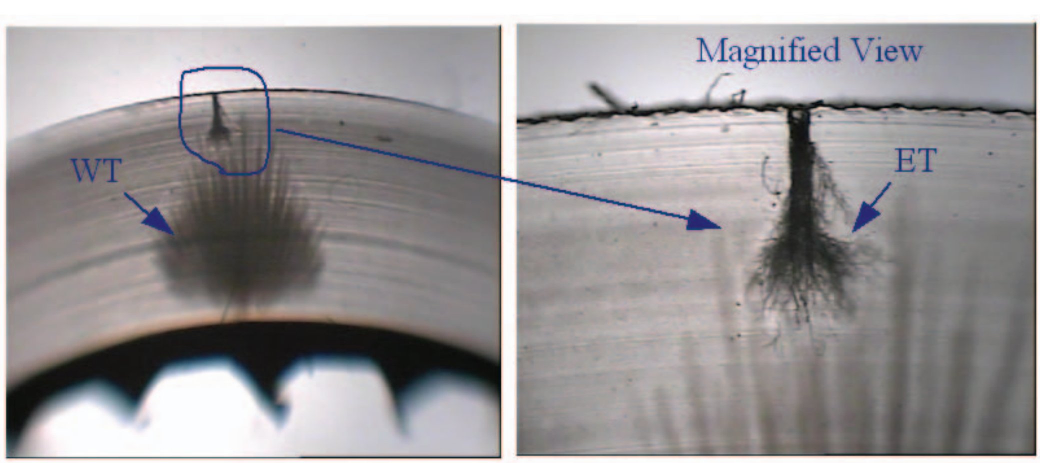

Figure 5. Vented water tree (WT) and electrical tree (ET) growing into each other from opposite screens.

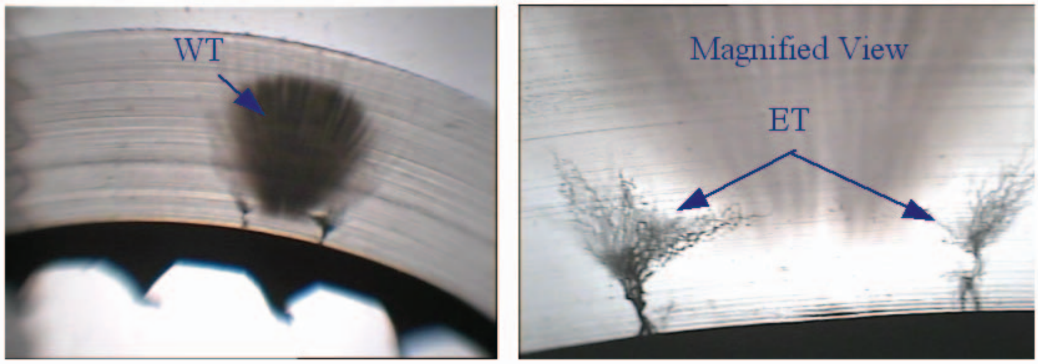

Figure 6. Vented water tree (WT) and electrical trees (ET) with deflected branches emanating from the conductor screen.

growing in a dry portion of the insulation in which the electric field is enhanced. In Figure 6, the ET branches growing into the WT are clearly deflected laterally (presumably because of a low radial electric field component), and the branches outside the WT are growing radially toward the insulation screen. This PD site was tracked in the field for 3 consecutive years. Its PDIV remained at the 2.0 p.u. level. Although Figure 6 indicates a dry region close to the screen, there may have been a thin, wet trunk that does not show in the cross section.

Electrical Tree Emanating from Screens on Both Sides of a WT: Figure 7 illustrates the case of a long, vented WT emanating from the conductor screen of a 15 kV XLPE cable with poor service performance. This unjacketed cable had been in service over 25 years. A PD was detected at 2.5 p.u. test voltage (the initial PDIV was somewhere between 2.0 and 2.5 p.u., the two consecutive levels at which PD was measured). The cable owner requested that a withstand test at 60 Hz be performed at this voltage for 5 minutes, immediately following the PD test. The cable survived this test, but its PDIV dropped to 1.5 p.u., presumably as a result of the further damage caused by the discharge in the insulation during the prolonged withstand test. A cable section containing the PD site was cut off and subjected to a laboratory investigation. The vented WT covered the entire insulation wall thickness and ETs were observed emanating from the screens on both sides of the WT. The magnified view shows that the tree branches were just about to meet when the withstand test was interrupted. This pattern also has been observed in the presence of bowtie WTs [9].

Electrical Trees Growing from Tip of a Finger-Like WT: Figure 8(a) shows a bowtie ET growing at the tip of a long, finger-like WT. This PD site was first noted in the field in 2001. It was reconfirmed in 2002 and 2003. The PDIV remained practically constant at 1.7 p.u. Figure 8(b) is another PD site in the same feeder cable. Again, bowtie ETs are growing at the tips of thin cactus-like WT branches. This PD site was first detected in 2002 and reconfirmed in 2003. The PDIV remained constant at 2.0 p.u.. The feeder was tested in the laboratory and dissected in 2004-2005. The phase resolved diagram for one cycle at 2.5 p.u. voltage for the specimen in Figure 8(a) is shown in Figure 9. It is compatible with that expected for such an ET.

C. Electrical Trees Associated with Contaminants

Solid contaminants embedded in the insulation sometimes have been found to be the sites of PD activity. No attempt was made to find the origin of the contaminants by analysis. Figure 10 is such an example. This site was first discovered in the field

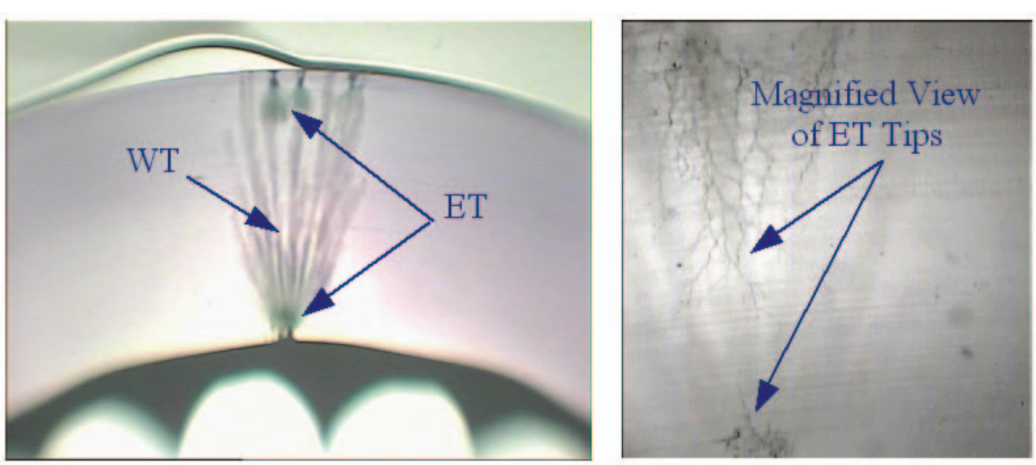

Figure 7. Electrical trees (ET), with tips close to meeting, on both sides of a long vented water tree (WT).

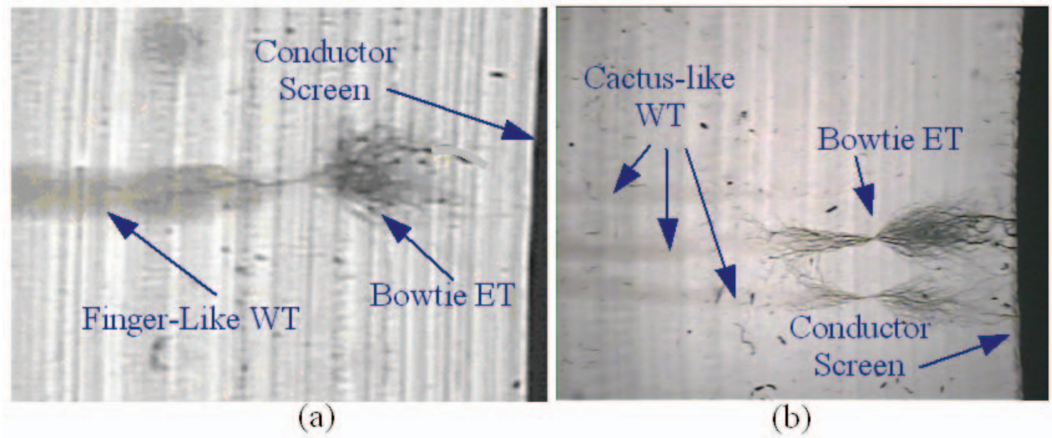

Figure 8. Micrographs of bowtie electrical trees (ET) growing at the tips of finger-like water trees (WT).

at 2.5 p.u. voltage in 2002 and was reconfirmed in 2003.

Laboratory testing and dissection were performed in 2004-2005. Electrical trees are seen linking two contaminants, and another elongated ET is seen emanating from the conductor screen, probably at the site of some surface roughness. A phase resolved PD diagram (PD magnitude versus phase angle at which PD occurred during one cycle of the applied voltage) obtained at 2.5 p.u. voltage is shown in Figure 11.

D. Bush-Type Electrical Trees

The bush-type tree has been observed repeatedly on 1000 kcmil (~500 mm^2) Al-conductor, 15 kV XLPE insulated feeders with copper concentric neutral and a jacket. No visual evidence of water treeing exists. Figure 12 provides an overall view of the tree, and Figure 13 is a magnified view of another such tree, showing more clearly the branches of the ET. The trees emanate from the insulation screen. Generally, they consist of a main bush and a large number of “seedlings” growing around its trunk, presumably at the sites of interface stress concentration areas. These trees, reminding one of certain sea shells, have a striking combination of blue, green, and rust colors. The tree tops are evenly rounded, minimizing any leading edge stress concentration. The PD site depicted in Figure 12 was observed at 2.0 p.u. voltage during PD tests conducted 12 months apart while the cable remained in service between tests. In the laboratory, several months after decommissioning and storing outdoors, the PDIV had dropped to approximately 1.2 p.u.. The different PD phase patterns of Figure 14 for one cycle at 10.0 kV and 13.0 kV are interesting and may shed light on how the PD evolves with increasing voltage.

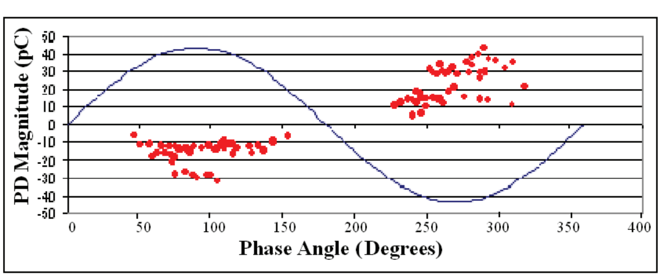

Figure 9. Phase angle diagram obtained at 2.5 p.u. for specimen in Figure 8(a).

E. PD and Treeing Associated with Silicone-Injected Cables

An aged XLPE insulated cable feeder, without prior failure history, was injected with silicone fluid to preclude failures due to water treeing. This was done without prior off-line PD testing, which could have revealed any existing ETs. After the injection was completed and the required conditioning time elapsed, the cable was returned to service. Within less than 50 hours, the cable failed, was repaired and failed again. The locations of the failure sites were not recorded. An off-line PD test at power frequency revealed four PD sites. At two of these sites, the owner induced failures in the cable upon application of repeated impulse test voltage (thumping). A 30 m long cable sample containing the remaining two PD sites were sectioned off and made available for laboratory examination. Figure 15 shows a cross-sectional view of the defect at one of the PD sites, together with a magnified view of the ET tips. The second site had a similar tree emanating from the insulation screen. Microscopic examination showed a faint silhouette in the background of a vented WT that was emanating from the conductor screen. Before injection, the WT was probably preventing rapid ET growth because of the low stress provided within its foliage. Upon removal of the WT by silicone injection, the ETs were allowed to grow rapidly.

F. Miscellaneous Other PD Sites

Partial discharge is almost invariably mentioned in conjunction with voids or microcavities in the insulation or at interfaces with screens. The only cases of PD of this category uncovered by the authors on installed cables had been caused by delamination between the screens and the insulation or by physical injuries inflicted on the cable insulation or its screen during manufacturing, transportation or installation. For instance, a new 15

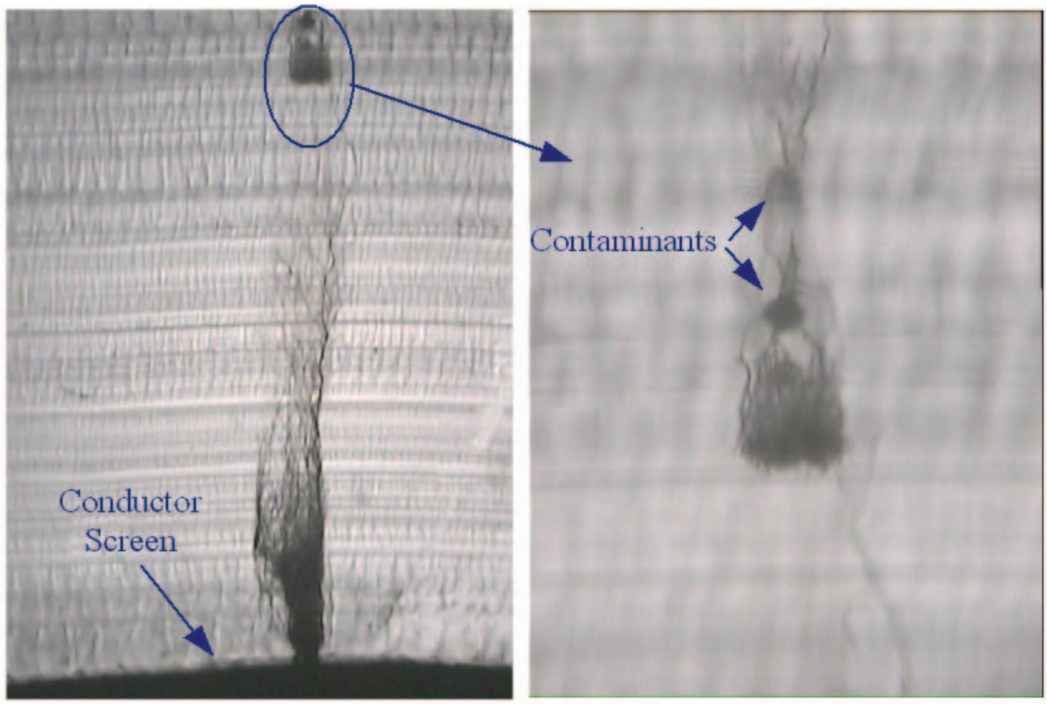

Figure 10. Electrical trees (ET) are linking two contaminants and another ET is emanating from the conductor screen.

kV ethylene-propylene rubber (EPR) insulated cable showed a PD site at 12 kV during commissioning tests after installation in a duct system. The PD magnitude was 38 pC. The PD location and magnitude were confirmed by an independent laboratory. The cause was reported to be a separation of the insulation from its screen. Normally, such a defect should have been detected by the manufacturer. Figure 16 depicts a defect found at a PD site with a PDIV of 17 kV. A neutral wire was found penetrating a gash extending through more than 50% of the insulation. The existence of a WT suggests that this defect probably had been inflicted during installation over 25 years ago, or some subsequent repair. The PD most probably was occurring on the insulation surface. These are by no means isolated cases of cable installed with imperfections, usually caused by rough handling. In rare cases, voids have been found in XLPE insulation that had been subjected to excessively high temperatures.

Discussion

The foregoing examples illustrate defects that have been found in medium voltage cables by means of off-line PD testing. Although these may not cover all possible defects, they were selected because they have been encountered frequently in cable samples that were made available by their owners. Some were due to solid contaminants present in the raw materials or introduced during the manufacturing process. High stress concentration areas at semiconducting screen-insulation interfaces have been observed to be the sites of ETs. Such defects occurred more frequently in old vintage cables. Nowadays, quality control is expected to reduce the likelihood of such defects. Other defects have been traced to rough cable handling during trans-

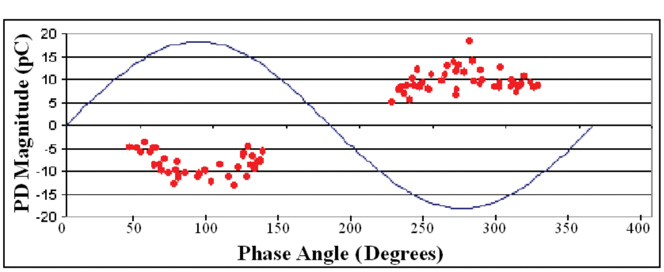

Figure 11. Phase angle diagram obtained at 2.5 p.u. for specimen in Figure 10.

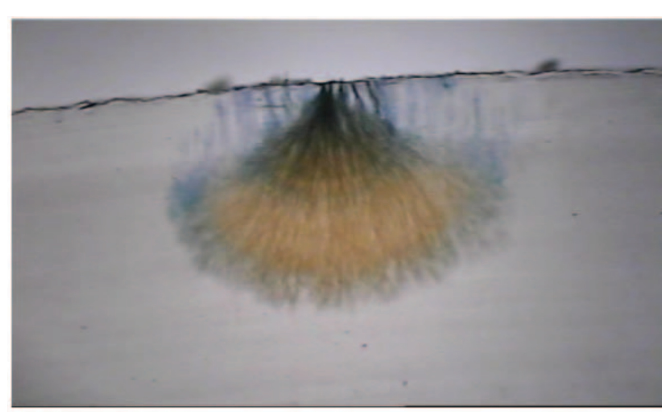

Figure 12. Bush-type electrical tree (ET) emanating from the insulation screen of 15 kV feeder.

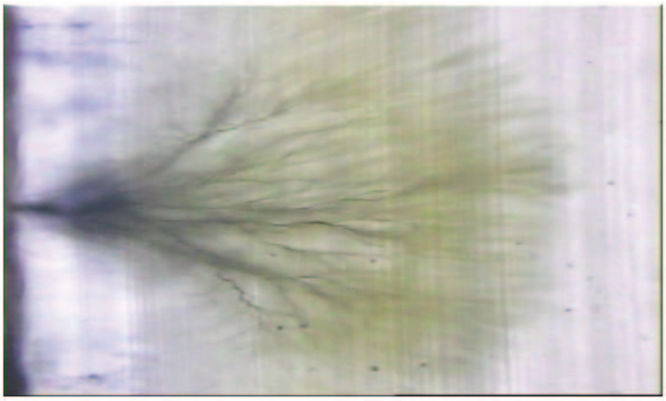

Figure 13. Magnified view of bush-type electrical tree (ET) showing structure of its branches.

portation or installation. By far the most prevalent PD sites were observed to occur at ET sites associated with WTs.

Water trees have significantly higher permittivity and conductivity than the dry portions of insulation. Under 60 Hz or higher frequency electric fields (such as those encountered under switching surge or lightning conditions), voltage distribution within the cable insulation occurs mainly through capacitive coupling and, therefore, is dictated by permittivity. Areas with water treeing have relatively higher capacitance and, therefore, assume a smaller proportion of the total voltage, while the adjacent dry areas of insulation become overstressed. This is depicted in Figure 17 by means of equipotential lines that show two enhanced stress areas around the WT. As the WT grows larger, so does the stress in these areas. Should there be, in addition, any unusual roughness over the surface of the screen or some other inclusion in these areas, an electric tree is generated, especially during transient overvoltage conditions. Electrical trees thus started tend to grow every time the stress exceeds the PD inception level at the tip of the ET. This continues until, relatively rapidly, the ET tip meets the boundary of the WT, which represents a low stress region. At this juncture, the

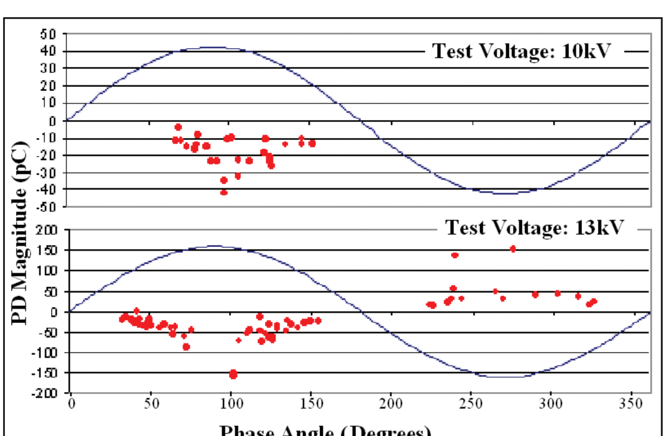

Figure 14. Phase angle diagram for the defect in Figure 12 at two voltage levels.

growth of the ET is markedly slowed down. This explains why PD, observed at certain cable locations over a period of 3-4 years, had yet to lead to failure. Eventually, some time (weeks to months) after a heavy lightning storm or following a withstand voltage maintenance test exceeding the PDIV level, the cable may fail at these locations during normal service.

Electrical trees associated with finger-like WTs may not grow until the WT becomes very long. A transient overvoltage or long time exposure to a withstand test (VLF tests last 15-60 minutes and, in Europe, some power frequency tests last 30 minutes, "thumping" may be performed at a relatively high voltage level) may trigger the formation of a bowtie ET at the tip of the WT.

Although a WT can retard the growth of an ET during service, this delay cannot last for ever. Experiments conducted in the field and in the laboratory have shown that withstand tests (with both power frequency and VLF voltage) lasting as long as 30 minutes can significantly decrease the PDIV at a defect site without causing failure. If the PDIV drops to operating level, an imminent failure should be expected. Figure 7 offers a pictorial example of ETs emanating from both screens just about to meet and cause a cable fault.

Water trees are the "curse" that leads cables toward their ultimate destruction. However, once initiated either at the top or at the bottom of a WT, ETs experience a growth that is effectively retarded by the low stress prevailing within the WT. Some trees are deflected around the periphery of the WT. Others stop growing altogether until the WT bridges the entire insulation thickness. During this stage, WTs act as a "blessing". As the WT bridges the entire insulation thickness, the electric stress distribution within the insulation reverts back to its original pattern that existed prior to water treeing and the ETs resume their rapid radial growth, each time the PDIV is exceeded, until failure occurs.

Bush-type ETs are characterized by rounded fronts that limit stress enhancement at the tree tips. Partial discharge sites monitored for several years were found upon dissection to consist of bush-type ETs. No apparent deterioration has been observed in the PD behavior over time. This could not have been guaranteed if the cable had been subjected to unduly high stress by lightning, maintenance withstand testing or thumping. In an unrelated case (encountered in Europe while the foregoing examples happened in the United States), dissection of a PD site revealed a typical ET emanating from the top of a bush. Highly aged cables afflicted with serious defects, such as those described in this article, could last many years in service if care is taken to apply proper surge protection and avoid mistreatment by withstand testing and thumping.

Summary and Conclusions

This article has documented several major types of cable defects that were discovered by PD testing. A summary of the findings and important conclusions reached are provided below.

- Off-line PD testing at power frequency effectively sorted out defective from serviceable cables.
- In testing service-aged cables, seldom was a cavity-type de-

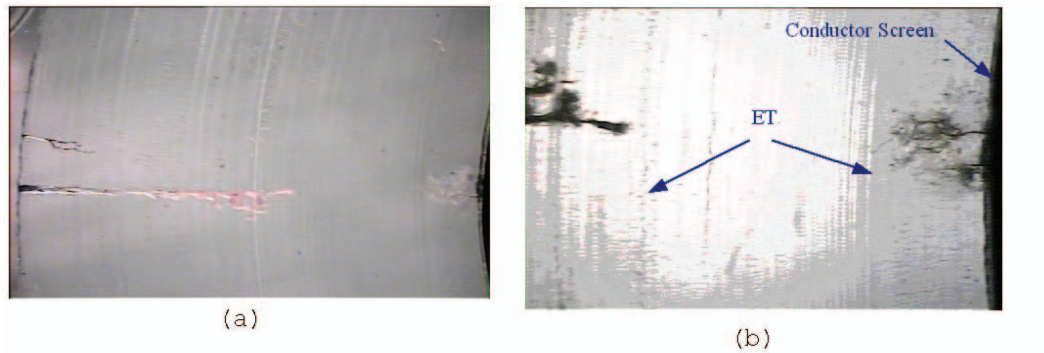

Figure 15. ETs growing from both screens at the site of an old water tree (WT).

fect encountered, except in cases in which a physical damage was inflicted during transportation or installation (Figure 16), or when, owing to poor factory quality control, delaminated layers of insulation and semiconducting shields went unnoticed. Of all such PD sites identified during field tests, none had lead to the development of ETs.

- A number of solid impurities within the insulation have been found to be the sites of ETs with PD activity. Material suppliers, cable manufacturers and cable owners should continue to be vigilant about keeping cable insulation clean.
- Most PD sites of highly service-aged cables (over 20 years in service) revealed ETs often associated with large WTs.
- Vented WTs bridging the entire insulation thickness had not resulted in service failures. Dissipation factor tests alone could not have been used economically in an effective assets management strategy, as WTs alone are not responsible for cable failure. Water trees could promote ET initiation, the ultimate failure mechanism. Dissipation factor tests may be useful as a supplementary test to minimize the number of cables that may benefit from treatment by silicone fluid injection. However, a prior PD test is necessary to identify ET sites.
- Repeated field testing of cables with PD sites at up to 2.5 p.u. over a period of 4 years caused no additional, apparent deterioration, as the PDIV levels showed no dramatic decrease over time, and no test-related failures could be documented. Apparent deterioration (lower PDIV and higher discharge levels) were encountered on some of the cables only after they were kept de-energized for long periods of time (over ~2 weeks).
- PD testing of defective cables following several weeks in a de-energized state often showed a clear decrease in PDIV. This may be ascribed to the partial drying of WTs, which could increase the electric stress at the tips of pre-existing ETs. Under the recommended test procedures, such long periods in the de-energized state are to be avoided. Under normal conditions, testing followed by repair and acceptance retesting should be performed in much less time than 1 week.
- Although phase-resolved diagrams obtained during testing could distinguish cavity type and ET type PD sites, no effective means has yet been found to exactly predict the remain-

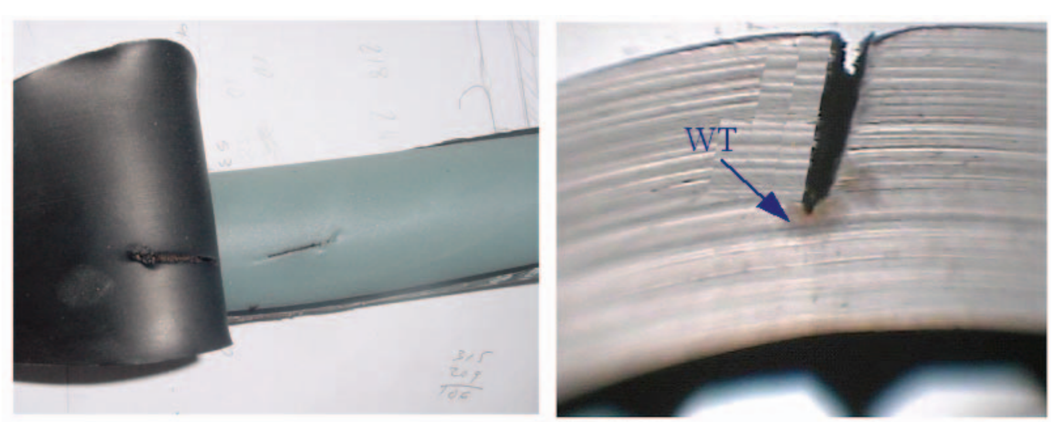

Figure 16. Deep gash, over 50% of the insulation, made during installation.

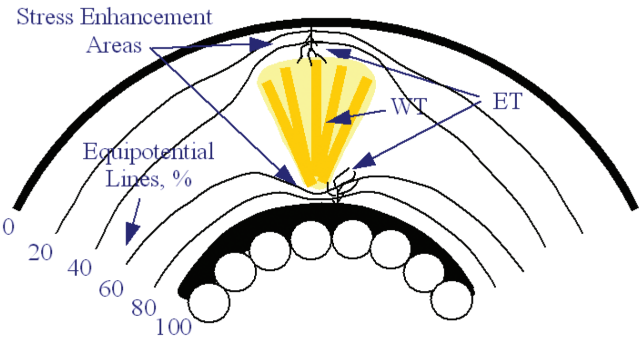

Figure 17. Stress enhancement areas, sites of possible electrical trees (ET), created by a water tree (WT).

ing operating time before the next failure for all PD sites.

- PD sites were identified in cables that had been treated by silicone injection or by drying of WTs. Some of these locations were later identified with service failure sites. Others were dissected to reveal the existence of very long ETs that, presumably, predated the treatment process. Removing WTs had helped accelerate the growth of pre-existing ETs.
- Withstand tests applied to cables in the field as a means of sorting poor cables from reliable cables were found to gradually increase the severity of certain defects without causing failure because of insufficient application time.

The foregoing information gathered over several years of field testing should help the cable owner make the right decision about preventive diagnostic testing.

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Dr. Mashikian holds 13 patents covering electrical insulating devices, surge protection systems, load leveling batteries, cable jacketing materials and cable diagnostic test systems. He is a Past Chairman of the IEEE/PES Insulated Conductors Committee, a Past Chairman of the IEEE/DEIS Education Committee, and a member of the Connecticut Academy of Science and Engineering.

Andrzej Szatkowski was born in Nysa, Poland, on July 21, 1973. He received his BSEE from the University of Connecticut in May 1999. He was employed by IMCORP as a co-op student in 1997–1998, and has been with IMCORP as a full-time employee since his graduation.

Mr. Szatkowski has conducted laboratory investigations on cables retrieved from the field and has developed several diagnostic instruments. He presently is manager of hardware engineering and development.