Return to Session

CONDITION ASSESSMENT OF POWER CABLE SYSTEMS IN THE ENERGIZED STATE

Nagu SRINIVAS, Vice President, UTILX Corp., (Kent, Washington, USA), nsrinivas@utilx.com
Bruce S. BERNSTEIN, Consultant, (Rockville, Maryland, USA), b.s.bernstein@ieee.org

ABSTRACT

CableWISE technology is an excellent predictive maintenance tool that has been used to assess the condition of electrical equipment in the energized state while operating in electrical utility and industrial plant environments. It is an on-line totally passive technique which allows the measurement of signals at high frequencies emitted by the cable system while it is operating in service. The technique is particularly applicable for identifying the type of defects that cause aging and loss of life of cable system components. The analyses of the results are used to assess the severity of aging in cables, splices, terminations and the electrical equipment connected to the system. This non-destructive, non-invasive approach assists the user in establishing a predictive maintenance program in a proactive manner. This paper describes the rationale for studying signals prior to and after partial discharge inception.

KEYWORDS

Diagnostics, Partial Discharge, Pre-Discharge Signals

INTRODUCTION

Insulating materials deteriorate with time. In some cases deterioration can progress to the point where breakdown occurs prematurely. This applies to paper-insulated cables as well as to extruded cables. While paper insulated lead covered cables (PILC) have significantly long useful lives, the fact is that they are also reaching their end of life (at different aging rates) and it is important to understand the degree of degradation that cable systems have undergone upon aging. The deterioration mechanisms in paper insulation involve moisture entry (which facilitates thermal runaway), partial discharges (in oil starved butt spaces & tapes) voids and cavities, tracking and eventual formation of wax due to aging.

The service life of medium voltage extruded cables based on HMWPE and XLPE insulation has historically been shorter then anticipated relative to when these insulation materials were first applied by the cable industry. This subject has been discussed thoroughly in the past; causes of rapid deterioration have been defined and are known to have resulted from multiple sources along the ‘chain of usage’. Issues have related to materials (contamination, ion presence serving as loci for water treeing, polymer nature), manufacturing (entrapped moisture within the insulation wall) and user practices (e.g. DC HiPot testing) that contributed to problems leading to premature loss of life. While most of these practices have been improved upon, nevertheless there are millions of meters of installed cable subjected to these earlier practices. With increased knowledge of these issues, modifications (including use of ethylene copolymers (EPR) and ‘tree-resistant’ XLPE) have led to improved and longer life installed extruded cable systems. However, with so many meters of the older systems still installed, the growing issue has become one of economically managing an aging system that is known to be of inferior quality relative to those cable systems that are being installed today. In other words, how does one decide whether and when to rejuvenate, repair or replace? Allowing the cable system to operate until failure has its own hazards, such as failures that will most often occur under harsh storm conditions (making replacement difficult), incorporation of splices onto aged systems that may better be replaced, etc. The merits of an on-line predictive approach as a diagnostic tool to assess the future performance of PILC and extruded cable systems, the limitations of non-predictive testing, and the issues that must be considered in setting up and using the predictive technology are reviewed in this paper.

Predictive Technology

Predictive methodology employed by CableWISE involves signal detection both prior to and during partial discharge inception. While partial discharge detection has been studied in depth, study of pre-partial discharge signals, their detection, measurement, and significance with focus on application of information from these signals as a diagnostic tool for predictive purposes, has not attracted as much attention. Prior focus on pre-discharge phenomena has focused primarily on charge storage, transfer and release, and the influence of these events on the mechanisms of aging, degradation and breakdown (1). This paper discusses signal detection from pre-partial discharge events, their application as a cable diagnostic tool, as well as conventional partial discharge detection and signal interpretation.

Signal detection R&D efforts with extruded cable materials have been presented earlier by Morel et al (2). Dorris, Pace, et al (3) had earlier demonstrated that signals from water trees could be measured in the absence of partial discharge (using specially designed sensitive equipment). Bruning (4) demonstrated that chemical changes could result without partial discharge. The work by Dorris and co-workers was performed on previously water-treed PE, while the latter work was with previously un-aged PE. Signals that were detected by Dorris, et al. in water treed regions of a low density polyethylene sheet were categorized as a ’slow’ pulse and a ‘fast’ pulse; they reported current waveforms as small as 66 nA being reliably detected for the former. For the latter, charges as small as 1.2 fC could be reliably measured. Noise filtration, an obvious concern, was discussed. The detection of signals from water trees, in the fC range demonstrates that with proper equipment, signals that emanate from aged insulation material can be measured in the absence of true partial discharges.

Bruning's studies focused on subjecting LDPE possessing gaseous cavities to an applied voltage stress both below and above corona inception voltage in air. They demonstrated that nitrogen-containing components (measured by XPS) were present on samples stressed both above and below the corona inception voltages. They concluded that sub-corona-induced aging in air can lead to chemical changes (a conventional partial discharge detector confirmed that the insulation was being tested below CIV).

Prior studies by Tanaka (5) discussed the subject of pre-discharge phenomena and the principles reviewed therein are of interest here. With reference to electrical trees, he reviews a mechanism for pre-tree formation and pre-partial discharge events within the tree. For the time period prior to electrical tree initiation, the induction period can be summarized as (a) charge injection and extraction at an interface (b) material degradation (electrochemical aging) and (c) distortion of the field as the electro-physical situation changes. Tanaka suggests that the repeated process of charge injection and extraction between the electrode and the dielectric may represent a tree initiation mechanism. Of interest is the concept that this allows electrical tree initiation without invoking partial discharge.

Charges injected into and extracted from the insulation under AC stress will lead to accumulation near the electrode. Polymer degradation due to chain scission and oxidation eventually occur. The link between space charge and electrical treeing from earlier work has been summarized by Dissado (1) who also notes that the true onset of electrical treeing is represented by appearance of current pulses. In addition, Okamoto and Tanaka (6) report on experimental studies where under AC, 'non-destructive current pulses' were observed in polyethylene. It is suggested that an electron avalanche precedes the local breakdown process leading to generation of 'non-destructive current pulses'.

These studies provide significant 'food for thought' relative to both electrical and water treeing; they suggest that (a) currents can be measured in water trees in polyethylene, (b) chemical changes can occur in polyethylene under voltage stress without partial discharge (corona), (c) non-destructive current pulses can be measured at PE or XLPE interfaces prior to electrical treeing, (d) pre-discharge signals can be measured in TR-XLPE, (e) electrical tree initiation does not necessarily have to involve partial discharge, and (f) non-destructive current pulses may initiate tree formation. From the CableWISE perspective, signals from pre-discharge events being detectable are significant.

General Approach and Detection

The CableWISE methodology encompasses the following:

- Evaluation is made without shutting the system down; the value of this is apparent.
- On-line testing determines what is happening at operating voltage; the test is therefore 'passive' in that no over voltage is applied, and therefore the test procedure itself cannot induce a minor defect to become a major one.
- Signal analysis and pattern recognition from signals at high frequencies (7) allows for determination of the type of defect causing the signal (the defects causing 'loss of life' help identify the extent of degradation) and locates the source of the defect within the equipment.
- The on-line test measures signals that result from both pre-discharge events and during partial discharge (conventionally measured) events. The CableWISE technology measurement of all signals facilitates estimation of future performance and rankings (see below).
- Measurements are made at discrete locations between sensors. Since cables age at different rates along their lengths, it is easy to separate heavily aged sections from lightly aged sections.

The CableWISE methodology measures the condition of equipment in the total system at operating temperature; this often overlooked fact is significant as at elevated temperatures, XLPE insulation will have undergone partial melting, and the degree of crystallization will change depending on the temperature in the cable wall (load cycling plays a role also). The defect nature influences its response to temperature changes. Also, at elevated temperature, wax present in PILC from degraded dielectric fluid (undoubtedly influencing oil flow and void formation at ambient) will have melted (depending on the temperature). Hence the information gathered by the CableWISE technique under operating conditions is more valuable and meaningful than information gathered after the insulation has cooled down, as void presence in XLPE or PILC will differ at ambient vs. at elevated temperatures.

The on-line test method measures signals (that are always present in the operating cable during the aging process while in service) in both the time and frequency domains (8). From analysis of the signals, the condition of the equipment between sensors is determined. The sensors are moved to different locations as testing is continued. This method therefore allows the estimation of future performance of all equipment located between sensors, and does not depend upon signals traveling along the length of the cable system, which may be indeterminate. Finally, from the signal analysis information developed, cableWISE will rank the equipment according to the 'degree of degradation'. Five levels are commonly employed. The most significant (Level 5) suggests immediate replacement; intermediate levels suggest potential retesting after different time frames. Equipment showing little or no aging-induced loss of life is categorized as Level 1. As noted earlier, the defect type influences the signal and its significance. Water trees and moisture will yield pre-discharge signals. Voids, cavities, imperfect interfaces yield post discharge signals (as do floating metal). The signal nature of each defect differs and is interpreted by CableWISE.

Return to Session

Verification

Measurement of pre-discharge signals in a cable model in the laboratory has been reported by Morel et al. (1). It was demonstrated that signals can be observed before the formation of the electrical tree (growing from a metallic needle point into the insulation of a 15 kV TR-XLPE insulated cable). In this work, in-situ measurements of partial discharge were made while at the same time observing the initiation and growth of an electrical tree with a stage microscope. The authors noted that (a) signals were observed immediately after applying the electrical field (11 kV/60 Hz) and before the first evidence of an electrical tree, and (b) partial discharges increased in intensity as the formation of the tree progressed. Figure 1 shows the pre-discharge signals measured on a 15 kV rated cable in the laboratory and Figures 2 and 3 shows the measurements obtained from the field in two different cable systems.

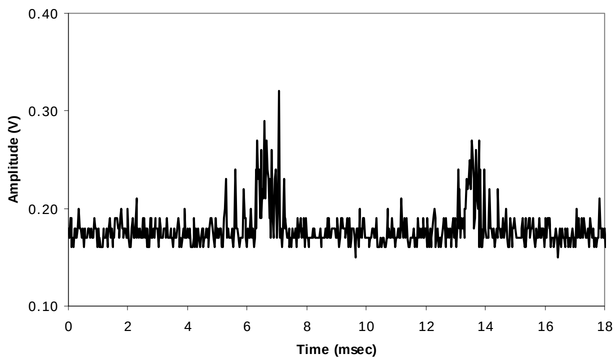

Figure 1: Pre-discharge signals observed in the laboratory on a 15 kV rated cable (60 Hz) (from reference 2).

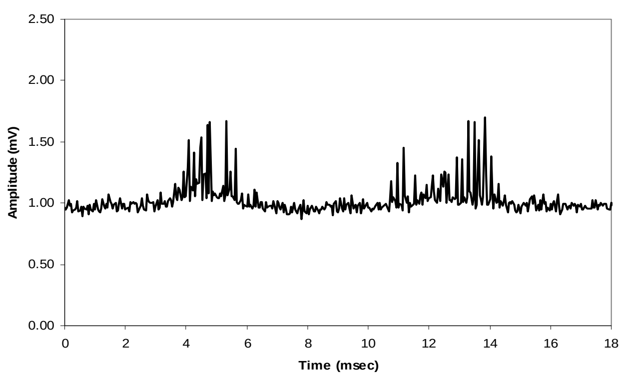

Figure 2: Pre-discharge signals. Data taken in the field in 2007 from a 15 kV rated (60 Hz), 750 kcmils conductor size, XLPE insulated cable, unjacketed and 1971 vintage.

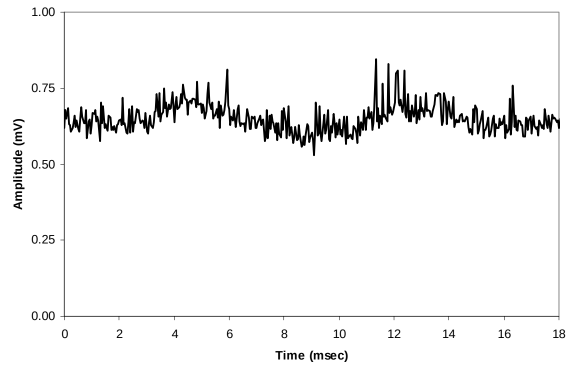

Figure 3: Pre-discharge signals of very low intensity observed in 2007 from a 15 kV rated (60 Hz), 750 kcmils conductor size, XLPE insulated, unjacketed and 1984 vintage.

APPLICATION

CableWISE technology has been employed in the field over the past nine years on energized cable systems operating in Utility and Industrial environments. Several million meters of cables systems with PILC, PE, XLPE, EPR and rubber insulation materials have been tested successfully. As an example, the technology described above has been applied in a planned program at a United States utility (9). Upon initial testing, a cable evaluated as a Level 5 defect was targeted for removal, but before replacement could take place, the Level 5 cable sections failed (a few weeks after testing). This utility has applied this technology to over 440,000 circuit feet of network cables and accessories at the time of this report (both PILC and XLPE cable were tested) and of this total, 4% of the cable was removed based on assessment results. Cables that were not removed have been performing satisfactorily after testing was completed.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Oscar Morel for developing the experiments for laboratory measurements of pre-discharge signals. He also analyzed the data from the field measurement and extracted the signals from the pertinent field data.

SUMMARY

A non-destructive predictive maintenance tool for estimating future performance of installed cable systems while they remain energized has been described. The technique has been applied in utility and industrial plant environments. The technique measures signals at high frequencies which are detected by sensors placed at discrete locations along the cable system length. Signals detected may precede partial discharge or be a result of partial discharge inception. Defect type and location influence interpretation of data collected. Relevant literature is reviewed indicating that pre-discharge signals can be detected and further indicating that physico-chemical changes leading to aging induced degradation may result in the absence of conventional

Return to Session

partial discharges.

REFERENCES

1. L.A. Dissado and J.C. Fothergill "Electrical Degradation and Breakdown in Polymers" G.C. Stevens, Edited by Peter Peregrinus Press (1992).

2. O. Morel, N. Srinivas and B.S. Bernstein "Partial Discharge Signals from TR-XLPE Insulated Cables" Conference Records IEEE International Symposium on Electrical Insulation (2004).

3. D.L. Dorris, M.O. Pace, T.V. Blalock and I. Alexeff, IEEE Trans. Dielectrics and Electrical Insulation (a) 3 (4) pp. 515-522 (1996); (b) 3 (4) pp. 523-528 (1996).

4. A.M. Bruning, D.G. Kasture, F.J. Campbell and N.H. Turner "Effect of Cavity Sub-corona Current on Polymer Insulation Life", IEEE Trans. Electrical Insulation Vol. 26, No. 4 pp. 826-835 (1991).

5. T. Tanaka "Space Charge Injected via Interfaces and Tree Initiation in Polymers" IEEE Trans. Dielectrics and Electrical Insulation Vol. 8, No. 5, pp. 733 (2001).

6. T. Okamoto and T. Tanaka "Detection of Non-Destructive Pulses in Polyethylene Prior to its Dielectric Breakdown" IEEE Trans. Electrical Insulation 20, (3), pp. 643-645 (1985).

7. S. Boggs "The Case for Frequency Domain Partial Discharge Testing in the Context of Distribution Cable" IEEE Electrical Insulation Magazine 19 (4) (2001).

8. N. Srinivas and N. Ahmed "On-Line Partial Discharge Testing in Power Cable Systems" Proc. IEEE T&D Conference, pp. 2-7, New Orleans (1999).

9. N. Srinivas, T. Nishioka, K. Sanford and B.S. Bernstein "Non-Destructive Condition Assessment of Energized Cable Systems". Proc. 2006 IEEE Summer Power Meeting, Paper 1-4244-0493-2/06, Montreal, Canada, June (2006).