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Long-Term Operations: Evaluation of the KEMA Smart Cable Guard System for On-Line Partial Discharge Detection

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Long-Term Operations: Evaluation of the KEMA Smart Cable Guard System for On-Line Partial Discharge Detection

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PRODUCT DESCRIPTION

This report documents an EPRI-sponsored evaluation of a commercially available system for the on-line detection of partial discharge in cables. The evaluation, performed in a testing laboratory, used model medium-voltage cable systems representative of the types of cables commonly installed in U.S. nuclear power plants. Specifically, ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) cables were chosen, and artificially created partial discharge sites were introduced in order to provide a foundation for the analysis. The researchers then evaluated the ability of the Smart Cable Guard® system, a product of DNV GL (formerly DNV KEMA) of the Netherlands, to monitor cable condition and diagnose problems in these cables.

Background

Operation of nuclear plants beyond their originally planned service life will require plants to have sound and reliable medium-voltage cable systems, which depends on accurate assessment and monitoring of in-place cables. One of the ways in which EPRI provides support to members is by keeping abreast of new and improved testing and monitoring technology and by performing assessments of some of the equipment that appears on the market. This report documents one such effort, involving the Smart Cable Guard system, which employs on-line partial discharge monitoring for assessing the health of a guarded cable system. The motivation underlying the assessment is that the ability to perform on-line evaluation of partial discharge signals on cables can enable the identification of certain cable degradation and allow plant operators to take actions to preclude in-service failures.

Objectives

- To assess the ability of the KEMA Smart Cable Guard system to identify and evaluate partial discharge in aged EPR insulated cable and in XLPE insulated distribution-type cables of the kind used in off-site feeds to nuclear plants
- To report on the evaluation results and the potential applicability of this system for use in diagnostic testing and monitoring of cable condition in U.S. nuclear plants

Approach

The equipment to be tested was purchased from the manufacturer, who also provided training and setup support for the test configuration. Test circuits were created in the laboratory with artificially induced partial discharge signals in order to provide a blind test of the ability of the manufacturer (who provides system control services from an off-site location) to receive data over the Internet and interpret the magnitude and location of signals from the artificially created partial discharge site. As the evaluation progressed, several attempts were made to maximize the test configuration to provide an optimum chance for partial discharge detection and to resolve difficulties that led to insufficient and limited success in accurately identifying and quantifying the partial discharge presented.

Results

Based on the relatively low sensitivity of partial discharge signal detection of the Smart Cable Guard system in the configurations evaluated, this device does not appear to be suitable for diagnostic testing and monitoring of extruded cable systems in U.S. nuclear plants. As a secondary issue, there were constraints on the ability to obtain technical support for system setup and troubleshooting because the equipment service provider is situated in Europe and the assessment was performed in the United States. The issues were not a reflection of the level of expertise of the service provider's personnel or their willingness to help. The support availability problems were mainly due to time zone differences that led to limited windows for communication during regular work hours. Additionally, the lack of proximity of technical personnel and the requirements of travel cost and travel time placed practical limits on the availability of on-site support.

Applications, Value, and Use

The information in this report is intended for use in supporting decisions regarding selection of on-line partial discharge monitoring equipment as a means of detecting degradation in extruded medium-voltage cables of the types commonly used in nuclear power plants. In this evaluation, the on-line system in question did not demonstrate sufficient sensitivity to capture the partial discharge at levels that would indicate a cable is degraded. Such information can be of significant interest to plant operators as they look for the best ways to target valuable resources and limited funds.

Keywords

Cable
Condition monitoring
Medium voltage
On-line monitoring
Partial discharge

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Research Overview and Motivation

This report documents an EPRI-sponsored evaluation of a commercially available system for the on-line detection of partial discharge in cables. The evaluation, performed in a testing laboratory, used model medium-voltage cable systems representative of the types of cables commonly installed in U.S. nuclear power plants. Specifically, ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) cables were chosen, and artificially created partial discharge sites were introduced in order to provide a foundation for the analysis. The researchers then evaluated the ability of the Smart Cable Guard® system, a product of DNV GL (formerly DNV KEMA) of the Netherlands, to monitor cable condition and diagnose problems in these cables.

Operation of nuclear plants beyond their originally planned service life will require plants to have sound and reliable medium-voltage cable systems, which depends on accurate assessment and monitoring of in-place cables. One of the ways in which EPRI provides support to members is by keeping abreast of new and improved testing and monitoring technology and by performing assessments of some of the equipment that appears on the market. This report documents one such effort, involving the Smart Cable Guard system, which employs on-line partial discharge monitoring for assessing the health of a guarded cable system. The motivation underlying the assessment is that the ability to perform on-line evaluation of partial discharge signals on cables can enable the identification of certain cable degradation and allow plant operators to take actions to preclude in-service failures.

Brief Description of the Smart Cable Guard System

The principle of operation for the Smart Cable Guard system consists of capturing partial discharge signals by using two sensors, magnetically coupled at both ends of the guarded cable length, and transmitting this information to a control center operated by KEMA. Thus, a client does not have direct access to the information but rather receives it from KEMA, already processed and analyzed. In the event that suspicious partial discharge activity is detected in the monitored system or an emergency condition presents itself, the client receives warnings from the KEMA center. A general description and philosophy of this technology is provided on KEMA's website at http://www.dnvkema.com/services/advisory/etd/am/scg/Default.aspx.

The Smart Cable Guard system consists of elements installed on site and a control system operated by KEMA. These elements communicate to each other through the Internet, using a general packet radio service (GPRS) or a local area network (LAN) connection. The on-site installed elements consist of partial discharge sensors/injectors plus control units connected via fiber optic cables to the sensors/injectors. The control units coordinate and control operation of the sensors/injectors, gather necessary data, and transfer the data to the control system. Data sheets for the above-mentioned components are available from the manufacturer (see website link above).

The sensor/injector unit does more than just measure partial discharge with an inductive coil. It also contains a device that injects pulses into the cable. This is done for both synchronization and calibration of the unit.

Synchronization is needed for accurate time-base alignment of the two measuring devices, to eliminate any pulses originating from outside the monitored cable circuit (that is, to eliminate noise and disturbances), and to locate the weak spots in the complete cable circuit by means of the detected partial discharge. The synchronization is done by injecting a pulse on one end of the cable circuit. This pulse travels in exactly the cable propagation time to the other cable end, where it is measured and recognized. Both internal clocks of the sensors/injectors will start their measuring sequence of one power cycle immediately after receiving the synchronization pulse. When the two records are later combined, the arrival times of partial discharge pulses at both sensors/injectors can easily be corrected for the cable propagation time and thus the partial discharge locations can be calculated.

The sensors/injectors offer the possibility of calibration because the injected pulse of each of the devices is measured by both unit sensors. This feature is supposed to allow for calculation of the actual partial discharge charge from the measured partial discharge pulse shape. Calibration also makes it possible to calculate and implement digital noise suppression if needed. This digital noise suppression is a task of the control unit.

The Smart Cable Guard system has limitations in its application. For instance, single-point bonded systems need to be grounded through additionally installed capacitors on the floating ends, cross-bonded systems cannot be measured, and so on. The main limitation encountered within this project was the fact that the guarded cable sections must be surrounded, from both sides, by other cable sections, sufficiently long to avoid abrupt termination of the line impedance. In some cases step-up or step-down transformers can be used to match cable impedance. In the training material provided with the purchase of their system, KEMA presents some examples of proper and improper connections.

2
DESCRIPTIONS OF THE MODEL CABLE SYSTEMS USED IN TESTING

Contrary to the initial expectations, instead of involving a two- to-three-week-long period, the project lasted for over half a year. Due to other requirements for use of the laboratory floor, experimental cable setups had to be moved from one place to another, using different cable sections, different test equipment, and matching impedances. Additionally, modifications to the model systems were made in response to unclear experimental results and because of failure of some of the components.

The initial goal was to evaluate a type of ethylene propylene rubber (EPR) insulated cable that is commonly used in U.S. nuclear power plants. A section aged in service during 30+ years was employed. This was done to take into consideration possible degradation of cable components and to model a real-world situation as realistically as possible. However, assuming a relatively high attenuation of high-frequency partial discharge signals in this cable type, a short cable section, 40 feet (12 m) long, was chosen for the initial trials. The cable design was as follows:

- **Conductor:** 250 kcmil copper, outside diameter (OD) = 0.531 in. (13.5 mm)
- **Conductor shield:** 15 mils (0.38 mm) extruded semiconducting compound, OD = 0.560 in. (14.2 mm)
- **Insulation:** 175 mils (3.3 mm) extruded pink EPR, OD = 0.904 in. (23.0 mm)
- **Insulation shield:** 110 mils (2.8 mm) extruded semiconducting compound, OD = 1.12 in. (28.6 mm)
- **Metallic shield:** 6 x 18 AWG bare copper wires embedded in the bulk of the insulation shield

The other test section was a typical 35-kV, concentric neutral, tree-resistant, cross-linked polyethylene (TR-XLPE) insulated cable. Due to the known relatively low attenuation of partial discharge signals in this cable design, a longer section, over 700 ft (213 m), was used. This cable length was selected mainly in consideration of the limited power that test equipment could supply, rather than from the partial discharge propagation and attenuation standpoint. This cable had the following design:

- **Conductor:** #1/0 AWG (7 strands) bare copper, OD = 0.35 in. (9.2 mm)
- **Conductor shield:** 20 mils (0.5 mm) semiconducting XLPE, OD = 0.40 in. (10.2 mm)
- **Insulation:** 345 mils (8.76 mm) TR-XLPE, OD = 1.09 in. (27.7 mm)

- **Insulation shield:** 30 mils (0.76 mm) semiconducting XLPE
- **Metallic shield:** 11 x 24 mils (0.6 mm) bare copper wires
- **Insulating jacket:** 90 mils (2.3 mm) linear low-density polyethylene (LLDPE)

There were other cable sections used as end matching impedances, to satisfy the conditions dictated by Figure 2-1. However, since these were not test objects, but rather they belonged to a test power supply, their design is of no significance.

Due to the long cable sections used and the limited laboratory test floor space, the cables were tested on reels, connected in series to each other. A sketch of the test configuration is presented in Figure 2-1.

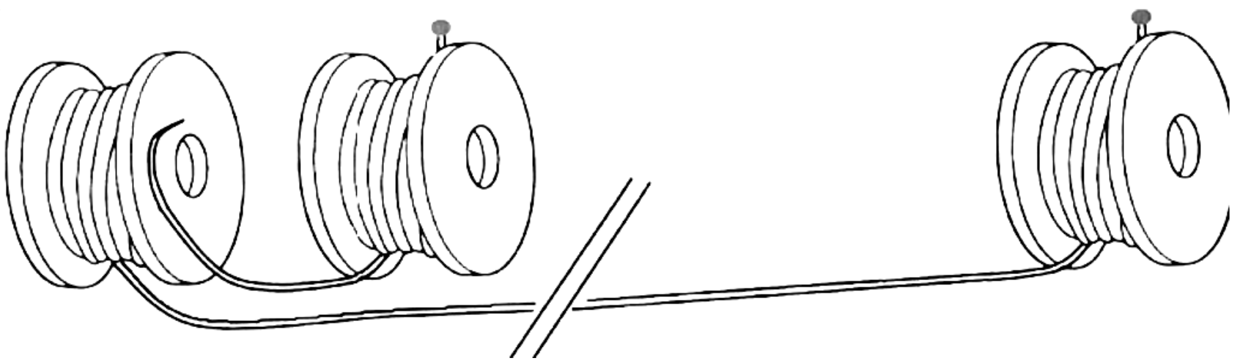


Figure 2-1
Configuration of cable sections in the test setup

Because of the extended duration of the project and the need to move the model cable system from one part of the laboratory to another, different power supplies, inductive coils, and transformers (to compensate for the cable capacitive load) were employed. In all cases, preliminary tests were performed to demonstrate partial discharge-free performance of the test setup, unless intentionally created partial discharge sources were introduced. Typical examples of the test configuration are provided in Figure 2-2.

Figure 2-2
High-voltage test setup

Different approaches to application of the sensor/injector unit application were tried in the course of the experiments:

- On top of the jumpers connecting cable neutrals (configured with higher or lower inductance)
- Over the entire cable, incorporating both the conductor and metallic shield
- On top of the cable core, with the metallic shield removed
- Over the cable with its neutral in place plus an additional neutral jumper running in the opposite direction (as compared to the original neutral)

Selected examples of the sensor/injector unit positioning are shown in Figure 2-3. In all arrangements the sensor/injector unit case was electrically insulated from the cable components, including the neutral jumpers.

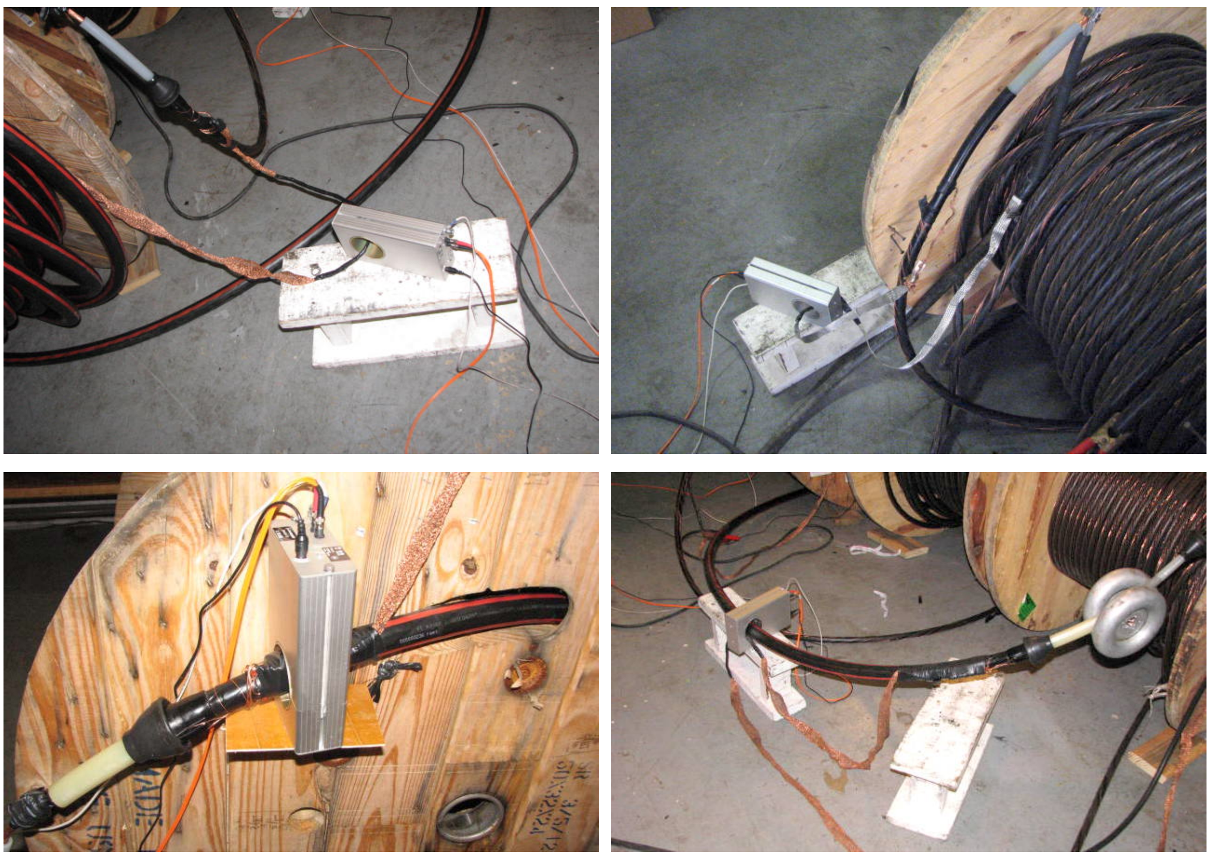


Figure 2-3
Placement of partial discharge sensors (sensors/injectors)

To simulate the generation of partial discharges from defective cable sections, artificial damage was imposed on the cores of the EPR and TR-XLPE concentric neutral cables. Only one defective cable section was incorporated into the model cable system at a time.

The defects in both cables were introduced in a similar way. First, the outer layers of the cables were removed using a grinding tool that left rough surfaces, so that a section of the insulation was exposed. Next, neutral wires that had been damaged to provide access to the cable core were placed directly over the exposed insulation and their continuity was re-established. Finally, the purposely damaged areas were covered by wrapping a few layers of semiconducting tape over them. Figure 2-4 shows the exposed insulation, using as an example the EPR insulated cable (top picture), and a completed artificial defect with the semiconducting tapes applied, using as an example the TR-XLPE insulated cable (bottom picture).

Figure 2-4
Artificial cable defects, introduced to serve as the source of partial discharges

3
TEST EXECUTION AND RESULTS

The project began with a visit by KEMA representative Mr. Ad Kerstens, who provided Cable Technology Laboratories (CTL) personnel with the main information related to the setup and operation of the Smart Cable Guard system. Project goals and approaches were also discussed during this visit. At the end of the project, because there were inconclusive test results and questions about possible malfunctioning of the equipment, another KEMA representative, Dr. Paul Wagenaars, visited CTL and performed additional testing and evaluation of the system.

For each individual section of cable containing artificial damage, the tests were started by performing calibration with the help of a partial discharge measuring system employed by CTL, the Lemke type LDD-5. Table 3-1 presents the partial discharge intensities (apparent charge transfer in picocoulombs) that were recorded for the respective applied voltages.

Table 3-1
Partial discharge characteristics of artificial defects

EPR Defect		TR-XLPE Concentric Neutral Defect	
Voltage, Kv	Partial discharge apparent charge transfer, picocoulombs	Voltage, kV	Partial discharge apparent charge transfer, picocoulombs
6.6	50	10	200
8.0	100	14	300
9.0	200	15	500

As shown by the data in Table 3-1, partial discharge between 50 and 500 picocoulombs (and higher, if necessary) could be reliably generated. It should be noted that cables, as manufactured, must be partial discharge free at a measuring sensitivity of 5 picocoulombs. On-site partial discharge test sensitivity is typically proclaimed by service providers as varying between 5 picocoulombs and 100 picocoulombs. The lower limit seems to be exaggerated, while the upper limit is believed to be more realistic. On the other hand, defective extruded cables usually generate signals at several hundred picocoulombs (at the most, just before they fail), in contrast with cable accessories that can sustain discharges of higher magnitude, up to several hundred nanocoulombs. Overall, the artificial defects created were believed to be quite representative of the conditions in cable systems in U.S. nuclear power plants that must be reliably detected by a partial discharge monitoring system in order to avoid misleading results and the possible overlooking of critical situations in the process of development.

Laboratory evaluations of the model cable systems began with the damaged EPR cable, while the TR-XLPE concentric neutral cable was still intact. A number of trials were attempted, with all of them being unable to create an adequate partial discharge record on the KEMA server. Next, the EPR insulated cable was removed from the system, and artificial damage was introduced in the TR-XLPE insulated cable. Again, several trials were performed, with no success. A brief test log is provided in Table 3-2 (some intermediate steps that were not conducive to any progress are omitted).

Table 3-2
Test log for evaluation of the Smart Cable Guard system

<table>
<tr><td>Date</td><td>Action Performed</td><td>Result</td><td>Reason(s)</td></tr>
<tr><td>5/16/12</td><td>Initial circuit configured to locate PD in a Unishield cable.

Initial circuit consists of two 200 ft #2 XLPE impedance coils, one 40 ft Unishield test cable and one 790 ft #2 XLPE load cable.

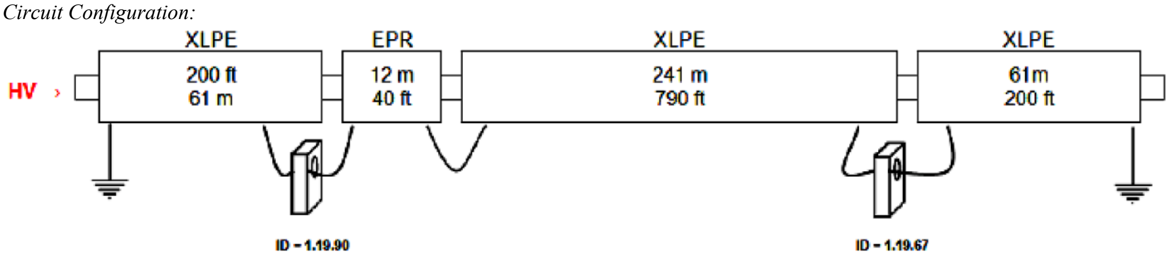
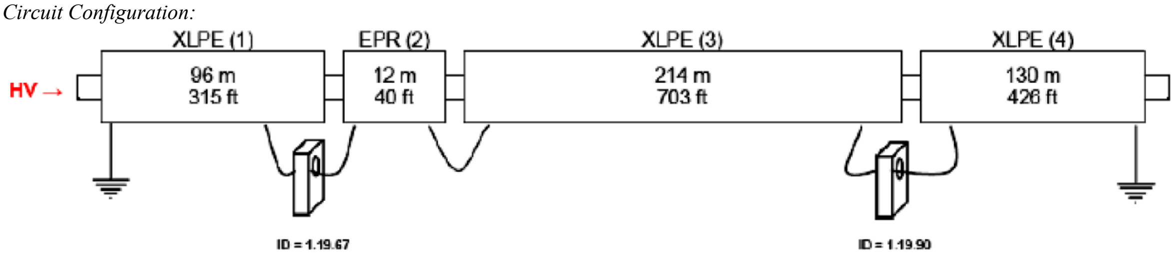
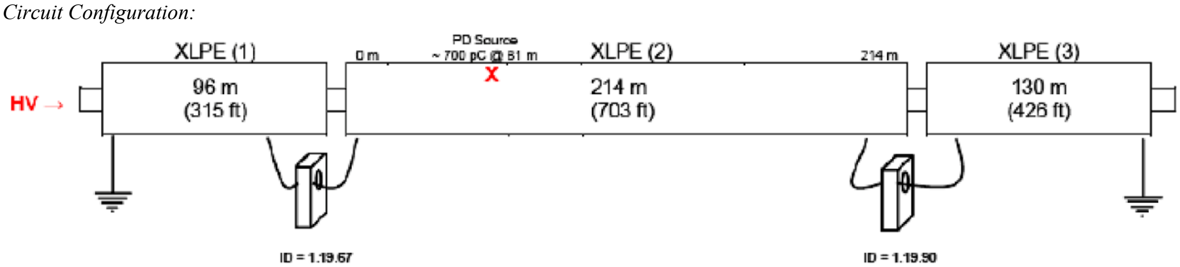
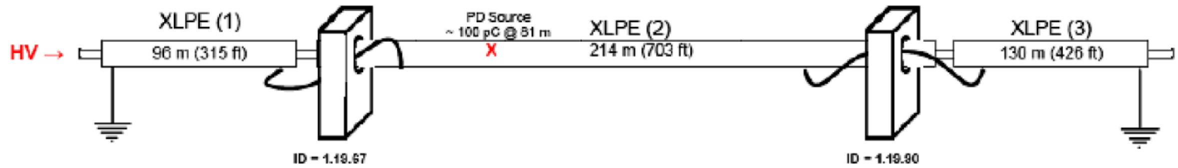
Initial application of 11 kV to the test circuit for two hours.</td><td>None</td><td>System was not configured on KEMA’s end per email from 5/21/12</td></tr>
<tr><td colspan="4">Circuit Configuration:

</td></tr>
<tr><td>5/24/12</td><td>SCG systems configured at KEMA</td><td>Online access granted</td><td>Systems configured on KEMA’s end as per email from 5/24/12</td></tr>
<tr><td>5/24/12</td><td>Attempted to log in to system with Firefox</td><td>Log on failed</td><td>Website seems only compatible with Internet Explorer</td></tr>
<tr><td>5/25/12</td><td>Power applied to circuit</td><td>Small impedance coil failed</td><td>#2 XLPE cables were of unknown quality. Removed from the circuit.</td></tr>
<tr><td>6/4/12</td><td>Circuit re-configured with (1) 315 & (4) 426 ft #1/0 XLPE impedance coils, (2) 40 ft Unishield test cable and (3) 703 ft #2 XLPE load cable.</td><td>No PD shown on KEMA system</td><td>No significant PD present in test cable.</td></tr>
<tr><td colspan="4">Circuit Configuration:

</td></tr>
<tr><td>6/5/12</td><td>Circuit re-configured by removing 40 ft Unishield test cable and reassigning 703 ft #2 XLPE load cable to test cable by introducing damage to the cable at 81 m that produces PD of ~700 pC locally.</td><td>No PD shown on KEMA system.</td><td>Sensor Units did not detect any PD. KEMA recommends a change in the positioning of the Sensor Unit and also only one connection to ground</td></tr>
<tr><td colspan="4">Circuit Configuration:

</td></tr>
</table>

Table 3-2 (continued)
Test log for evaluation of the Smart Cable Guard system

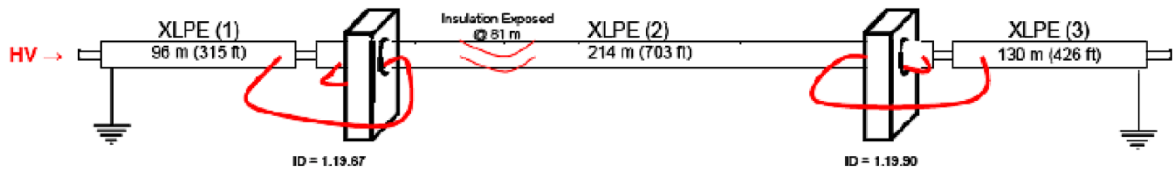
Date	Action Performed	Result	Reason(s)
6/12/12	Sensor Units moved and circuit energized with PD of ~1000 pC locally.	Large percentage of PD shown on KEMA website at wrong location	Grounding issues with one of the stress relief cones. Corrected and re-energized, however some PD shown in approximate location of the damaged area of the cable.

Circuit Configuration:



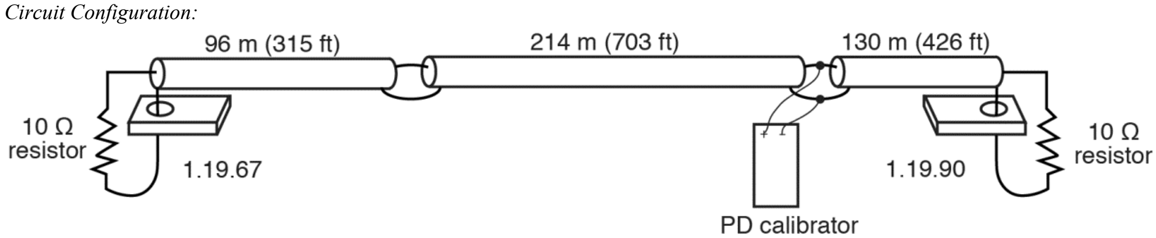
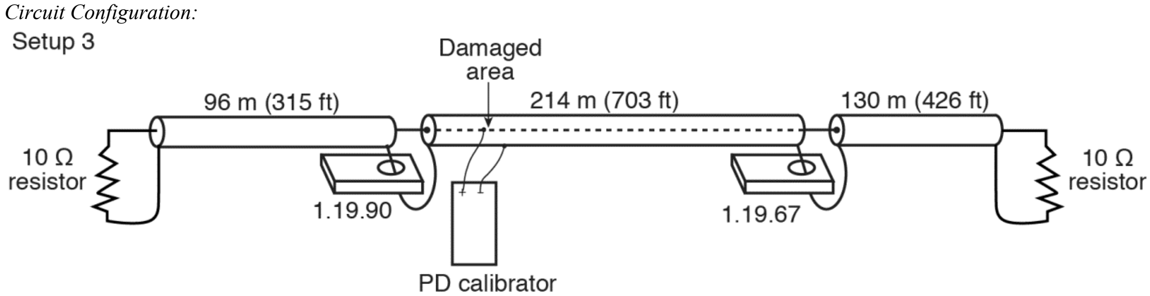
Date	Action Performed	Result	Reason(s)
6/19/12	Circuit energized	No PD shown on KEMA system	KEMA confirmed no difference on the website between a circuit without PD and a circuit that is simply not recording anything. Recommends positioning the neutral jumpers through the Sensor Unit units.

Circuit Configuration:



Date	Action Performed	Result	Reason(s)
7/22/12	Testing resumed. Circuit energized at 15 kV with 500 pC calibrator connected to system neutrals at previously damaged area and neutral jumpers run back through the Sensor units as recommended.	PD shown on KEMA system well outside of expected area	The terminations used to connect the test cable and impedance coils are suspected. Cold shrink joints purchased to address the problem.
8/1/12	When preparing to install Cold shrink joints it was discovered the cut-backs on the semi-conductor of the 703 ft test cable were not good. Corrected and termination PD problems resolved. Joints not installed. Circuit energized.	PD shown on KEMA system but not at the magnitude or location expected.	Possible feedback interference suspected from Sensor Units being too close to each other.
8/1/12–8/8/12	Various reconfigurations of the locations of the Sensor Units and neutral connections tested.	PD shown on KEMA system but not at the magnitude or location expected.	Unknown.
8/10/12–8/17/12	Approximately 60 ft of the test cable, including the damaged area, moved 30 ft away from bulk of the test cable, along with one impedance coil. Sensor unit re-connected between the impedance coil and the test cable, now 30 ft away from the other sensor unit. Calibrators with 10 000 pC and 500 pC signal magnitude connected between: 1) Cable conductor and cable neutral wires 2) Cable conductor and outside ground 3) Cable neutral wires and outside ground During these trials sensor unit was installed in 3 positions as show in KEMA brochure "Smart Cable Guard."	Each of the 9 combinations were tried for several hours each. No discharges were recorded on the KEMA system.	Unknown

Table 3-2 (continued)
Test log for evaluation of the Smart Cable Guard system

Date	Action Performed	Result	Reason(s)
9/25/12	System re-configured as recommended by KEMA. Additionally, one end of the cable and one sensor located behind a screening wall.	PD shown exactly where it was expected on KEMA website.	
Circuit Configuration: 			
9/27/12	PD Calibrator moved to damaged area of the cable, everything else remains the same.	PD shown exactly where it was expected on the KEMA website.	
10/1/12	System re-configured per KEMA's instructions. Effectively restored to original configuration with the addition of load resistors. Note sensor and cable were returned to the same side of the wall as primary sensor.	PD shown where expected with the addition of some noise.	Possibly due to the second sensor not being shielded by the wall.
Circuit Configuration: 			
10/2/12	Second sensor moved to the other side of the shielding wall.	No data received at KEMA website.	CU of the 1.19.67 sensor not transmitting data to KEMA. After extensive troubleshooting it appears the CU is defective.

Three types of problems were encountered during this stage of the project:

- Failure of cable end sections in the test setup, which prompted their replacement
- Difficulties in establishing a reliable connection with the KEMA server
- Lack of any reliable record on the server that would correspond to the partial discharge pattern in the model cable systems as measured by the local partial discharge measuring equipment

The first two issues do not appear to warrant analysis and discussion. The major problem was the inability of the Smart Cable Guard system to record partial discharge, after the initial issues with establishing the connection to the server were resolved and the manner in which the sensors should be installed was evaluated and eliminated as an issue to be questioned, along with all other issues with configuration of the model cable and monitoring systems.

At the end of this stage of the project, several tests were performed employing partial discharge calibrators (using an impulse generator injecting repetitive partial discharge-like impulses into the cable without applying high voltage). Additionally, wave impedance matching resistors were used at the cable ends, to avoid impulse reflection at these points (a measure that cannot be used during real tests on energized cable systems). Some of these tests were conducive to recordings on the KEMA server, as evidenced by there being elements in common with the actual partial discharge pattern. For the most part, the tests showed the correct location of the partial discharge activity spots in the cable system; however, they recorded significantly lower magnitudes for the partial discharge pulses.

None of the trials that were performed could clarify the situation. Different possible scenarios were analyzed and discussed between the parties involved, including malfunctioning equipment, use of wrong procedures, lack of experience in application of the Smart Cable Guard system on the cable types being evaluated, and differences in the on-site and laboratory application (for instance, cross-talk through the air between the sensor/injector units that in the field are normally located very far apart, whereas in the laboratory they were only a few dozen feet apart).

In the end, a visit by the KEMA representative Dr. Paul Wagenaars was arranged and additional testing performed. This round of tests was mostly executed employing partial discharge calibrators. Partial discharge-like pulses were injected into the cable neutrals, and even into the cable conductor. To achieve this latter connection, a nail was driven through the cable insulation, all the way into the conductor. The pulses were injected at the location of the artificial defect in the TR-XLPE insulated cable, at a location approximately 34% of its length from one of the ends.

After the visit, Dr. Wagenaars summarized the results as follows. (The original text of Dr. Wagenaars's message is in italics. Additions and comments made by CTL are bracketed and shown in regular font.)

Communication problems

One of the units stopped communicating with KEMA's server in the beginning of October. After investigating this problem we discovered that the local network in the lab produced errors on that particular connection. The Smart Cable Guard (SCG) units are sensitive to these network problems. After connecting the unit to a different network connection the communication problems were gone. [Note: Other equipment could use this network channel due to more advanced software that could work around the problem. Therefore, the problem remained hidden before the Smart Cable Guard equipment was tried.]

Sensor defect

When changing the setup it turned out that the ferrite core in one of the sensors (1.19.90) came loose. This sensor can be replaced by the new sensor that was sent along with the measurement equipment. Because the measured equipment had not arrived yet all the experiments below were conducted with the broken sensor. [Note: The equipment was delivered late, after Dr. Wagenaars left CTL, due to customs requirements.] *The loose ferrite core most likely did not have a significant influence on the result. The pulses injected by the sensor and the partial discharge calibrator pulses detected by this sensor seemed normal. Therefore, the fact that this sensor was broken has no significant effect on the experiments below.*

Experiments – partial discharge calibrator

Some adjustments were made to the test setup to make it possible to energize the test setup. In the end the test setup was as shown below. At the left end the cable under test was terminated by the transformer. The secondary side of that transformer was not connected to anything else. At the right-hand side a transformer energizes the test setup and CTL's partial discharge measurement equipment is connected [Figure 3-1].

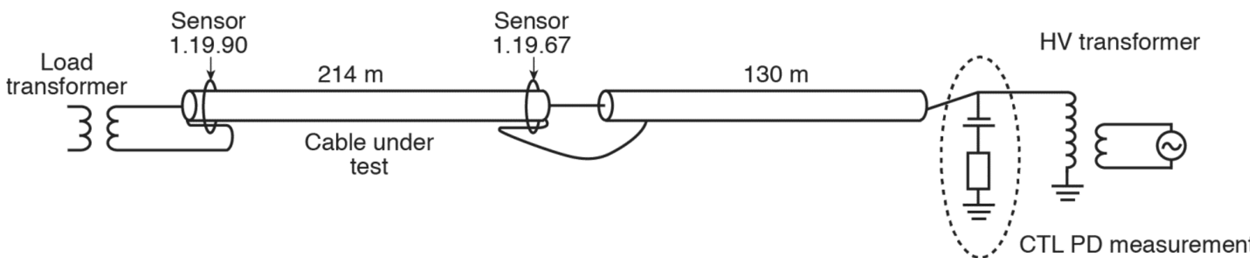


Figure 3-1
Sketch of the model cable system used during the final stage of the project

The cable under test contained an artificial defect at about 1/3 of the cable length. For this defect a nail was put in the insulation, touching the conductor. A partial discharge calibrator was connected between the nail and the metallic earth screen of the cable.

Partial discharge calibrator set to 2000 picocoulombs: the Smart Cable Guard system detected partial discharge pulses with a constant repetition rate of about 410 Hz and an amplitude of about 350 picocoulombs. The location of the partial discharge origins was detected as 34% of the cable length. The charge estimation seems to be 6 times too low, the location is correct.

Partial discharge calibrator set to 500 picocoulombs: the Smart Cable Guard system detected few partial discharge pulses with an amplitude of about 50 picocoulombs. The Smart Cable Guard system missed most of the partial discharge pulses. The location of the partial discharge origin was detected as 34% of the cable length. The charge estimation seems to be 10x too low, the location is correct.

Smart Cable Guard correctly located the partial discharge origin. But, there was a large error in the estimated partial discharge amplitude. In order to verify that the test setup itself did not cause this, a wire was connected to the partial discharge calibrator and put through the Smart Cable Guard sensor. Now the sensor sees a "perfect" partial discharge pulse that is not influenced by the rest of the test setup. When the calibrator was set to 2000 picocoulombs the sensor detected these pulses as 1000 picocoulombs. Normally, in a cable a partial discharge pulse splits in two (one in each direction) and a sensor sees only half the pulse. To correct for this the sensor multiplies the detected charge by two. Therefore, it should have detected the pulses as 4000 picocoulombs. This means an error of 4 times.

Experiments – Real partial discharge from defect

Next, the nail was removed from the test setup and the setup was energized up to 10 kV. Using CTL's equipment it was verified that partial discharges originated from the location of the artificial defect, that the amplitude of the discharges was about 2000 picocoulombs, and that the repetition rate was a few partial discharges per cycle. The Smart Cable Guard system did not detect any pulse. Configuration and operation of the Smart Cable Guard system was checked. No problem found, it seemed to be performing measurements as it should.

The artificial defect was covered with semiconducting tape and copper wire mesh in order to make sure that the full partial discharge signal couples into the cable under test. This resulted in a flashover before any partial discharge activity occurred.

The defect was cleaned out, it was covered by a metal part at a distance of a few centimeters (see photo below [Figure 3-2]*). The setup was energized again. Partial discharges were detected by CTL's equipment with amplitude of about 1000 picocoulombs and a repetition rate of a few partial discharges per cycle. The Smart Cable Guard system recorded* [completed] *about ten measurement records of 20 ms each. A single partial discharge was detected by Smart Cable Guard* [during the 200 ms window, presumably containing close to one hundred individual partial discharge pulses] *at 34% of the cable length with amplitude of 125 picocoulombs.*

Figure 3-2
Hole in the cable insulation covered with a donut—compare to Figure 2-4

Conclusions

Communication problems were caused by problems in the local network.

One of the sensors is broken. Despite this problem it is still able to perform measurement without significant problems.

All partial discharge pulses by the calibrator were correctly detected when set to 2000 picocoulombs.

The detection sensitivity of the Smart Cable Guard system seems to be about 500 picocoulombs.

The partial discharge charge estimated by Smart Cable Guard is too low. It is off by a factor of four or more.

The partial discharge origin was correctly located by Smart Cable Guard during all experiments in which it did detect calibration pulses or partial discharges.

Almost no partial discharge pulses from the artificial defect were detected. Only a single partial discharge originating from the defect was detected.

Discussion

It is unclear why Smart Cable Guard detected only one partial discharge from the artificial defect. There are several reasons why this may occur:

There was a problem with the Smart Cable Guard system because of noise generated by the high voltage equipment. During the measurement it was verified that Smart Cable Guard was still in sync and that the noise level it reported was still normal.

Additional verification can be performed by injecting pulses (inductively) while high voltage is applied. [There was no noise above 5 picocoulombs detected by CTL's conventional partial discharge measuring system.]

Partial discharge pulse shape / frequency content of the partial discharges originating from the artificial defect are different from the partial discharge calibrator and different from normal internal partial discharges. Smart Cable Guard measures in the frequency range 100 kHz – 10 MHz. CTL's partial discharge measurement equipment follows standards for cable testing, which uses a lower frequency band. The artificial defect is not a typical internal defect, i.e. a void in the cable's insulation. If the partial discharges generated by the artificial defect have "normal" low frequency content, but much lower high frequency content, they would be picked up by CTL's equipment, but not by Smart Cable Guard. Two scenarios:

The defect produces several smaller partial discharges very quickly after each other. Because of the lower bandwidth CTL's equipment combines them into a single larger partial discharge. But Smart Cable Guard sees them as individual pulses. Each of these pulses is too small to be detected by Smart Cable Guard.

Due to surface currents over the insulation from the earth screen to the conductor, onset of the partial discharge is much slower than a normal internal partial discharge. Such a partial discharge would have the same lower frequency content (<100 kHz), but a much lower high frequency content (> 100 kHz).

We have no indication as to whether this is happening or not. Verification can be performed by measuring the partial discharge pulse shape with a current probe at the same location as the Smart Cable Guard sensors. As a reference the pulse injected by the 2000 picocoulombs calibrator should be used.

Partial discharge radiates mostly to the environment and only a small part couples into the cable. CTL's partial discharge measurement also picks up part of the partial discharge via the air. A metal cover with relatively large hole was covering the second experiment with partial discharge. It seems unlikely that a partial discharge would radiate to the environment in this situation.

Additional verification measurement can be performed by installing the current probes next to the Smart Cable Guard sensors and comparing the amplitude of detected partial discharges to the amplitude of pulses injected by the 2000 picocoulombs calibrator.

The repetition rate is too low. If there are only a few partial discharges every second there is only a small chance that a partial discharge is detected by Smart Cable Guard. The system performs a 20ms measurement every minute that is sufficient for online partial discharge monitoring. This could explain why Smart Cable Guard detected only a single partial discharge. The single partial discharge that was detected had the correct location and amplitude. However, using CTL's partial discharge measurement equipment it was verified that multiple partial discharges were detected per cycle.

Additional verification measurement can be performed with a current probe next to the Smart Cable Guard sensor and using the oscilloscope to verify the repetition rate of partial discharge pulses coming by (using the triggers/second option of the scope, or by measuring a long record in single shot mode).

The tests were completed when KEMA's additional equipment arrived at CTL. Unfortunately, by that time, Dr. Wagenaars had already left. The main goal of these additional tests was to measure the impulse shape of the pulses generated by the partial discharge calibrators employed, to address concerns indicated in Dr. Wagenaars' discussion. For this purpose, Fisher high-frequency current probes were used as a reference during these tests. An example of a probe placed next to one of the sensors/injectors is shown in Figure 3-3.

Figure 3-3
Sensor/injector unit and Fisher current probe attached to the model cable system

Figure 3-4 provides a single pulse oscillogram recorded from the Fisher probe outputs, at the 2000-picocoulomb (left picture) and 500-picocoulomb (right picture) settings of the partial discharge calibrator. The shift between two pulses on each oscillogram corresponds to the travelling time of the partial discharge signal along the 214-m (703-ft) cable section.

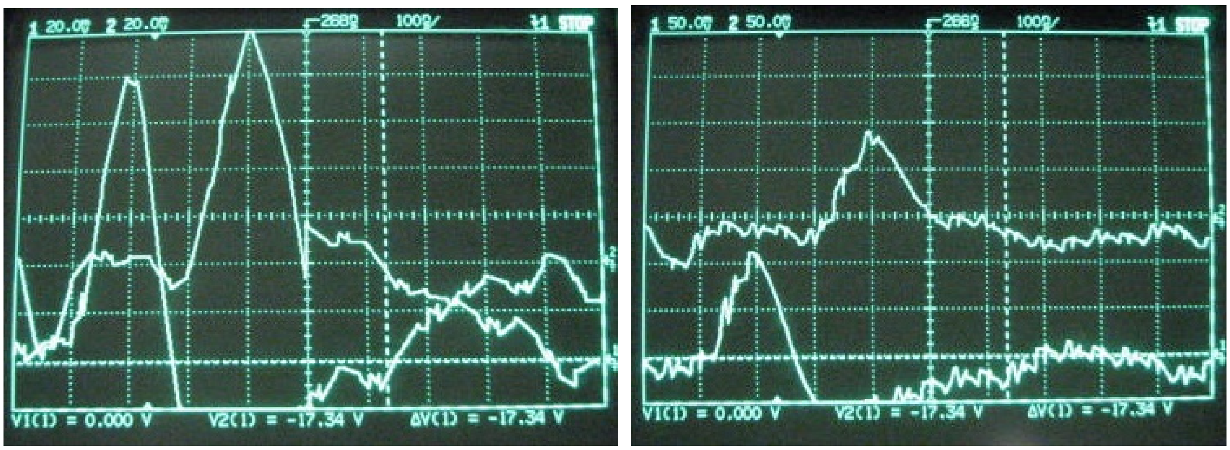


Figure 3-4
Calibration partial discharge pulses recorded with the help of Fisher current probes

It should be noted that the pulse width is about 200 ns. Assuming that this corresponds to a half-cycle of a sinusoidal wave, one can roughly estimate that the main frequency of the signal (carrying most of the impulse power) is about 2.5 MHz, which perfectly fits into the Smart Cable Guard frequency band of 100 kHz to 10 MHz. The oscillograms also show that there was no noise close (or even comparable) to 500 picocoulombs.

Finally, an attempt was made to estimate attenuation in the EPR cable. Due to the nature of the test setup and the short length of the cable available at the time of the experiment (140 ft [43 m]), only a rough estimate could be made. The analysis was performed by Dr. Paul Wagenaars as follows.

I determined the transfer function as function of frequency of the pulse propagation through the cable. This transfer function can be converted into the attenuation. This attenuation can then be compared to cable types with which we have experience with Smart Cable Guard. At a frequency of 6 MHz the attenuation is about 0.02 Np/m. My estimate is that due to the limitations of the test setup this value can have an error of a factor of 2 times, giving a range of 0.01 Np/m to 0.04 Np/m. As a comparison, a typical PILC cable has an attenuation of 0.0025 Np/m at 6 MHz. This means that the attenuation is 4–16 times higher than for a typical paper-insulated lead cable (PILC) cable.

Considering this result, it was not surprising that no partial discharge could be recorded by the Smart Cable Guard system, even on the 40-foot (12-m) cable section evaluated in the model cable systems within the project.

4
CONCLUSION AND DISCUSSION

Numerous attempts to record partial discharges with the help of the Smart Cable Guard system failed to provide reliable results. It was demonstrated that the main culprit in this endeavor was the relatively low sensitivity of the Smart Cable Guard system, significantly exceeding the typical level of discharges in cables with extruded insulation that were the subject of this study. It may be that only mass-impregnated cables (similar to paper-insulated lead cables), which are more commonly found in Europe and Asia, and cable accessories (joints and terminations), which are usually characterized by significantly higher partial discharge amplitudes (in orders of magnitude) and repetition rates, can be successfully monitored with the Smart Cable Guard systems.

Based on the results of laboratory evaluations, it appears that the Smart Cable Guard systems, in the configuration evaluated, cannot be recommended for diagnostic testing and/or condition monitoring of cable designs commonly used in U.S. nuclear plants. This system may be of value for power plant operators using PILC cables, or for distribution and transmission cable systems of that type.

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