Sensors and Inspection Techniques for Extruded Dielectric Transmission Cable Systems – Overview and Demonstration Preparation

1019985

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Technical Update, December 2010

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Electric Power Research Institute (EPRI)

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ACKNOWLEDGMENTS

The following organization prepared this report:

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This report describes research sponsored by EPRI.

The following EPRI Underground Transmission Task Force advisors provided guidance throughout the project.

Sudhakar Cherukupalli – BC Hydro

Reza Ghafurian – Consolidated Edison Company of New York

Mohammad Pasha – The United Illuminating Company

Morris Reid – New York Power Authority

Nirmal Singh – Detroit Edison

Allen MacPhail, EPRI technical consultant, reviewed the report and provided detailed comments and suggestions.

This publication is a corporate document that should be cited in the literature in the following manner:

Sensors and Inspection Techniques for Extruded Dielectric Transmission Cable Systems – Overview and Demonstration Preparation. EPRI, Palo Alto, CA: 2010. 1019985.

ABSTRACT

Underground extruded dielectric cable systems provide reliable performance. However, opportunities exist to improve on-line condition assessment of cable systems, so that preventive maintenance can be performed during planned outages rather than corrective maintenance during forced outages. Some of these opportunities can be realized by incorporating improved sensors, more efficient sensor power sources, enhanced data collection systems, and better integration with utility operation systems. With increased system reliability needs, the need for automated, unstaffed, continuous monitoring of underground transmission lines is increasing. Technology advancements will enable an effective, comprehensive, automated inspection and monitoring system for underground transmission lines, leading to improvements in reliability and maintenance costs.

The report describes the first phase of a multiyear project to achieve these improvements. Tasks completed in this phase included evaluation of existing monitoring technologies, identification of a cable circuit, sensors, data acquisition systems, monitoring software, power supply, and communication system for the demonstration.

In the next phase of the project, researchers will install the demonstration system, monitor system performance, report the results of the demonstration, and determine future research and development tasks.

Keywords

Cable movement monitoring
Cross-linked polyethylene (XLPE) cables
Extruded dielectric cables
On-line condition assessment
Partial discharge monitoring
Vibration monitoring

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1 INTRODUCTION

Underground extruded dielectric cable systems provide reliable performance. However, opportunities exist to improve on-line condition assessment of cable systems, so that preventive maintenance activities can be performed on a planned outage basis, instead of corrective maintenance during forced outages. Some of these opportunities can be realized by incorporating improved sensors, more efficient power sources to the sensors, enhanced data collection systems, and better integration with utility operation systems. With increased system reliability needs, the need for automated, unmanned and continuous monitoring of underground transmission lines is increasing. Technology advancements will enable an effective, comprehensive, automated inspection and monitoring system for underground transmission lines, leading to reliability and maintenance cost improvements.

1.1 Overall Project Scope

The first phase of this multi-year project is to evaluate and demonstrate current technologies for extruded dielectric cable system monitoring. The monitoring systems will include sensors, data acquisition, data collection and transmittal to data centers, and post-processing to analyze and display results. The need for power harvesting will also be an important part of the overall project. The monitoring results will help to implement predictive maintenance procedures, as opposed to scheduled maintenance.

The following properties and components are of interest for real-time monitoring. Details of each will be discussed in later sections.

- Partial discharges in cables, joints and terminations
- Grounding and sheath bonding effectiveness, e.g., through monitoring of cable sheath current, grounding impedance, and sheath voltage limiter and link box condition
- Cable movement through measurements of displacement of cable, cable racking and clamps as a function of load current, and surface temperature of joints and cables
- Strain and compression on cable cleats and racks as a function of load current and surface temperature of joints and cables
- Vibration of manhole walls, joints, cables and racking systems, for example, caused by nearby traffic or construction work

1.2 Project Approach

This document reports evaluation and preparation for demonstration of existing monitoring technologies on a host utility cable circuit, including identification of a cable circuit, sensors, data acquisition systems, monitoring software, power supply, and communication systems for the demonstration.

2
MONITORING NEEDS

The monitoring systems are fueled by a list of sensing needs. Table 2-1 lists inspection and monitoring of underground extruded dielectric transmission lines, grouped into three sections.

1. Presently available on-line, continuous monitoring methods
2. Desirable on-line, continuous inspection and monitoring methods
3. Presently available off-line maintenance inspection, with opportunities for continuous monitoring methods

Figure 2-1 shows a schematic diagram of the inspection and monitoring applications for extruded dielectric transmission lines [1]

Table 2-1
Inspection and monitoring of underground transmission lines

Failure Modes/Indicators	Diagnostic Method	Overall Status	Monitoring Capability	Sensor Opportunity	Comments for Future Research and Prioritization
Presently available on-line, continuous monitoring					
Hot spots along cables - limiting factor of loading capability and insulation aging	Temperature	On-line monitoring available	Monitor through distributed fiber optical sensors and thermocouples	Distributed fiber optic temperature sensing and thermocouples available	Commercial systems available, EPRI Tailored Collaboration opportunity available
Deterioration of cable insulation and shield systems, localized defects especially at joints, terminations, and interfaces	Partial discharge (PD) detection, shield current measurement	On-line monitoring available. Expensive and time consuming inspection	Monitor through capacitive and/or inductive coupling or acoustic emission sensors. Off-line and on-line maintenance inspection	Various sensors available (UHF, HF current transformers, inductive and capacitive couplers, acoustic emission). Optical fiber sensors under investigation. Distributed sensor development opportunities exist along cables	R&D on sensors, sensitivity, effectiveness, integration, noise filtering, data processing, etc.
Desirable on-line, continuous inspection and monitoring					
Thermo-mechanical behavior	Strain sensing, sidewall pressure sensing	New	On-line monitoring desirable	Sensor development opportunities exist	On-line monitoring desirable
Moisture barrier degradation	Moisture level	New	On-line monitoring desirable	Sensor development opportunities exist	On-line monitoring desirable

Table 2-1 (continued)
Inspection and monitoring of underground transmission lines

Failure Modes/Indicators	Diagnostic Method	Overall Status	Monitoring Capability	Sensor Opportunity	Comments for Future Research and Prioritization
Presently available off-line maintenance inspection, with opportunities for on-line, continuous monitoring					
Bonding and link box corrosion, loose connection, insulation damage	Sheath current measurements	In-person inspection	Off-line maintenance inspection	Sensors available but need integration	On-line monitoring desirable
Sheath voltage limiter (SVL) failure	SVL current	In-person inspection	Off-line maintenance inspection	Sensors available but need integration	On-line monitoring desirable
Vault hardware and component (ceiling, walls, pipe, clamps, ground wires, racks, pumping, etc.) degradation, corrosion, overheating, flooding, safety related gas	Optical image infrared image, vibration, acoustic sensing, and temperature indicating strips on components for cracks, leaks, corrosion, coating damage, component damage, safety related gas level, etc.	Time consuming inspection with safety concerns	Off-line or on-line maintenance inspection	Sensor development opportunities exist. Some sensors available but need integration	On-line monitoring desirable
Internal movement, misalignment or damage of cables and accessories	X-ray inspection	Expensive and time consuming inspection	Off-line maintenance inspection	Portable X-ray equipment available	On-line monitoring unlikely
Fault location	Fault current	On-line monitoring available	Monitor fault current at each end of a cable section	Fiber optic current sensors developed	Systems under development by Tokyo Electric Power Company for extruded dielectric cables

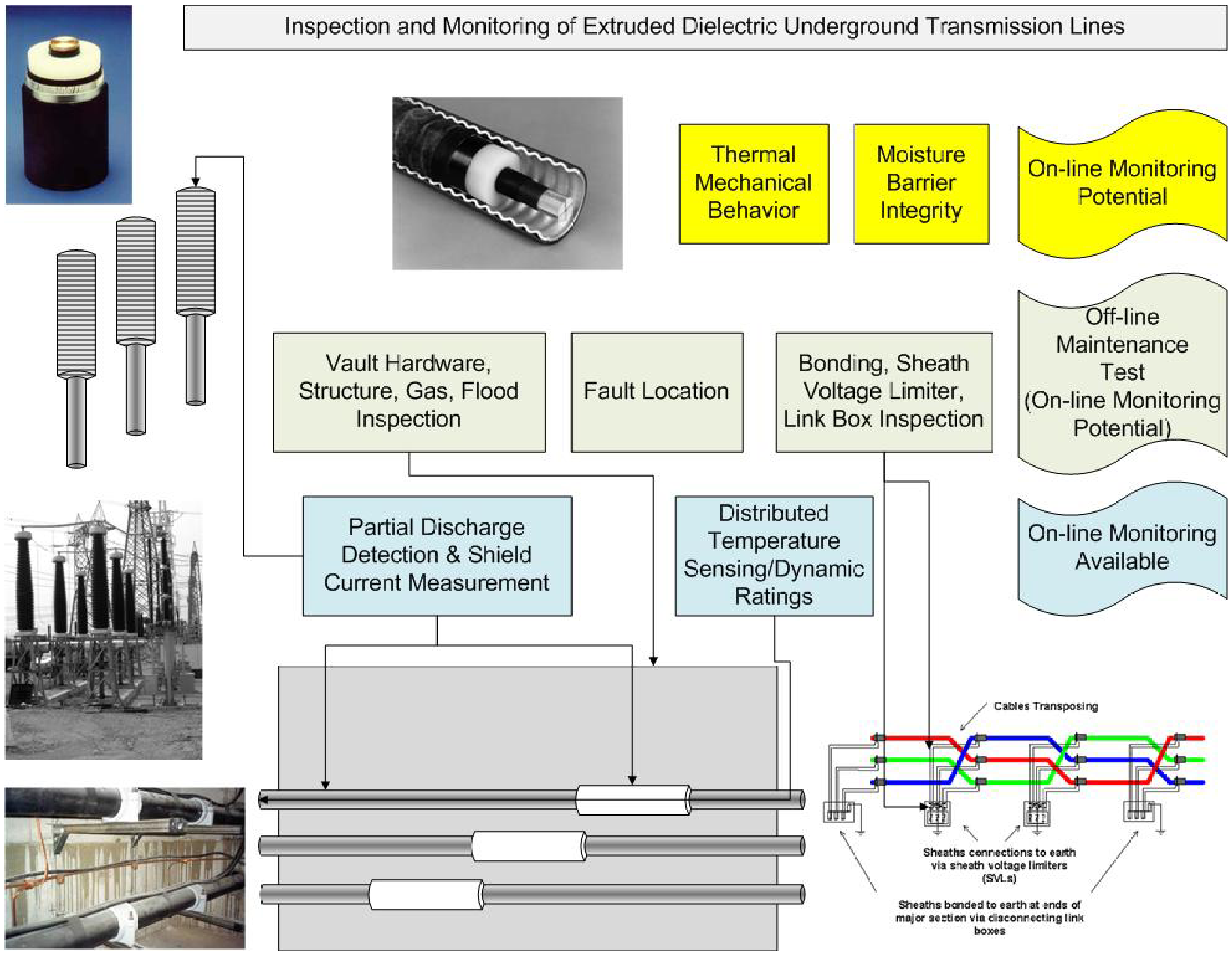

Figure 2-1
Inspection and monitoring of extruded dielectric underground transmission lines

3 REVIEW OF SENSOR AND MONITORING TECHNOLOGIES

This section provides insight into some of the enabling sensor and data communication technologies.

3.1 Partial Discharge Sensing

Partial discharge (PD) measurements are used to assess insulation condition of cables and accessories. They can be used to verify proper installation of a cable circuit and assess insulation aging or degradation, if applied continuously or at certain time intervals. A PD is confined in some way that does not immediately result in complete failure of the system, that is, a collapse of the voltage between the energized electrodes such as the cable conductor and outer metallic shield. PD does not necessarily need to occur next to a conductor. PD can result from conditions such as breakdown of gas in a cavity, breakdown of gas in an electrical tree channel, breakdown along an interface, and breakdown between an energized electrode and a floating metallic component.

An electrical discharge within cable insulation generates a corresponding voltage (or discharge signal) between the cable conductor and the grounded screen (or shield). Consider, for example, a cavity within the insulation. If the voltage across the cable insulation is increased, the electric field within the cavity increases. The electrical field within the cavity is greater than that in the surrounding dielectric (insulation) because the gas within the cavity has a lower dielectric constant. The magnitude of the field will also depend on the shape and the location of the cavity. When the field in the cavity becomes sufficiently high, the gas within it will break down. In this process, the cavity goes from nonconducting to conducting, and the field within the cavity decreases to practically zero immediately after the discharge.

The voltage in the cavity collapses within a few nanoseconds (ns) so that the resulting voltage pulse that propagates in both directions away from the PD source has an initial pulse width also in the nanoseconds range. The voltage pulses that arise from PD at the interfaces (shield/insulation) may be of some tens of nanoseconds in duration. In the frequency domain, PD pulses consist of frequencies greater than a gigahertz (GHz). PD detection circuits are designed to locate the PD pulses by detecting and measuring over a range of frequencies, a narrow band, a wideband, or an ultra-wide-band (UWB).

The frequency range can be determined by the bandwidth of the PD sensor or coupler in the circuit or the instrumentation connected to the coupler. If two couplers are installed, one at each end of a joint or splice, it is possible to determine the direction of travel of the PD pulse by comparing the time the pulse arrives at each coupler. It is possible to distinguish between pulses that arrive from a source external to the joint and those generated within the joint. This type of PD coupler system is called a directional coupler.

It must be remembered that all shielded power cables have substantial high-frequency attenuation as a result of losses in the semiconducting shields and the insulation. Such high-frequency attenuation increases the pulse width and decreases the pulse amplitude. This will limit the optimum signal detection bandwidth to the range of 10 to 20 MHz for cross-linked polyethylene (XLPE) cable.

International Electrotechnical Commission (IEC) 60270 [2] defines three types of instruments for PD detection:

- Wide-band instruments have a lower cutoff frequency (f_1) greater than 30 kHz and less than 100 kHz, an upper cutoff frequency (f_2) of less than 500 kHz, and a bandwidth $\Delta f = f_2 - f_1$ above 100 kHz and less than 400 kHz.
- Narrow-band instruments have a bandwidth Δf greater than 9 kHz and less than 30 kHz with the center frequency f_m above 50 kHz and less than 1 MHz.
- Ultra-wide-band (UWB) instruments that are not defined in terms of bandwidth but partial discharges are "detected by oscilloscopes providing very high bandwidth or by frequency selective instruments (for example, spectrum analyzers) with appropriate coupling devices. The aim of application is to measure and to quantify the shape or the frequency spectrum of partial discharge current or voltage pulses in equipment with distributed parameters, for example, cables.…"

It should be noted that there are two types of UWB instrumentation:

1. Those with a relatively large bandwidth of several MHz or even greater to measure the true shape of the discharge pulse
2. Those with a relatively narrow bandwidth of less than 1 MHz operating at a center frequency greater than 1 MHz

In the literature, other classifications are used. For example, ultra-high-frequency (UHF) is used for frequencies in the gigahertz region.

UWB detection systems consist of a high-speed digitizer, often a digital oscilloscope, capable of sampling rates of 100 MB/s or greater. In conventional PD detection as practiced in the laboratory, PD signals are usually detected with a bandwidth of 100 kHz or less, that is, a wide-band instrument according to IEC 60270, so that the detector acts as a low-pass filter or integrator.

For complex test objects, the high-frequency stimulus of the PD pulse inevitably causes substantial ringing in the voltage pulse. The low-pass characteristics of a conventional PD detector integrate this ringing to an effective charge that can be measured in picocoulombs (pC).

UWB PD detection is usually practiced with field PD testing of cable systems. Modern UWB detection systems consist of a sensor or coupler, a high-speed analog-to-digital (A/D) converter (digitizer), digital filters, and a pattern recognition analyzer. The high-speed digitizer must have sampling rates of up to 1 Giga-sample per second (GS/s) or greater to achieve the necessary bandwidth.

PD pulses can be detected by either of the following methods:

- Triggering pulses that remain above the noise level after some initial filtering. The reflected pulse from the end of the cable is used for PD location and may be attenuated sufficiently to be below the noise level. Signal processing is used to extract the reflected pulse below the noise level but cannot be used to process and enhance the initial pulse.
- Digitizing complete cycles of the sensor output and then applying digital signal processing to analyze the data. In this way, the initial and reflected pulses are detected even if they are buried in noise. For on-line monitoring, this process must be carried out in real time.

To achieve the desired bandwidth, digitizers with very high sampling rates (up to ~1 GS/s) must be used; this results in the collection of large amounts of data (for example, up to 500 MB for one cycle), which then must be stored in memory. Thus, from a practical viewpoint of limited memory, time to store the data, and time to complete the analysis, data from only a limited number of cycles can be collected during a measurement. However, the sensitivity is very good because signals buried in noise can be extracted in real time.

Although the definitions of the types of PD detection instruments are taken from IEC 60270, it should be remembered that this standard does not make any recommendations for UWB measurement methods or bandwidth frequencies of the instruments to be used because these do not directly quantify the apparent discharge magnitude of the PD pulses.

PD can occur within the cable insulation, but the insulation may not fail immediately. Indeed, some sources of PD in medium-voltage cable circuits can continue for years without causing failure. These sources include discharge to a floating metallic component, discharge between the neutral wires and insulation shield, and various corona. However, there are no published data claiming transmission cable systems continuing to operate for extended periods in the presence of PD.

For a PD source to cause failure of an extruded dielectric, it must cause tracking along an interface or create an electrical tree, which will grow through the dielectric and bridge the conductors. Electrical trees can be caused by any of the following:

- PD within a cavity, which gradually erodes and pits the surface
- The conversion of a water tree (in extruded insulation) to a failure path by a transient overvoltage (lightning or switching impulse)
- Conversion of a large water tree by high ac voltage
- Charge injection from a stress enhancement such as a metallic contaminant in the dielectric or a protrusion at the semiconducting/insulation interface

Interfacial pressure and cleanliness of interfaces is essential to long-term, high voltage endurance. Tracking along interfaces of distribution accessories is a major source of PD-induced failure, often caused by poor workmanship, lack of cleanliness during assembly, or insufficient contact pressure on the surfaces. Similar defects in transmission cable accessory installations would also result in PD and failure. Materials differ greatly in their resistance to degradation by PD, from the low resistance to degradation shown by unfilled polyolefins such as XLPE, to the much greater resistance for filled polymers, such as ethylene propylene rubber (EPR). However, PD (tracking) along an interface can cause failure even if the extruded insulation is completely immune to the PD-induced electrical tree initiation. Thus, the severity of a PD source must be judged not only in the context of the PD activity, but also in the context of the material in which that PD is taking place. The operating conditions to which the material is being subjected, such as temperature and mechanical and electrical stresses, are also significant factors.

Both capacitive and inductive couplers are used in underground transmission cable partial discharge detection. Inductive couplers can be in the form of high-frequency current transformers (HFCT) placed around cable bonding lead or cable sheath bonding links. The inductive coupler is used with splices and terminations without capacitive taps. Capacitive couplers can be integrated into the splices or joints by splice manufacturers or installed in the field. The capacitive couplers are of higher sensitivity and broader bandwidth.

3.2 Voltage and Current Measurements

For extruded dielectric cable systems, one of the most expensive maintenance activities is the periodic testing of cable jackets to guard against corrosion or other damage. Corrosion or damage could result in water ingress. Jacket faults could also cause electrical safety hazards as sheath currents are injected into the ground, possibly causing high local ground potential rises and step and touch potentials. Because the effectiveness of special sheath bonding systems to improve ampacity would be lost, cables could also be overheated. Industry practice is to apply a dc test voltage between the sheath/shield and ground, to verify integrity of the jacket. Depending on utility practice, this is usually done about every 3 to 5 years. The test is expensive and disruptive because line outages are needed, all manholes must be entered to change and restore sheath bonding connections and in the case of double circuits sharing a duct bank, safety hazards can exist due to induction.

There would be many benefits if such maintenance could be eliminated (or the interval increased), if jacket conditions could be measured remotely, perhaps in real-time. Such methods would comprise placing small current transformers around each sheath bonding connection and each sheath voltage limiter (SVL) connection, to check for irregular readings indicative of a jacket fault or a SVL failure. Currents and phase angles would be relayed to a hub and then to a control center for action, if needed. Alternatively, alarm levels could be established so that only alarm signals would be telemetered to a control center. Of course the sheath currents vary proportionately to load currents, so conductor currents would also need to be considered, as well as the effects of cross-bonding interconnections.

3.3 Strain, Vibration, and Displacement Sensing

Strain measurements are typically made on structural components to determine the forces acting on them, whether the yield strength of the material has been exceeded, or if periodic vibrations or cyclic movements are severe enough to cause fatigue problems in the material. Strain measurements could be used to identify deformation of structural members caused by excessive mechanical loading. Typical examples include thermal-mechanical bending of power transmission cables and deformation of underground vault structure components, such as cable support racks and clamps. Strain measurement sensors would need to be applied directly to the structural members being measured.

Vibration sensors measure various quantities related to vibration, including displacement, velocity, and acceleration. The most commonly used vibration transducer is the accelerometer. Most commercially available accelerometers are piezoelectric transducers. They use a pre-polarized piece of piezoelectric material that produces a charge proportional to forces acting on it. A piezoelectric accelerometer typically employs a mass (either in a shear or a compression configuration) that produces a force on the piezoelectric element that is proportional to the acceleration experienced by the mass. Many piezoelectric accelerometers contain integral electronics that convert the charge produced by the piezoelectric material to a voltage or current.

With the advent of MEMS (MicroElectroMechanical Systems) devices, a new class of accelerometers is now commercially available. MEMS accelerometers are typically capacitive devices that employ parallel plates or interdigitated fingers whose capacitance changes as a function of applied acceleration. MEMS accelerometers are increasingly being used in many commercial applications. Such devices can be produced with extremely small form factors, requiring very little power.

Commercially available accelerometers can be obtained in a variety of form factors and with widely varying sensitivities and frequency responses. Piezoelectric accelerometers can be used for sensing vibration with frequencies as low as 0.1 Hz or less, and up to 10 kHz or more. Capacitive accelerometers are available that respond in a frequency range from dc up to a few kHz. Transducers are available that are capable of measuring vibration levels ranging from a few micro-Gs to several thousand Gs.

Vibration data can be used to identify a wide variety of phenomenon, from transient effects to nondestructive damage identification. For high voltage transmission cable applications, vibration transducers could be used to identify heavy construction equipment operating near vaults and detect some forms of foundation damage.

3.4 Fiber Optic Temperature Sensing

Fiber optic sensing has been applied for many decades to detect various physical and chemical parameters. The characteristics of the fibers and the way light interacts with the fiber and fiber coating or environment around the fiber are the basis for various sensor technologies. Fiber optic sensors have many advantages over conventional sensors:

- Immune to electromagnetic interference
- Can be configured as a distributed sensor as well as a point sensor
- Can operate at high electrical potential
- Resistant to humidity and corrosion
- Can be made small in size and light in weight

In remote sensing applications, a segment of the fiber is used as a sensor gauge while a long length of the same or another fiber is used to convey the sensed information to a remote station. There is no electrical power supply needed at the sensor locations. A distributed sensor can be constructed by multiplexing various point sensors along the length. Signal processing devices (e.g., splitter, combiner, multiplexer, filter, delay line) can also be made of fiber elements.

Both point sensors and distributed sensors are used for measuring temperatures. Point sensors use a phosphorescent material at the end of the fiber. The temperature of transmission cable splices, for example, can be monitored using the point sensors.

Distributed temperature sensors (DTS) apply the technology of laser injection into the optical fiber. A fraction of the laser pulses is absorbed in the fiber and is backscattered as Raman signals. The local temperature determines the intensity of the Raman signals. The intensity is used to calculate the temperature at that location. The time of flight of the laser light, opto-electronics and a computer is used to determine location of the specific backscattered Raman light. Multi-mode or single-mode fibers are used for distributed temperature sensors. In multi-mode systems (1°C accuracy), about one meter of fiber length is needed to create a significant backscatter signal, while 4 to10 meters is needed for the single-mode fiber (2.5°C accuracy). These requirements designate the spatial resolution of the multi-mode and single-mode fibers. Multi-mode optical fibers are suitable for most DTS applications, with a maximum range of 8 to 10 km. They are typically used for short range communication systems, for example within office buildings. Single-mode optical fibers are used only for very long range DTS applications with a maximum range of 30 to 40 km. They are commonly used for long distance communication systems.

The DTS fiber sensors can be integrated in the cable or arranged separately near the cable. The sensors integrated in the cable lead to faster thermal response to the conductor and more accurate conductor temperature measurements. The fibers can also be installed in a spare duct or a separate duct designed specifically for the purpose. Both installations can be used for hotspot management, overload detection, and real-time dynamic thermal circuit ratings.

4 DESIGN OF MONITORING SYSTEMS FOR DEMONSTRATION

4.1 Demonstration Circuit Description

Figure 4-1 shows the circuit considered for the sensor technology and monitoring system demonstration. It is a three-phase 138-kV cable system of total 2632 ft (800 m) long between two substations. A vault of 21×6×6 (H) ft (6.4×1.8×1.8 m) is located at approximately the middle of the circuit. Straight joints are used in the vault. The straight joint sheath connections are not grounded but cable sheaths are grounded at one cable end and protected by sheath voltage limiters (SVLs) at the other cable end. A ground continuity conductor (GCC) is used and the SVLs are grounded to it at one end. Cable racks are used to support the cables and joints within the vault. The racks are bonded to the vault ground. There are no optical fibers installed with the cable.

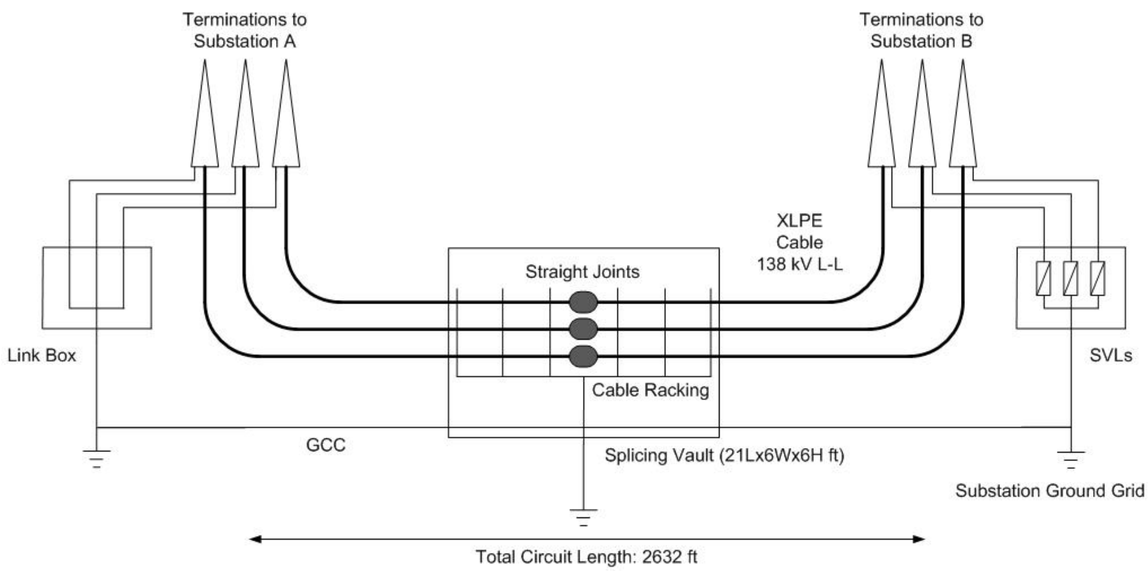

Figure 4-1
Schematic diagram of a circuit for sensor and monitoring system demonstration

4.2 Partial Discharge Monitoring System

4.2.1 PD Monitoring System Requirements

The PD monitoring system will consist of

- Partial discharge sensors to acquire PD signals
- Data acquisition units

- Fiber optic/wireless, internet/LAN communications
- Battery or ac power supplies
- Central control units to collect, process, store and display data

For this example circuit, three HFCTs will be installed within or adjacent to the grounding link box within Substation A. It is optional to install three HFCTs on the straight joints within the vault. A data acquisition unit will be located at each sensor location. For this case, one unit is at the substation-A location to acquire data from the three HFCTs, and optionally one within the vault from the three couplers (See Figure 4-2). The complete system can monitor PD activities inside the cable, joints and terminations. A separate system can be used to monitor cable sheath current.

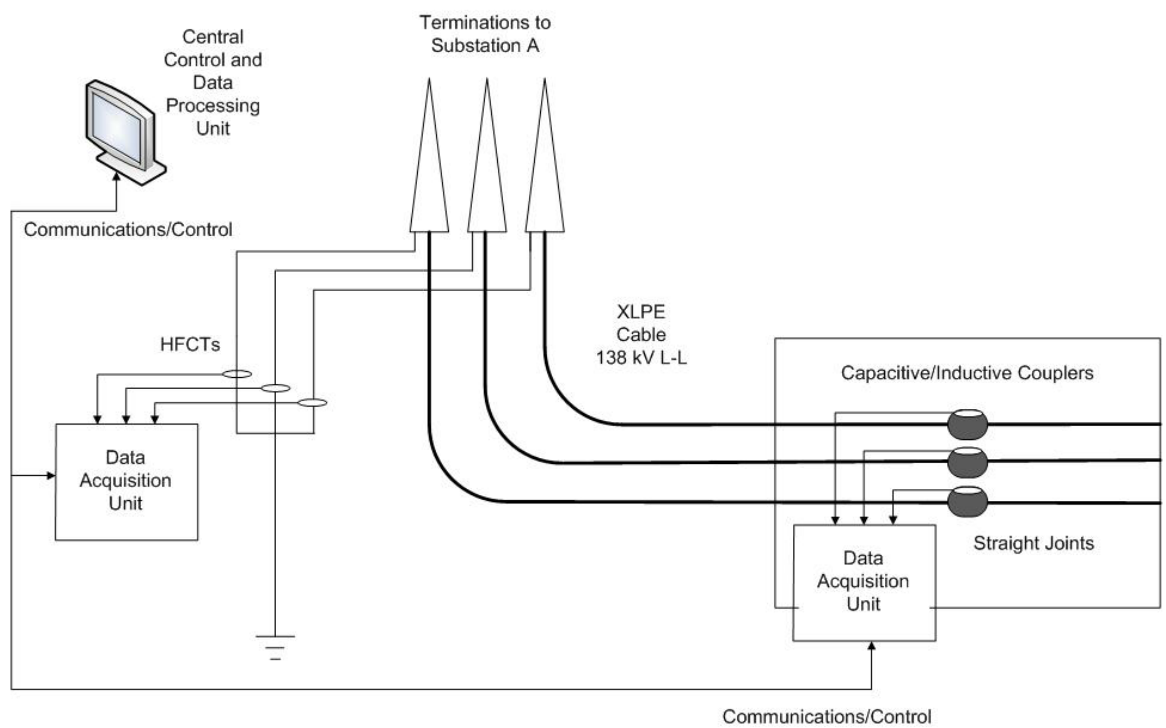

Figure 4-2
Schematic diagram of PD monitoring system for the demonstration circuit

4.2.2 Sensors

High frequency current transformers (HFCTs) can be used as an inductive coupler for PD sensing. Bandwidth of the HFCTs should be sufficient for the PD monitoring, normally in the range of 1 to 8 MHz. The HFCTs can be installed on the grounding leads from the cable shield/sheath to ground at the terminations or on the bonding leads from the joints to ground outside or inside of the link box, without the need of disconnecting the leads. The HFCTs should be suitable for outdoor installations.

If integrated capacitive couplers are not available, direct magnetic couplers with the cable or any other type of PD sensors can be applied to the joints. The bandwidth of the sensor is in the range of 30 kHz and 50 to 200 MHz depending on installation configurations. The couplers can be installed on the sheath bonding leads at cable joints. The joints within the demonstration circuit vault do not have integrated capacitive couplers.

Locations to place these sensors in the cable system are sometime critical because the locations can directly affect the sensitivity of detecting the PD in the circuit. The locations can be determined by PD measuring specialists using detailed engineering analysis of the circuit and noise levels around the circuit.

4.2.3 Data Acquisition Units

As a requirement, one data acquisition unit is usually installed at the termination location or optionally within the vault to acquire data from multiple PD sensors at the location. The data sampling rate of the digitizers is in the range of 100 MS/s or higher to record signals in high frequency for later processing and characterizations. It is desirable that the data pre-processing includes noise filtering, separation, temporary storage, and synchronization with other units (see Figure 4-3).

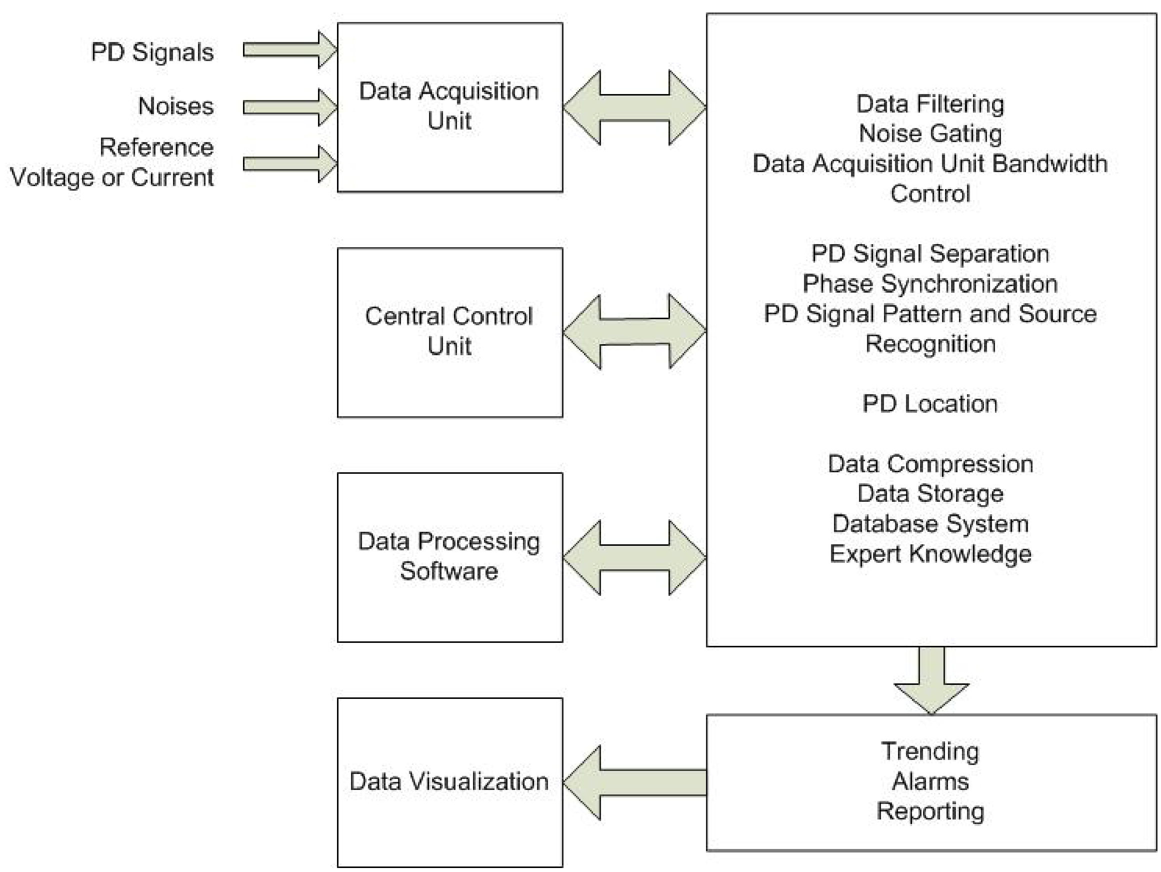

Figure 4-3
Schematic diagram of data processing functions for PD monitoring

4.2.4 Communications Systems

The PD signals acquired from the sensors and the acquisition units are transferred to a central control and data processing system through a wireless or optical fiber communication system. The communication system is isolated from the high voltage cable system.

4.2.5 Power Supplies

Power supplies are required by the data acquisition units and communication systems. A local low voltage ac power supply can be utilized. If the ac voltage supply is not available, a long-lasting battery or a battery with a charging unit, e.g., a solar panel or a magnetic and electric field inductive unit from the power cable, or other power harvesting sources, can be used.

4.2.6 Central Control Units with Data Processing Software

The central control unit includes servers and processors where the data can be stored and processed in real time, simultaneously from all data acquisition units. The data processing software is to characterize the PD signals and display information that can be used to determine PD levels and trends, also as shown in Figure 4.3. The software should also allow pattern recognition and possibly locations of the partial discharges. It should also be used to control and configure the data acquisition units.

4.2.7 Monitoring System Verification

After the PD monitoring system is installed, the PD detection is verified by injection of pulses close to the PD sensors. The software can be normalized based on the response of the software to the system.

4.2.8 PD Monitoring Challenges

Sensitivity: The partial discharge signal is a function of time (e.g., ac voltage cycles, and daily load cycles, and environmental condition changes), stresses (e.g., voltage and current magnitude, thermal or mechanical stresses), insulation materials and state of the materials (e.g., aging), state of the defect cavities (e.g., gas content and pressure, space charges, shapes), and signal attenuation and dispersion at the time the signal is measured. To improve measurement effectiveness, partial discharge sensors can be placed at terminations of both circuit ends and at accessible joints and grounding or cross bonding leads within vaults. PD signal attenuation and dispersion rates across the cables, joints, and crossing bonding connections can be determined by testing. The sensitivity for the PD measurements is an extremely critical issue because it determines at what levels the PD can be detected, regarding all the varying quantities during the monitoring duration, but especially background noise.

Noises and disturbances: Electrical noises and disturbances exist especially during real-time monitoring. The monitoring system needs to achieve a high and acceptable signal-to-noise ratio. Various ways are used to reject the noises, e.g., filtering in frequency domain, gating in time domain – magnitude, phase, or dynamic, and pattern recognition and separation. For example, pulses originating near the sensors will still contain high frequency components near the wave front while if the pulses have already traveled for a certain distance the high frequency components may not be detectable. The discharges on the surface of an outdoor termination bushing, on the bare conductors, or within terminations will have distinct patterns compared with discharges within the cable insulation. Polarity of the pulses will also help to determine pulse origins.

Interpretation: Once the PD signals are acquired, their levels can be used to determine if the insulation is in a critical condition. Then it becomes important to determine the cause of the PD and its location along the cable circuit or within an accessory. Interpretation of the measurements can be used to determine maintenance schedules and replacement strategies.

4.3 Cable Constraint System Monitoring within Vaults

4.3.1 Case 1: Internal Movement of Cable and Joint Insulation

Movement of the cable core and joint insulation inside and through the joint housing could occur in a straight-through constraint design, as illustrated in Figure 4-4:

- Top Diagram: Cable core in starting position
- Center Diagram: Both cable core and joint are pushed for a distance of ‘m’ by a differential thermo-mechanical force from right to left (F_R-F_L).
- Bottom Diagram: Starting from the position shown in the center diagram, the cable core is pushed further and it has moved for a total distance of ‘m+n’. The conductor connector has moved out of the connector shield.

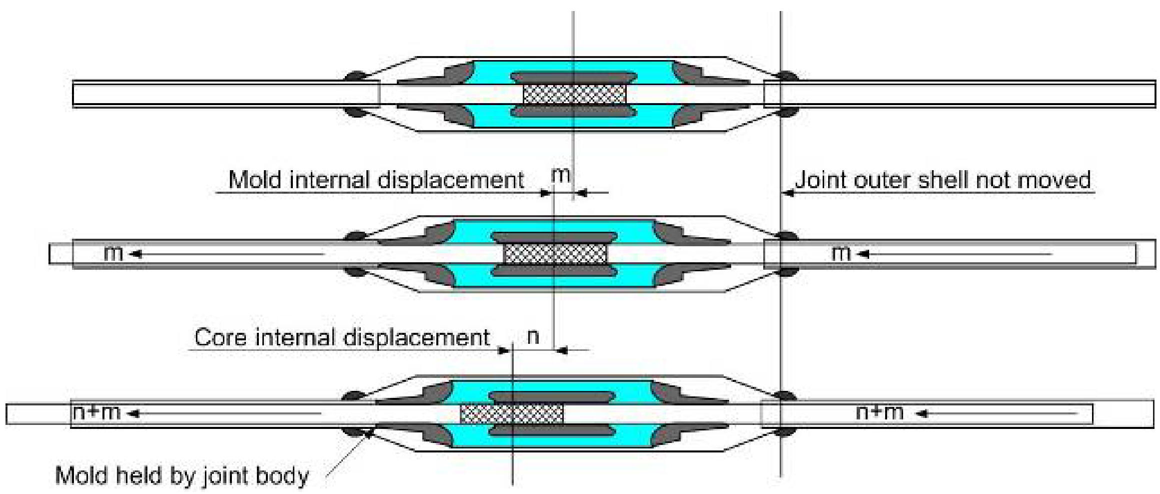

Figure 4-4
Movement of cable core in a straight-through design with joint casing restrained [3]

Since the joint outer shell and cable sheath/jacket do not move in these scenarios, the movements inside are not visible. Inspection or monitoring techniques such as radiography inspection will need to be utilized to reveal the movement.

It is noted that these internal cable core movements may not actually occur if the distributed internal friction forces between the cable jacket and core is greater than the differential forces across a manhole. It is also possible that the presence of bends external to the vault may provide additional locking of the cable core. Verification is needed, based on the configurations of the particular cable conductor size, cable-to-duct clearance, cable operating temperature, cable to duct frictional constraints, cable construction and joint designs, and route geometry.

4.3.2 Case 2: Movement of Cable and Joint Through all Cleats within Vault

The cable and joint as a whole may move within the vault if the differential thermo-mechanical force applied to the cable exceeds the total withstand force of the cable constraint system, as shown in Figure 4-5:

- Top diagram: stable condition - no cable and joint movement because the differential thermo-mechanical force (F_R-F_L) to the cable is less than the withstand force of the cable constraint system.
- Bottom diagram: unstable condition - the cable and joint has slipped for a distance of ‘p’ through the constraint cleat system because the differential thermo-mechanical force (F'_R-F_L) is above the withstand force of the constraint system. The movement has stopped because the joint casing has contacted a first fixed clamp cleat.

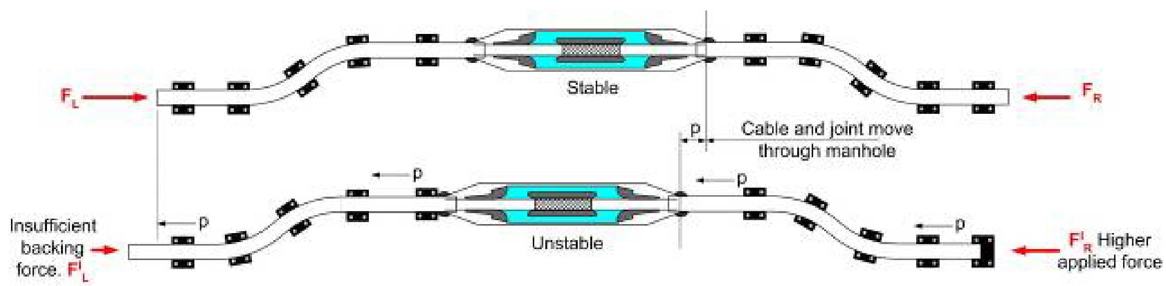

Figure 4-5
Movement of whole joint and cable system through vault with unrestrained joints [3]

Movement of the cable and joint as a whole can sometimes be visible and it is possible to monitor a few points on the cable and joint for the movement.

4.3.3 Case 3: Slipping of the Cable Through a Limited Number of Cleats

Slipping between the surfaces of the cable jacket and the cleat liner may occur when the force applied across an individual cleat exceeds the withstand value. When this occurs physically, the cable jacket may slide a short distance through the rubber liner (if present). During thermal cycling, the short distance slipping may produce a small cyclic ratcheting movement that may eventually deteriorate the interface between the cable jacket and cleat liner.

Figure 4-6 shows that nine of the cleats (colored black) are gripping the cable and that three cleats have slipped (colored white). The withstand strength of the three cleats will need to be increased to hold the differential force (F_R-F_L) to avoid the slipping. It is noted that the distribution of force across the cleats is non-linear. The cleat at the right hand end may be required to withstand the highest force.

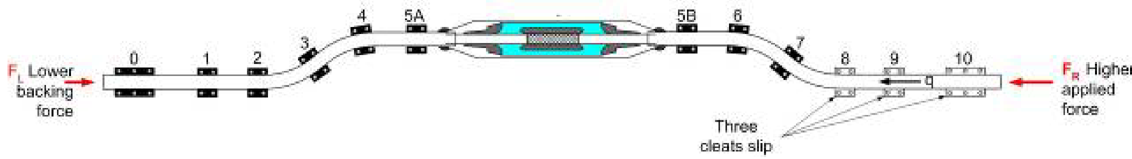

Figure 4-6
Cable slipping through three cleats [3]

One of the consequences of slipping is that the total inwards movement of the cable at the right hand end is increased. The cable held by the left hand cleat remains stationary. The cable within each of the other cleats exhibits a progressively increasing movement by the elastic deformation of the liner in each cleat and by the compressive deflection of the cable. In an acceptable design of constraint system upon removal of the applied cable forces (FL and FR), the cleat liners and the cable may elastically return to their starting positions.

The slipping of the cable through the cleats and cleat movement and strain can sometimes be visible and it is possible to monitor a few points on the cable and cleats for strain and movement.

4.3.4 Cable Movement Monitoring System Requirements

As indicated above, displacement and strain are both possible in three dimensions (x, y, and z) of cable and cleats in Cases 2 and 3, and may be measured to monitor cable movement and cleat overstress or even distortion. The strain or force applied to the cleats by the cable constraint system can be estimated. The range of sensors and location of their installations can then be determined.

The displacement and strain are a function of cable temperature which can be measured or estimated by cable load current, cable construction, and installation environment.

The displacement and strain monitoring system consists of displacement and strain sensors, data acquisition units and signal conditioners or filters, and data recording, processing, analysis and display.

The measurement range of the linear displacement transducers is about 1 in (25 mm) or higher. The housing material (e.g., stainless steel) of the sensors must be designed for moist environment (waterproof, submersible). Resolution and sensitivity of the sensors shall be properly selected for the applications. Locations for sensor installation can be on the cable, cleats or other components of the cable constraint systems with a reference point. Mounting blocks can be used to support the transducers. The monitoring system should be designed properly to reduce interference of electric and magnetic field from the power cables.

General requirements for communication systems, power supplies and central control units with data processing software are similar to the ones used for the partial discharge monitoring systems as described in the previous section.

4.4 Monitoring of Vibrations Caused by Traffic and Construction Work

Many utilities have experienced longitudinal movement of cable within pipes and ducts associated with vibrations induced by road or rail traffic, and maybe construction operations. Traffic vibrations are generated when vehicles, mostly heavy vehicles such as trucks and buses, make contact with irregular objects on the road surface like an uneven manhole cover, potholes or road cracks. The impacts move to the vault walls and floors, ducts or pipes, and then to the cable constraint systems, cables and joints. The frequency of vibrations is determined by the natural vibration frequency of the soil or other materials around the vault and by the characteristics (e.g., suspension hop) of the vehicle. The vibration levels are determined by the weight, speed and suspension system of the vehicles and the nature of the irregular objects.

Reference [4] reports a modeling of cable spans in its full high speed dynamic mode using the finite element explicit modeling technique. Traffic vibration levels of 0.032 mm amplitude and 13 Hz frequency, for duration of 0.375s, were applied to replicate the suspension hop when a truck wheel encounters an irregular object on the road surface. The modeling revealed that the application of traffic vibrations to both pipe and duct systems resulted in the sudden release of thermal strain and growth of thermomechanical patterns to the cable. The traffic vibration lifts a short length of cable off the duct or pipe surface, momentarily reducing the frictional constraint and unbalancing equilibrium. This results in the sudden release of strain, which cascades along the cable into the thermomechanical pattern, which grows in length to accommodate it. In the case studied, the thermomechanical patterns formed at low temperature and by $90^{o}C$ had already released and absorbed the largest proportion of locked-in thermal strain. However the release of the small percentages of residual strain was still dramatic in suddenly lengthening the thermomechanical patterns and reducing the magnitude of axial force.

The vibration induced effects may result in an impulsive change in force, positive or negative, to the cable section within the vault and to the cleats and joints due to the additional thermal strain released. The design of the cable constraint systems will need to consider the effects by reinforcing the accessories and cable within the vault, if determined necessary.

The traffic ground-borne vibration levels are determined by the following factors:

- Road surface irregularity size
- Speed of vehicles
- Type of vehicles
- Soil or road types
- Distance from vibrations to road surface

The vibration monitoring system is to measure traffic vibrations to the vault and measure the magnitude of forces induced to the cable constraint system and the joints by the road vibrations. The measurements can then be used to quantify the effects of vibration induced movement.

4.4.1 Vibration Monitoring System Requirements

The vibration monitoring system consists of vibration sensors, data acquisition units and signal conditioners or filters, and data recording, processing, analysis and display.

The frequency range of the sensors is between 5 to 25 Hz or higher. The vibration level is in the range of 0.001 to 0.100 mm for a normal duration of 0.5 s. Velocity and acceleration transducers are usually applied to measure vibrations induced by traffic. Resolution and sensitivity of the sensors shall be properly selected for the applications. Locations of the sensors are critical to correctly characterize the vibration levels. The locations can be on the walls near the cable entrance or racking anchors, or on the floors near the racking anchors, on the cleats and other components of the cable constraint systems, on the cable jacket or joint casing surfaces. The instruments should be suitable for the environment such as water and submergibility and should be corrosion resistant. The monitoring system should be designed to reduce the interference of magnetic fields from the power cables.

The general requirements for communication systems, power supplies and central control units with data processing software are similar to the ones used for partial discharge monitoring systems as described in the previous section.

5
EVALUATION OF EXISTING MONITORING SYSTEMS

5.1 Introduction

Technical proposals from three partial discharge on-line monitoring system providers were received to demonstrate their systems. These three providers are TechImp/Italy, HVPD/UK, and Omicron/Austria. The proposals include:

- Specifications of items to install for PD monitoring
- Items to install for optional sheath current monitoring
- Options for communication methods
- Options for power supplies
- Cost of individual items to install
- Cost of engineering services provided by the supplier
- Items and engineering services not included in the proposal

In addition, monitoring options for displacement, strain and vibration are also evaluated.

This section provides a summary of technical aspects of the proposals.

5.2 TechImp Systems – PD and Sheath Current

TechImp offers both PD and sheath current monitoring systems for the 138-kV cable circuit. The systems consist of the following items:

1. PD Monitoring System and sensor kit
2. Sheath current monitoring system and transducer kit
3. Data processing unit

One PD monitoring system will be positioned in a substation where one set of three cable terminations are installed. One data processing unit will be installed near the substation. PD sensors will be positioned at both the terminations at the substation and the straight joints within the manhole. The sensors at joints will also allow on-line PD test performed at joints for diagnostic purposes after PD is detected by the PD monitoring system.

5.2.1 PD Monitoring System

The PD monitoring system is used to acquire and process PD signals from the PD sensors located at the termination and joints. A data acquisition unit will be located in each detection point. For this system, two units will be used, one at the termination location (three sensors) and one in the manhole for the three joint sensors. A fiber optic cable will be used to connect the two acquisition units to the data processing unit to process, store, and display the data. One power supply and protection device will also be included in the system. The data processing unit includes a server mounted on a rack.

5.2.2 Partial Discharge Sensors

Two PD sensor options are provided.

Option 1: Flexible Magnetic Coupler

The flexible magnetic coupler uses a direct magnetic coupling with the cable conductor and sheath. It detects magnetic signals from partial discharges travelling along the cable. It has directional sensitivity and is a passive sensor. Amplifiers and signal conditioning devices can be added but are optional. Power supply is needed for the amplifiers and conditioning devices. Bandwidth of the sensors is 30 kHz to 50 MHz. The sensors are attached to the cable near the cable joints or terminations. Figures 5-1 and 5-2 show two examples of the sensor's installation configurations. (All Pictures in Section 5.2 are courtesy of TechImp Systems.)

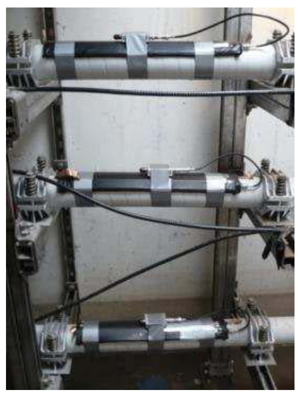

Figure 5-1
Flexible magnetic coupler installed on cable outside jackets

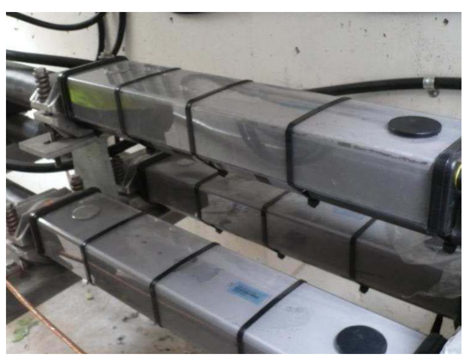

Figure 5-2
Flexible magnetic coupler with additional protection installed on cable outside jackets

Option 2: High Frequency Current Transformer (HFCT)

Figure 5-3 shows an example installation configuration in which the HFCT is installed on a ground connection from the cable termination base. The HFCT can also be installed on a ground lead within a link box (Figure 5-4). The bandwidth (-6dB) of the HFCT is 1 MHz to 80 MHz.

Figure 5-3
HFCT installation to a cable termination

Figure 5-4
HFCT installation within a link box

If a capacitive tap is provided with the cable joint, the HFCT is used to isolate the monitoring system from the high voltage cable system. For this configuration, the HFCT is installed to detect the current of the loop when the capacitor output is connected to the shield through impedance that is equal to the impedance of the HFCT (50 Ω for this case). Figure 5.5 shows an example of this application. The HFCT can also be installed on a bonding cable (if available) outside or inside a link box. These two installations are not applicable for this example circuit because of the absence of external sheath bonding leads.

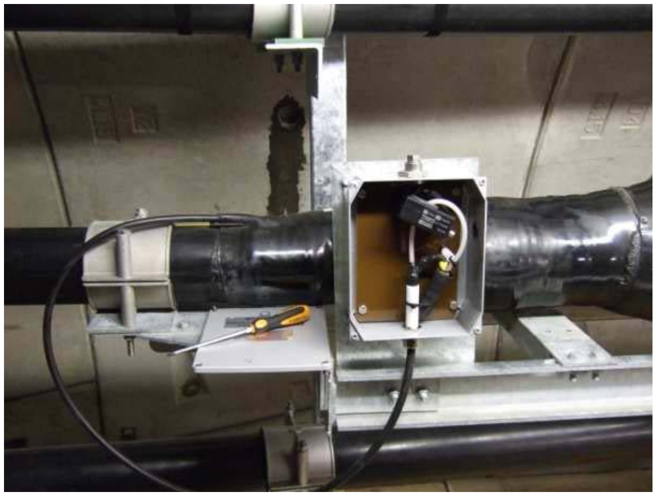

Figure 5-5
HFCT installed as an isolator for joints with a capacitive tap

5.2.3 Partial Discharge Acquisition Unit

A PD acquisition unit is installed at the detection point (terminations and joints) with power supplies. The unit is connected to PD sensors via coaxial cables to acquire the PD signals. The sampling rate of the unit is 100 MS/s for each channel. The data is transferred using a standard Ethernet 10/100 Mb interface. The unit can characterize PD pulses, improve signal-to-noise ratio and derive pulse features for separation purposes. The bandwidth of the unit is 16 kHz to 30 MHz, resolution 10 bit partial discharge sensitivity of 1,4000 mV_{pp}.

5.2.4 Communication Network

The communication network uses fiber optic links to connect the data acquisition units together and then to the data processing unit. This system allows the automatic detection of a fiber optic link interruption and automatic commutation of the communication through a different fiber optic link route. A multi-core, multimode fiber optic cable is installed from the data acquisition units to the data processing unit and server along the cable.

5.2.5 Data Processing Unit and Server

The PD data from the data acquisition units are stored, processed and displayed by a data processing unit. The unit includes a server, uninterrupted power supply, contact board, rack, software, and database. The PD monitoring system can be controlled remotely.

5.2.6 Software, Filtering Tool and Diagnostic Database

The software can be used to set parameters, trigger levels, alarms and visualize the situation.

The system main features include indicators of a main PD parameter (Maximum PD height, 95% percentile of PD height distribution, number of PD per acquisition, number of PD per period), traffic light logic to emphasize apparatus state, and implementation of new warning criteria based on experience, custom requirements, and trend of parameters.

The data are stored into a database to compress the data to be saved with an easy and efficient memory structure and use queries for possible cross correlations among the stored data. The database can then be interrogated remotely.

5.2.7 Current Monitoring Sensors

The current monitoring sensors are used to detect currents flowing through the cable sheath. The sensors can be installed on the ground lead. The sensors offered are a modified version of FLUKE 12000 FLEX.

5.3 HVPD – Partial Discharge

5.3.1 PD Monitoring System Overview

The PD monitoring system comprises of one PD monitor unit installed at Substation A and one PD monitor unit installed at the splicing vault if PD sensors can be attached within the vault. The system uses synchronous data acquisition of (4) PD sensors (typically 3-HFCT sensors and 1-TEV sensor, as described below) at each measurement node.

5.3.2 PD Sensors

Both High Frequency Current Transformer (HFCT) and Transient Earth Voltage (TEV) sensors are used. The HFCT sensors are to measure PD signals from both the cable and cable accessories. The TEV sensors are only to measure PD signals in the accessory where the sensors are installed. The HFCT sensors are installed on the sheath grounding lead of each termination and splice if accessible. The TEV sensors are attached to the cable terminations and on the joint in the splicing vault, depending on the suitability of the joint design and accessibility to the joints.

5.3.3 Data Storage

An internal hard disk from the PD monitor is used to store data from the PD sensors. The data is then extracted from the device through remote access to the unit.

5.3.4 Power and Grounding Requirements

Power supply of 110 to 263 V ac is required. The units are grounded to a local earth point.

5.3.5 Summary of the PD Monitor System Specification

Detection Frequency Range: 100 kHz - 50 MHz
Input Connection Internal Impedance: 50 Ω
Acquisition Period: 16.67 ms
Sample Rate: 100 MS/s
PD Data Display:

- PD level bar charts
- PD in time graphs
- Peak PD Level
- Summary Table

5.3.6 PD Monitor Operating Process

Data of one power cycle in duration are captured. The data is then scanned for PD signals and noise events. These events are categorized as PD in cable, PD in accessories, and noise through event recognition. Integrated values of PD and noise activity are summarized and the raw data are then discarded to free memory.

5.3.7 Noise and Interferences

Filtering and event recognition in software are used to reduce noises from the measurements.

5.3.8 Remote Communications

Remote access over the cellular communication networks is available to the PD monitor.

5.3.9 Installation Environment

The PD monitor units are to be installed in an indoor environment such as the substation control building or an outdoor cabinet.

5.3.10 Sheath Current Monitoring

Continuous sheath current monitoring is not included in the system proposed.

5.4 Omicron – Partial Discharge

The PD equipment is used with monitoring system software for PD detection, defect localization and interpretation of the PD data.

5.4.1 Technical Description

The monitoring system proposed includes:

- One monitoring box to be installed close to the cable termination in Substation A
- Three PD acquisition channels and one ac power supply module including over voltage protection, line filter and insulation transformer
- Three inductive PD sensors mounted on each phase grounding connection of the termination
- Fiber optic communication cables between the monitoring box and the server
- Monitoring server for system configuration and control, storage of continuously acquired PD data, data post-processing and evaluation. The server can be remotely accessed.

The PD acquisition unit detects PD events via HFCT sensors connected to the control station by means of a fiber optical network. The PD Monitoring software running on the Monitoring server receives, displays, stores and analyzes the PD data. The server software can also configure and control the system.

The acquired data are filtered digitally via software. PD monitoring software continuously monitors for PD activities inside the cables, joints, or terminations. The software also identifies external noise and separates it from PD signals relating to the cable system. The system can be remotely controlled.

Continuous sheath current monitoring is not included in the system offered.

5.4.2 Installation Procedure

Installation and performance check procedure is:

1. Laying of ac power supply cable from substation to the termination
2. Laying of fiber optical cable from end substation to the termination
3. Installation of the inductive sensors and PD units
4. Installation of server in control room of end substation
5. Check of performance of the system

5.4.3 Check-of-Performance Procedure

1. Activate internal test signal generators to verify system functionality.
2. Check server hardware and software, including PD detection, transmission, quantification and further transmission to the substation server.
3. Determine measuring frequency ranges for all channels.
4. Calibrate each PD acquisition channel by injection of defined calibrator impulses close to appointed inductive sensor placement.
5. Configure the monitoring server software and system features.

5.5 Techkor Instrumentation – Vibration

A wireless vibration monitoring system offered by Techkor Instrumentation was evaluated. The basic components of the system are depicted in Figure 5-6. This set of components is in their starter kit, which includes the application software, a network access point (NAP), an NAP antenna, and five accelerometers. The accelerometers are available in three forms: standard, plastic housing, and a high-temperature version.

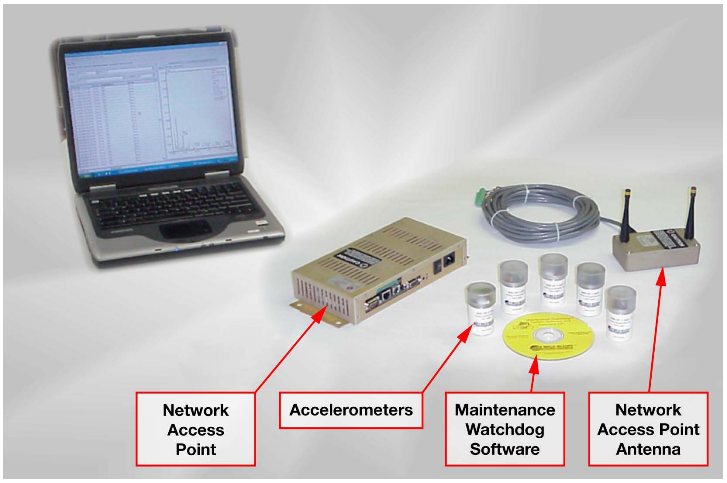

Figure 5-6
Wireless vibration monitors [5]

The software operates as a background application and handles the sensor configuration and transfer of data from the NAP to a database to store sensor configurations and the data from the sensors and to display the recorded data (acceleration, velocity, or displacement).

The following lists specifications of Techkor Wireless Accelerometer Model 7034:

- Piezoelectric sensor
- Temperature sensor
- Digital signal processor
- Number of Axes: 1
- Selectable ±50G or ±5G full scale range
- Acceleration Sensitivity: 0.003G
- 0.45 Hz to 10 kHz response
- 125 Hz to 40 kHz sampling rate
- Data memory, 65,000 sample storage capacity
- Programmable data form:
  - Time waveform
  - Fast Fourier Transform
  - Historical trend
- Configurable wireless node
- Normal battery life: 2+ years

5.6 MicroStrain – Displacement, Vibration, and Strain

5.6.1 Displacement Sensor

A displacement sensor was acquired for this project. (Figure 5-7) This sensor was designed for linear control and precision applications and the sensing head was short-term submersible. For long-term submersion, the units can be custom built. The sliding transducer core is corrosion resistant.

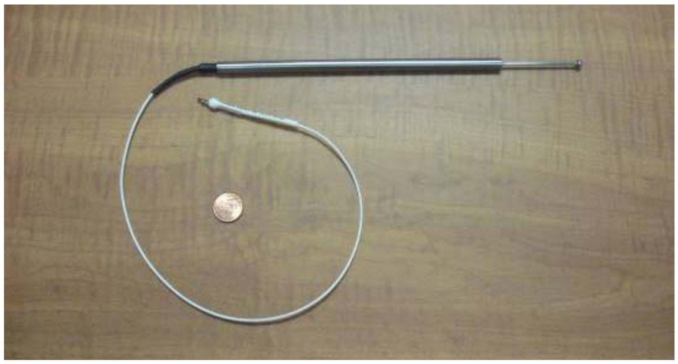

Figure 5-7
Displacement sensor

The sliding transducer core is used for position detection. Core position is measured by differential reluctance of the coil within the sensor case, using a sine wave excitation and synchronous demodulator. This differential detection method cancels out any temperature effects.

Major electrical and mechanical specifications of the displacement transducer are as follows.

Electrical:

- Linear stroke length: 38 mm
- Accuracy at constant temperature: ±1.0 % using straight line; ±0.1 % using polynomial
- Signal to noise ratio: 4200 to 1 (with filter 3 dB down at 800 Hz, standard resolution); 466 to 1 (unfiltered)
- Resolution (0.025% of full scale for standard version): 9.5 µm for 38 mm stroke
- Frequency response: 800 Hz standard
- Temperature coefficient offset: .002% / °C (typical)
- Temperature coefficient offset: .030% / °C (typical)

Mechanical:

- Overall case length: 124 mm
- Outside diameter: 4.76 mm
- Case material: 300 stainless steel

- Flexible lead: 450 mm, multi-strand, shielded, stainless steel reinforced Teflon insulated cable
- Connector: Keyed Lemo 4-pin
- Operating temperature: -55°C to 175°C

5.6.2 Signal Conditioner

A signal conditioner is used with this displacement transducer (Figure 5-8). The conditioner provides a linear dc output. It requires a dc power supply and the output is a dc voltage proportional to linear position. The conditioner uses a filter for incoming transients from the line voltage and a sine wave excitation is supplied to the transducer. This excitation measures impedance changes of the sensor.

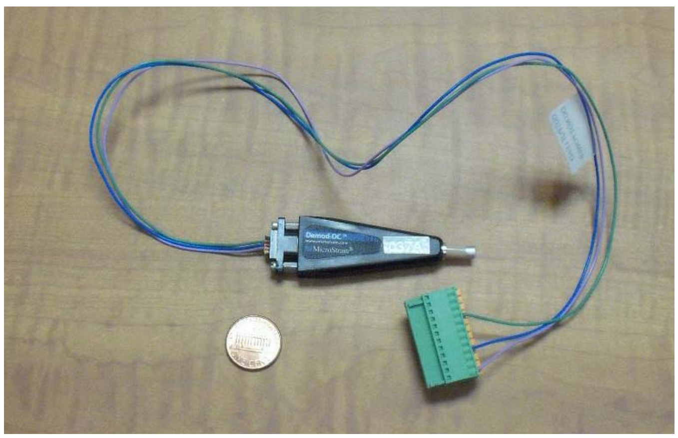

Figure 5-8
Signal conditioning unit

Major specifications of the signal conditioner are as follows.

- Output: 0 to 5 V typical
- Gain: factory adjustable from 10 to 10,000
- Low pass filter: 2 pole, 3 dB down @ 800 Hz standard; Factory adjustable 10 to 20 kHz
- Supply voltage: + 6.0 to + 16 Vdc
- Supply current: 22 mA
- Operating temperature: -40˚C to 85˚C
- Enclosure size: 50×20×10 mm
- Connections: power, ground, and analog output
- Connector: Micro-D (MIL-C-83513/5) mating connector

5.6.3 Communications Link

A wireless unit also provided by MicroStrain is used that operates as part of a wireless sensor network. (Figure 5-9) The unit uses 2 kHz sweep rate and 2 Mbytes flash memory. The unit also provides sensor excitation, bridge completion, programmable gains and offsets, and differential and single ended inputs. The radio frequency (RF) communications link can trigger a sample and request real-time data from about 70 m. In addition to the displacement sensors as used for this application, the unit is also compatible with strain gauges, accelerometers, temperature sensors, and others. A software development kit is provided that includes source code and a compiled executable for Microsoft® Visual Studio C++ .NET 7.1, Microsoft® VB 6.0, Microsoft® VB.NET 2003, Microsoft® VB.NET 2005 and LabVIEW® 7.1.

Figure 5-9
Wireless communication unit (left) and receiver to computer (right)

Major specifications of the wireless communications link are as follows.

- Input channels: up to 8 (4 full differential, 350 Ω resistance or higher, 3 single ended inputs (0-3 V maximum), and 1 internal temperature sensor)
- Temperature sensor: -40˚C to +70˚C, accuracy ±2˚C (at 25˚C)
- Measurement accuracy: ±0.1% full scale typical
- Programmable gain: software programmable for differential input channels from 210 to 4844
- Analog to digital (A/D) converter: successive approximation type, 12 bit resolution
- Data storage capacity: 2 MB (approximately 1,000,000 data points)
- Data logging mode: Log up to 1 million data points at sampling rates from 32Hz to 2048Hz per channel in fixed (from 100 to 65,500 samples) or continuous (until memory full) sessions
- Sensor event driven trigger: Commence data logging when threshold exceeded
- Real-time streaming mode: Transmit real time data from node to PC - rate depends on number of active channels: 1 channel - 4 KHz, 2 channels - 2 KHz, 3 channels - 1.33 KHz, 4 channels - 1 KHz, 5 channels - 800 Hz, 6 channels - 666 Hz, 7 channels - 570 Hz, 8 channels - 500 Hz
- Low duty-cycle mode: Supports multiple nodes on single RF channel
- RF transceiver carrier: 2.4 GHz direct sequence spread spectrum
- RF data packet standard: IEEE 802.15.4, open communication architecture
- RF data downloading: 8 minutes to download full memory

- Range for bi-directional RF link: 70 m line-of-sight, up to 300 m with optional high gain antenna
- Internal Li-Ion battery: 3.7 V lithium ion rechargeable battery, 600 mAh capacity. External power from 3.2 to 9 V can also be used.
- Power consumption: real-time streaming - 25 mA, data logging - 25 mA, sleeping - 0.5 mA; external sensors: 350 Ω strain gauge - 8 mA, 1000 Ω strain gauge - 3 mA
- Operating Temperature: -20˚C to +60˚C with standard internal battery and enclosure, extended temperature range optional with custom battery and enclosure. -40˚C to +85˚C for electronics only
- Maximum acceleration limit: 500 g standard
- Dimensions: 88×72×26 mm (enclosure without antenna)
- Enclosure material: ABS plastic
- Software: Node Commander®, Windows XP/Vista compatible
- Compatible Base Stations USB, RS-232, Analog, and WSDA®

5.6.4 Software

A 2.4 GHz software development kit provides protocols and source code samples to support the wireless sensors including the wireless units.

5.6.5 Displacement Measurement System

Figure 5-10 shows the displacement measurement system with sensor, signal conditioner and communications link connected.

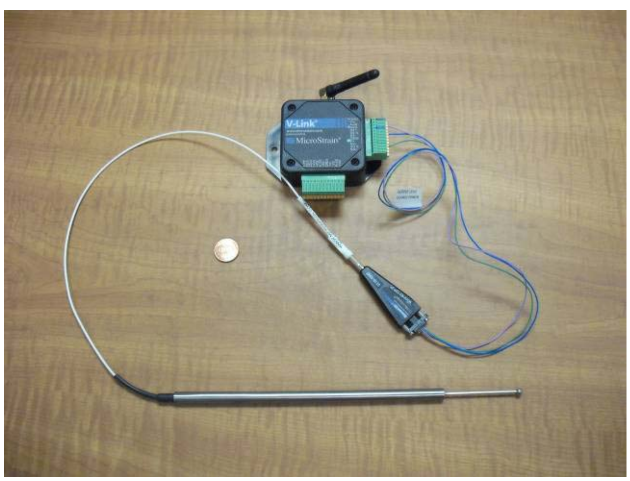

Figure 5-10
Prototype system for displacement measurements (sensor, signal conditioner, and wireless communications link)

5.6.6 Vibration

Vibration is measured by an MEMS accelerometer with a data logging transceiver system. (Figure 5-11) The system uses a wireless tri-axial accelerometer node as part of a wireless sensor network system. A bi-directional RF communications link can trigger a sample or request real-time data. The system uses a software development kit that includes source code and a compiled executable for Microsoft® Visual Studio C++ .NET 7.1, Microsoft® VB 6.0, Microsoft® VB.NET 2003, Microsoft® VB.NET 2005 and LabVIEW® 7.1.

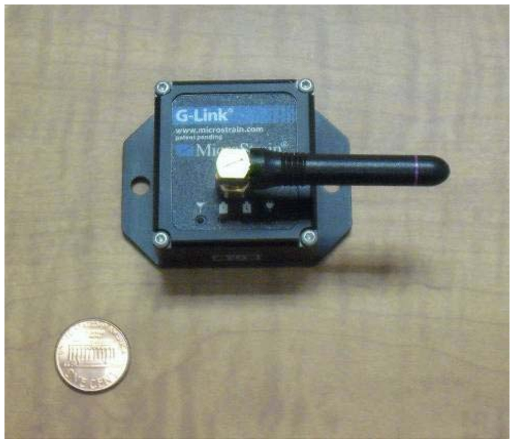

Figure 5-11
Vibration sensor and wireless communication unit

Major specifications of the wireless communications link are as follows.

- Accelerometers: Tri-axial MEMS accelerometers, Analog Devices AD22293 (2g) or ADXL210 (10g)
- Accelerometer range: ±2 g or ±10 g
- Measurement accuracy: 10 mg
- Resolution: 1.5 mg RMS (2g), 9 mg RMS (10g)
- Temperature sensor: -40˚C to +70˚C range, accuracy ±2˚C (at 25˚C)
- Analog to digital (A/D) converter: Successive approximation type, 12 bit resolution
- Data storage capacity: 2 MB (approximately 1,000,000 data points)
- Data logging mode: Log up to 1 million data points at sampling rates from 32 Hz to 2048 Hz per channel in fixed (from 100 to 65,500 samples) or continuous (until memory full) sessions
- Sensor event driven trigger: Commence data logging when threshold exceeded
- Real-time streaming mode: Transmit real-time data from node to PC - rate depends on number of active channels: 1 channel – 4 kHz, 2 channels – 2 kHz, 3 channels – 1.33 kHz, 4 channels (including temperature) – 1 kHz
- Low duty-cycle mode: Supports multiple nodes on single RF channel
- RF transceiver carrier: 2.4 GHz direct sequence spread spectrum
- RF data packet standard: IEEE 802.15.4, open communication architecture

- RF data downloading: 8 minutes to download full memory
- Range for bi-directional RF link: 70 m line-of-sight, up to 300 m with optional high gain antenna
- Internal Li-Ion battery: 3.7 V lithium ion rechargeable battery, 250 mAh capacity. External power from 3.2 to 9 V can also be used.
- Power consumption: real-time streaming - 25 mA, data logging - 25 mA, sleeping - 0.5 mA
- Operating Temperature: -20˚C to +60˚C with standard internal battery and enclosure, extended temperature range optional with custom battery and enclosure. -40˚C to +85˚C for electronics only
- Maximum acceleration limit: 500 g
- Dimensions: 58×43×26 mm (enclosure without antenna)
- Enclosure Material: ABS plastic
- Software: Node Commander® Windows XP/Vista compatible
- Compatible Base Stations: USB, RS-232, Analog, WSDA®

6 CONCLUSIONS

On-line condition assessment of extruded dielectric cable systems can be realized by incorporating improved sensors, more efficient power sources to the sensors, enhanced data collection systems, and better integration with utility operation systems.

This first phase of the multi-year project evaluated current technologies on extruded dielectric cable system monitoring. The monitoring system included sensors, data acquisition, data collection and transmittal to data center, and post processing to analyze and display results.

The following technologies were evaluated and different monitoring systems were described.

- Partial discharge monitoring on cables, joints and terminations
- Cable movement monitoring through measurements of displacement of cable, cable racking and clamps
- Cable cleat and rack strain monitoring
- Manhole wall, joint, cable, racking system vibration monitoring

The project planned a demonstration of the discussed technologies on a host utility cable circuit. The tasks of this demonstration would include the following and the tasks will be carried out in the following years.

- Provide and install sensors, data acquisition systems, monitoring software, power supply, and communications.
- Monitor system performance, report results, and determine future R&D work.

This project would help to investigate effectiveness of applying on-line PD monitoring. Probability of detecting measurable PD at line voltage and time between onset of detectable PD and insulation breakdown of a transmission level cable are also emerging topics to study.

Programs such as NSPAN [3] can assist with analyses for the mechanical property monitoring.

7
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