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Underground Transmission Cable Monitoring – Lessons Learned at AEP

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SUMMARY

As part of its system and asset health monitoring initiative, American Electric Power (AEP) has deployed several new online health monitoring systems on its cross-linked polyethylene power cables. Two different types of monitoring systems have been deployed, including partial discharge monitoring and distributed temperature sensing monitoring on a total of 4 different 138kV power cable circuits and 1 69kV power cable circuit. These continuous health monitors provide multiple indicators about the power cable assisting in the health assessment of an otherwise invisible asset. The first of these installations was completed in 2016, with the latest installation being completed in 2019. The nature of the monitoring systems, the possible benefits, as well as some of AEP's lessons learned from these pilot installations will be discussed in the following paper.

KEYWORDS

Asset health, power cable, online monitoring, partial discharge, distributed temperature sensing, sensors

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I. Introduction:

American Electric Power is one of the largest transmission companies in the United States with over 40,000 miles of transmission lines. Of those 40,000 miles, only about 100 miles are comprised of underground transmission power cables. This proportionally small number of underground power cables consist of high pressure fluid filled (HPFF) lines (installed in the late 1950-1970s) and cross-linked polyethylene (XLPE) lines. Even though AEP only owns a small number of these circuits, they are typically used in highly congested areas, where normal overhead lines are impractical, feeding critical customers and metropolitan areas. Failures of these types of power cables result in long outages [1] and for HPFF cables, there can be environmental impacts as a result of failures.

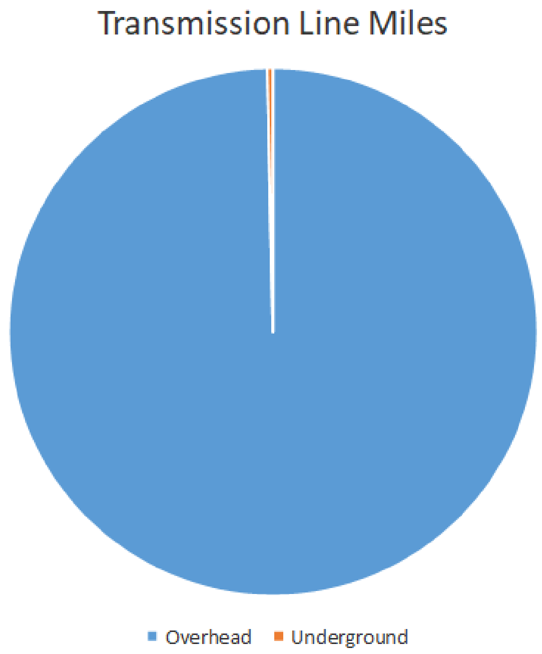


Figure 1: Composition of AEP's transmission line networks

Thus, the key question becomes how to manage the lifecycle of the power cable which includes: preventing failures, optimizing operations & maintenance expenditures and prioritizing asset renewal decisions. An initial attempt at lifecycle management for the power cable would be to base all decisions on asset and component age. With this time based approach, failure of the cable conductor and accessories is rarely prevented, resulting in possible safety hazards to both AEP and the public as well as costly repairs to the power cable. Power cable maintenance activities are performed on regularly scheduled intervals, but may miss possible failure indictors that develop between these maintenance cycles. With regards to renewal decisions, regulators and stakeholders are now requiring extensive condition and performance information for replacement projects, rendering age based justification methods less likely of receiving approval.

Rather than using time as the main factor for asset decisions, a condition based approach can be utilized. With a condition based asset management plan, the following goals can be realized:

1. Prevention of equipment failures
2. Optimization of operation and maintenance expenditures
3. Prioritization of asset renewal decisions

To support these goals, in 2015, AEP deployed the Asset Health Center, a web based analytics solution designed to manage, track and visualize the health of AEP's asset populations [2]. This system uses asset performance algorithms to analyse incoming condition data, generating health scores, replacement priority scores and maintenance priority scores. In parallel with this software deployment, AEP began a systematic installation of online sensors on its extra high voltage (EHV) power transformer fleet. These online monitoring installations have enabled AEP to prevent 14 out of a possible 20 EHV transformer failures using dissolved gas and partial discharge monitoring systems.

The online sensor deployments have expanded to include pilot installations of monitoring equipment and sensors on non-EHV transformers, transmission circuit breakers, substation batteries, and underground transmission cables. AEP's experiences with monitoring of underground transmission cables will be discussed in the following sections.

II. Online Cable Monitoring

Accurate assessment of the condition of underground transmission power cables becomes critical to the lifecycle maintenance and replacement plan for these assets. Unfortunately, visual condition assessment practices used for normal overhead transmission lines are not as applicable to underground cables. Inspections are limited to the termination points of the underground cable and the cable splice locations inside of manholes. With most of the cable invisible from visual inspection it can become difficult to determine the condition of the asset.

With a major failure of the AEP underground distribution network in downtown Columbus [3] and multiple splice failures of a critical 138kV XLPE power cable in 2014, AEP Leadership began looking for possible solutions to address the failing power cable systems. One result of the investigations was to look into online monitoring systems for power cables.

AEP has become very experienced with permanently installed online monitoring systems. The comprehensive monitoring package that has been deployed on more than 350 of AEP's EHV transformers consists of dissolved gas analysis monitoring, electrical and ultra-high frequency (UHF) partial discharge monitoring, temperature monitoring, bushing health monitoring, and cooling system monitoring. Of these systems partial discharge and temperature monitoring seemed the most applicable for condition monitoring of XLPE power cables.

Partial Discharge Monitoring

The first technology deployed on a transmission power cable was an online partial discharge monitoring system. Partial discharges (PD) are partial electrical breakdowns in the insulation system of an asset. The effects of partial discharge are shown in Figure 2. Continued partial discharge activity within defects of the dielectric insulation can lead to a full breakdown of the insulation system leading to a catastrophic failure of the asset.

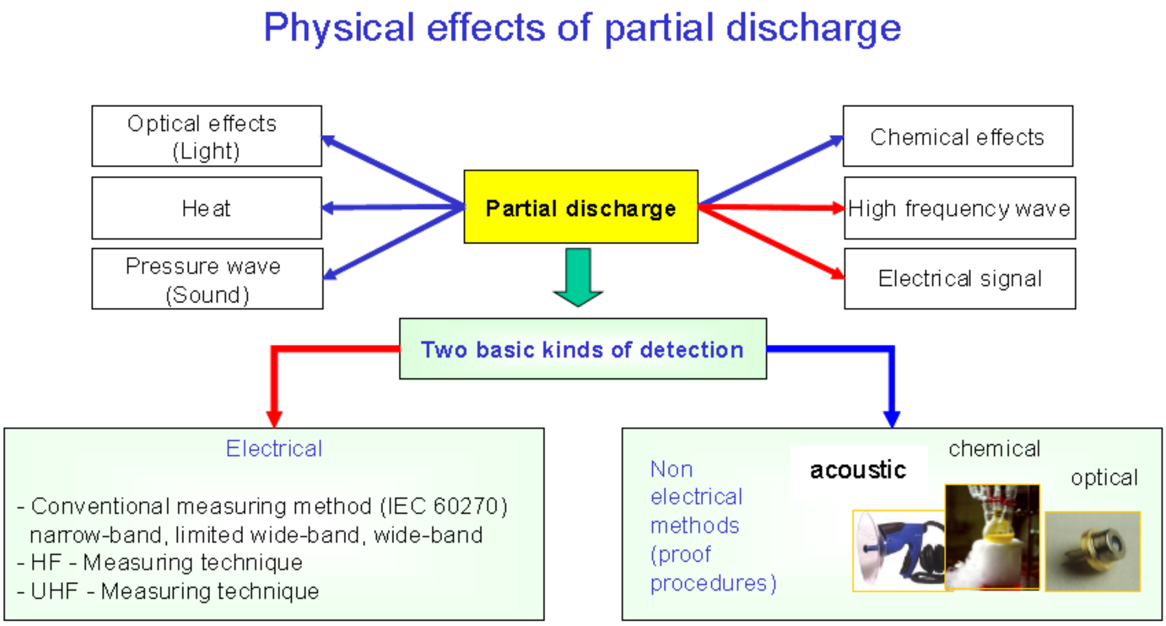


Figure 2: Overview of the physical effects of PD [4].

AEP has deployed multiple partial discharge monitoring technologies on its EHV transformers with successful failure detection and prevention as described in [5]. Since transmission power cables consist of high voltage apparatus surrounded by a dielectric medium, it seemed appropriate that partial discharge monitoring of a power cable could lead to the same benefits as partial discharge monitoring of power transformers.

Working with one of AEP's transformer partial discharge monitoring vendors, a permanently installed partial discharge monitoring system for transmission power cables was provided. This system was designed to monitor XLPE power cables by using high frequency current transformers (HFCT) installed on the cable earth shields found at the termination ends of the power cables. The HFCTs would continuously monitor for partial discharge signals that would be induced on the earth shield cables by the PD source. The data from these HFCTs would be collected in the substation yard by a Remote Acquisition Unit and then sent to a server in the substation control house for analysis and storage. An overview of the system can be seen in Figure 3 below.

The first installation of the partial discharge monitoring system was completed in December 2016 on Circuit#1 (2.63 miles) and Circuit#2 (0.53 miles) 138kV circuits. This system required sensor installations at each end of the two circuits for a total of four data acquisition units monitoring the two lines. Each HFCT records the following parameters every 10 minutes: pulse shape, maximum/average amplitude (uV), maximum/average pulse (uV), maximum/average discharge rate, and the phase resolved distribution plot. It would then send this data to the server system for storage and visualization. The system also classifies the pulse as to whether it appears to be partial discharge or non-partial discharge based on the phase resolved distribution plot compared against known PD patterns. A typical recorded pulse can be seen in Figure 4. Monitoring the trend of these partial discharge signals over time is crucial to the analysis of the health of the power cable. Increasing discharge rate and amplitude would indicate a destructive partial discharge that could lead to arcing and cable failure.

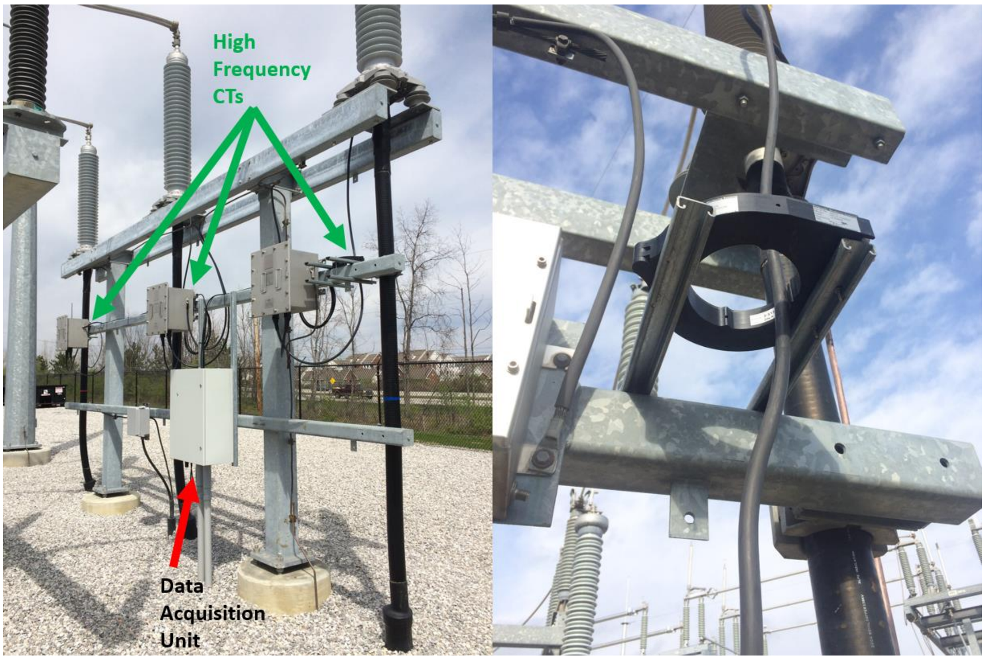


Figure 3: Overview of partial discharge monitoring system

The second installation of partial discharge monitoring equipment was completed in July 2019 with another two 138kV XLPE underground cable circuits monitored, Circuit#3 (1.13 miles) and Circuit#4 (4.42 miles). Circuit#3 is currently being monitored from both termination locations, while Circuit#4 is being monitored from only one end. The remote end of Circuit#4 converts to overhead transmission prior to terminating at the substation. Power and communication infrastructure was not available at the riser structure, thus no data acquisition unit was installed.

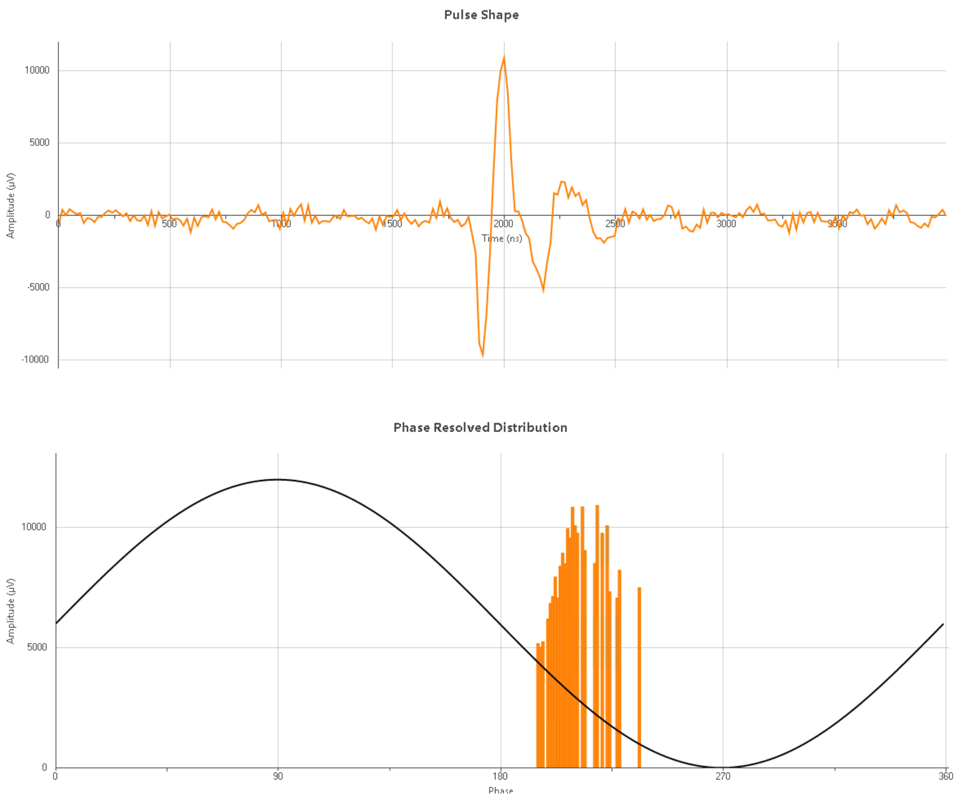


Figure 4 : Typical Partial discharge pulse shape and phase resolved distribution plots for a PD event.

Distributed Temperature Monitoring

Distributed temperature sensing (DTS) uses the Raman Effect to measure temperature along a length of fiber optic cable. A laser pulse is sent down the fiber and the back scattering of the stoke and anti-stokes allow for the calculation of the temperature of the fiber. The position along the fiber is determined by measuring the arrival time of the returning measurement pulse. Figure 5 demonstrates the principle of the Raman Effect [6].

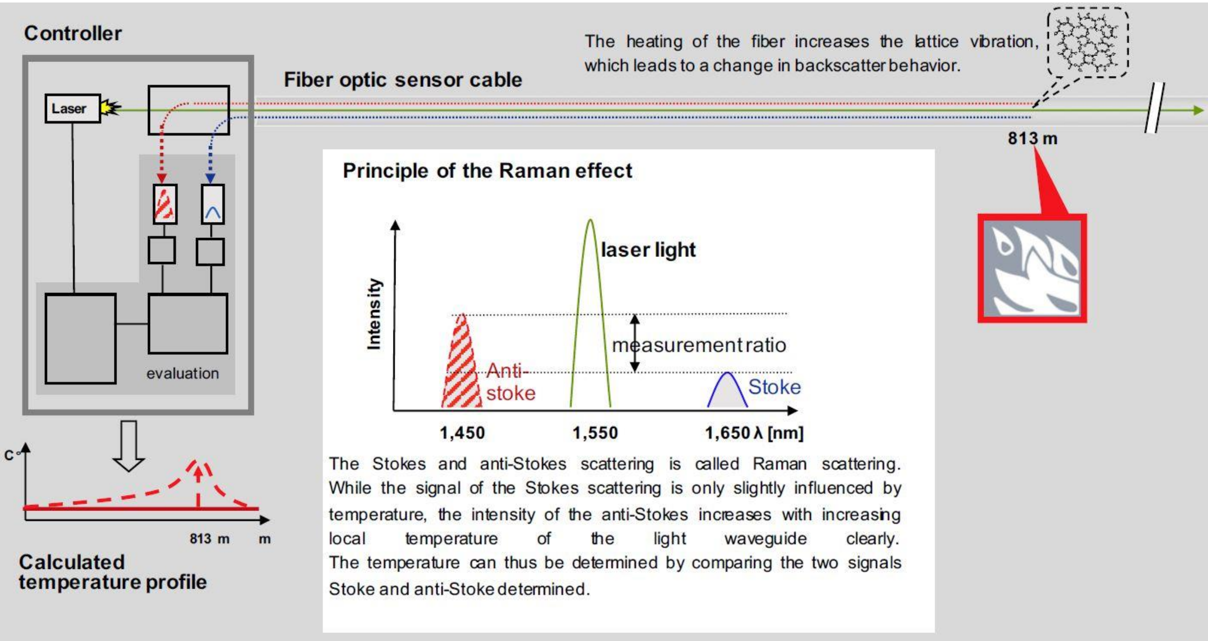


Figure 5: Raman Effect principle for distributed temperature sensing applications [6]

After an initial installation of partial discharge monitoring on a transmission underground power cable in 2016, AEP asset monitoring engineers began working with the transmission line engineering group to plan an installation of DTS monitoring. Compared with the online cable PD monitoring system, where only one vendor at the time offered online continuous PD monitoring, there were several DTS monitoring vendors on the market. To test the effectiveness of some of the leading DTS products, AEP decided to pilot two different vendors for DTS monitoring on multiple projects. The goal of this evaluation was to evaluate the overall monitoring solution which includes such categories as: hardware, software, data transmission, user interface, and vendor support, rather than directly compare two vendors on the same power cable to prove which technology was more accurate (both vendors had been proven in the industry). This analysis would be used to determine a standard offering for AEP power cables in the future.

The first installation of DTS monitoring with Vendor 1 was completed in February 2019, on Circuit#5, a 1.34 mile 69kV XLPE cable that is currently being operated at 40kV. This cable consisted of a termination in a substation where the DTS unit was located with the remote end converting from underground to overhead transmission. There are two splicing manholes along this route. During the project, some minor adjustments were made to the DTS fiber run to be compatible with the monitoring system, which resulted in the fiber being routed in the Spare power cable conduit. The location of the DTS fiber in relation to the three phases of the power cable is shown in Figure 6. While this distance from the actual power cable limits the accuracy of the measurement, the goal of the DTS system is to look for changes in temperature that could indicate a hotspot and future failure. The thermal characteristics of all components in the duct bank are known, so a calculation of the temperature of the power cable would be possible.

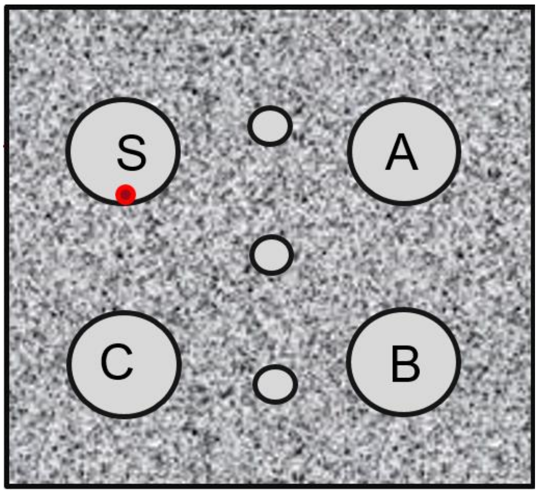


Figure 6: Typical location of DTS fiber for Circuit#5 installation

Vendor 1’s system is highly user configurable, with user selectable traces, zone data and points of interest that can be plotted vs. time. One interesting feature of Vendor 1’s DTS monitoring system is the ability to create a color map of temperature vs. position vs. time. As can be seen in Figure 7, the DTS monitoring system has shown the effects of the extremely high ambient temperatures being experienced in July on the power cable. The large cooler section to the left of the graph consists of a bore under a major interstate freeway, where the power cable gets to a depth of about 34ft below grade, resulting in more stable temperatures.

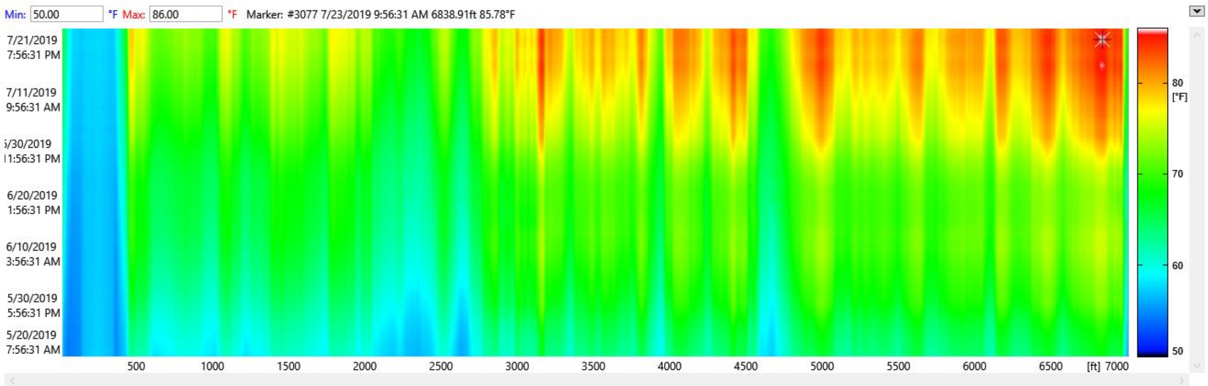


Figure 7: DTS Color map, ploting distance, temperature and time for May – July 2019

The second monitoring installation of DTS with Vendor 2 was completed in June 2019 in parallel with the underground PD monitoring installation on Circuit#3 and Circuit#4. This system consists of two channels where the DTS system was installed at the substation where both Circuit#3 and Circui#4 terminate. Existing DTS fiber was utilized for both circuits which was installed in its own conduit in between the phase A power cable and spare phase power cable conduits. The typical location of the conduit and DTS fiber is found in Figure 8.

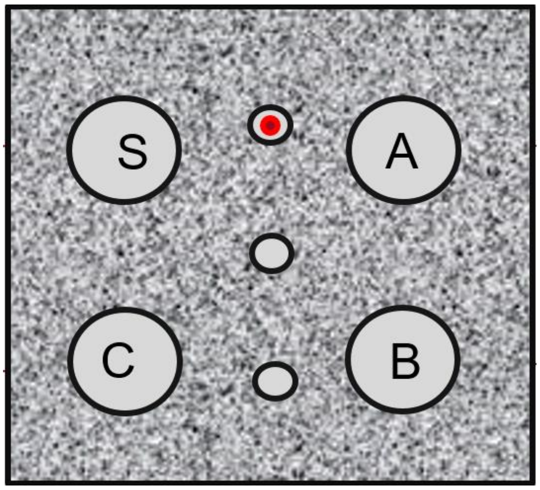
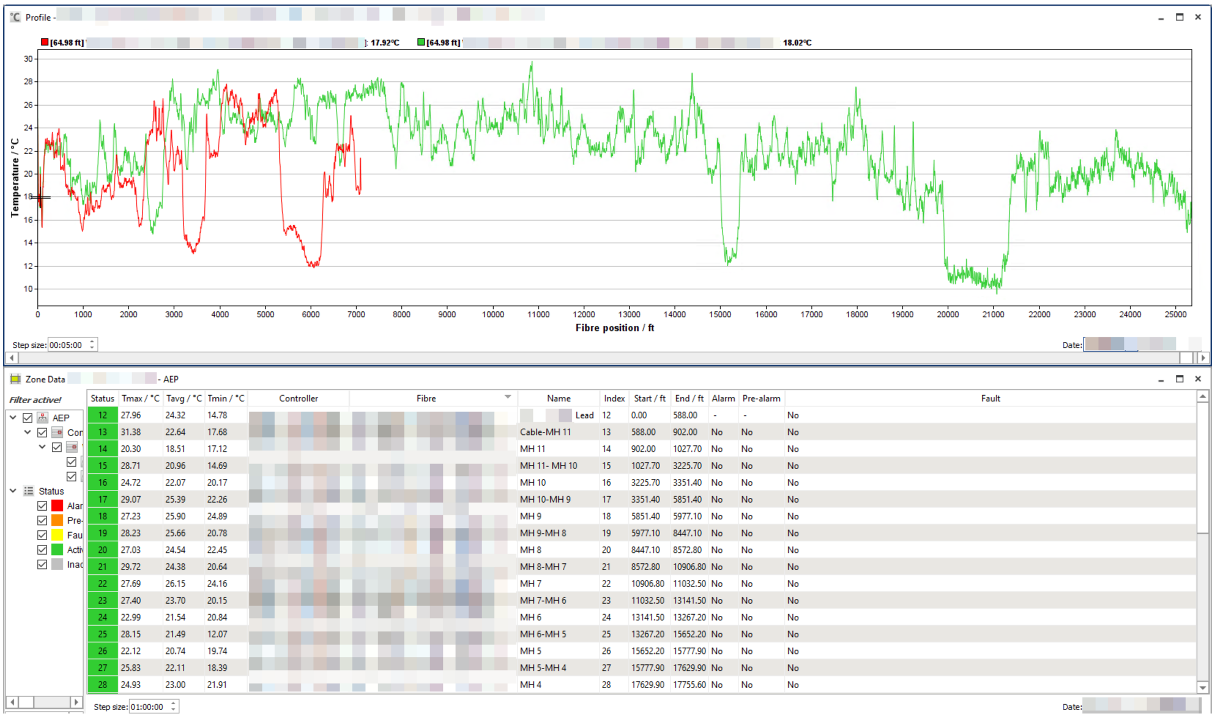


Figure 8: Typical location of DTS fiber for Circuits#3&4 installation

Like Vendor 1, the Vendor 2 system is highly configurable. The data for this system can be visualized in traces, hotspot locations as well as an enhanced view showing the temperature plotted along the power cable path. Temperature traces as well as defined temperature zone data is shown in Figure 9.



Status	Tmax / °C	Tavg / °C	Tmin / °C	Controller	Fibre	Name	Index	Start / ft	End / ft	Alarm	Pre-alarm	Fault
12	27.96	24.32	14.78			Lead	12	0.00	588.00	-	-	No
13	31.38	22.64	17.68			Cable-MH 11	13	588.00	902.00	No	No	No
14	20.30	18.51	17.12			MH 11	14	902.00	1027.70	No	No	No
15	28.71	20.96	14.69			MH 11- MH 10	15	1027.70	3225.70	No	No	No
16	24.72	22.07	20.17			MH 10	16	3225.70	3351.40	No	No	No
17	29.07	25.39	22.26			MH 10-MH 9	17	3351.40	5851.40	No	No	No
18	27.23	25.90	24.89			MH 9	18	5851.40	5977.10	No	No	No
19	28.23	25.66	20.78			MH 9-MH 8	19	5977.10	8447.10	No	No	No
20	27.03	24.54	22.45			MH 8	20	8447.10	8572.80	No	No	No
21	29.72	24.38	20.64			MH 8-MH 7	21	8572.80	10906.80	No	No	No
22	27.69	26.15	24.16			MH 7	22	10906.80	11032.50	No	No	No
23	27.40	23.70	20.15			MH 7-MH 6	23	11032.50	13141.50	No	No	No
24	22.99	21.54	20.84			MH 6	24	13141.50	13267.20	No	No	No
25	28.15	21.49	12.07			MH 6-MH 5	25	13267.20	15652.20	No	No	No
26	22.12	20.74	19.74			MH 5	26	15652.20	15777.90	No	No	No
27	25.83	22.11	18.39			MH 5-MH 4	27	15777.90	17629.90	No	No	No
28	24.93	23.00	21.91			MH 4	28	17629.90	17755.60	No	No	No

Figure 9: Temperature traces and zone data for Circuit#3 and Circuit#4 cables

III. Benefits of Cable Monitoring

Using these underground cable monitoring techniques, there are many benefits to the power cable as well as those who maintain and operate the power cable. These benefits can be categorized into the following areas: prevention of equipment failures, optimization of operation and maintenance expenditures and prioritization of asset renewal decisions.

Prevention of Equipment Failures

The monitoring systems allow for continuous online health assessment of the power cable. This can allow for the observation of developing failures in real time, whether it be from increasing partial discharge intensity or sustained high temperature along a portion of the power cable. These indicators can allow operators to track the condition of the asset and remove it at an opportune time for repair or investigation. The continuous aspect of the monitoring system allows for 24/7/365 analysis of the power cable. Defects that develop in between maintenance cycles often lead to failures with no way to proactively detect. AEP has experienced and prevented failures on EHV transformers where the indication of an imminent failure lasted a matter of hours. These monitoring systems allow for the opportunity to prevent cable failures, proactively repairing or replacing rather than reactively responding to a forced outage on a cable asset.

Optimization of Operation and Maintenance Expenditures

Historically, AEP would plan to conduct a thermal inspection of each XLPE cable splice. This required opening up the manhole and placing a thermal camera into the opening to inspect the splices while the power cable is energized. With this activity, there are several safety concerns including: the possibility of falls, possibility of dropping equipment into the manhole and confined spaces. By being able to monitor the power cable's temperature, including the manholes via the distributed temperature monitoring, these yearly maintenance activities may not be necessary, leading to improved safety for the field service group in addition to the cost savings. Process changes are currently being developed around these optimizations.

Prioritization of Asset Renewal Decisions

With an accurate condition assessment of the power cable, data driven decisions can be made with regards to the renewal and replacement of power cable assets. The data from the online sensors can be fed into an asset health condition model, enabling the output health indices to be positively or negatively affected by online parameters. The more online measurements that can be obtained from an asset, the better the estimation of the asset's overall health.

With the real time thermal rating (RTTR) features offered by both DTS vendors, more insight can be gained into how the real time load is affecting the health of the power cable. The monitoring system can alert to any abnormal hotspot temperatures and how these coupled with the current load are impacting that portion of the power cable. Decisions can then be made about whether the cable should be removed from service immediately due to an impending failure, or whether loading should be reduced to decrease possible degradation to the power cable to prevent a possible failure. With the continuous online temperature profile, there is a feedback loop of information on the power cable and how it is performing under current loading conditions, enabling more informed decisions pertaining to the health of the asset to be made.

IV. Lessons Learned and Knowledge Gained

As a result of the installations of partial discharge and distributed temperature sensing monitoring equipment there have been some key lessons learned at AEP.

Data and Alarm Transmission

For the monitoring data, it is important for the data to not stay local at the substation or to stay only in a server, where users need to proactively log into a system to look at the collected data. Data from these monitoring systems is transmitted over the AEP telecom infrastructure back to a centralized Station PI system as described in [7]. This data transmission makes use of the IEC 61850 MMS protocol to collect the analog and digital information in a centralized location. From there, the data can be published to various web dashboards for visualization or alarm email notifications can be generated when data meets certain thresholds and requires engineering analysis. Since AEP is still in the evaluation period for the cable monitoring systems, any alarms from the cable PD or DTS monitoring systems are not sent to the Transmission Operations group. AEP is still learning about these systems and the data being transmitted. Once the data is fully understood, and operational plans with action items and owners have been created, then the alarms will be transmitted to the Operations group so that real time failure prevention actions can be taken as described in the preceding sections.

2018 Cable Failure

In October of 2018, a failure occurred on the phase A splice at manhole#4 on the 138kV XLPE Circuit#1. The failed splice can be seen in Figure 10. At the time of the failure the PD monitoring system was operational and collecting data with no interesting PD signals found on the phase A sensors at either end of the circuit. Additional analysis was conducted by AEP and the PD Monitoring Vendor. This failure revealed a severe limitation in how the partial discharge monitoring system was deployed on Circuits #1.

Figure 10: Manhole 4 Phase A failed cable splice for Circuit #1

With the current grounding configuration for Circuit#1, shown in Figure 11, the partial discharge signals will be attenuated at each manhole where there is a sheath interruption. There are sheath interruptions at manholes 2, 4 and 5 for Circuit#1, thus to have accurately detected the splice failure at manhole#4, there would have needed to have been PD sensors at either between manhole 2 and 4 or between manhole 4 and 5. For this initial installation of cable PD monitoring, the sensors as mentioned above were only at the substation terminations for Circuit#1. This results in only a portion of the power cable being monitored, specifically from Substation 1 to manhole 2 and from manhole 5 to Substation 2. To completely monitor longer power cables that have sheath interruptions, additional sensors and data acquisition units need to be deployed. There are several technical engineering questions that need to be answered for those types of deployments such as: how to power the remote acquisition units, how to transmit data back to the central server and even where to mount the equipment. In addition to the answers to these technical questions, the cost effectiveness of the solution will need to be considered.

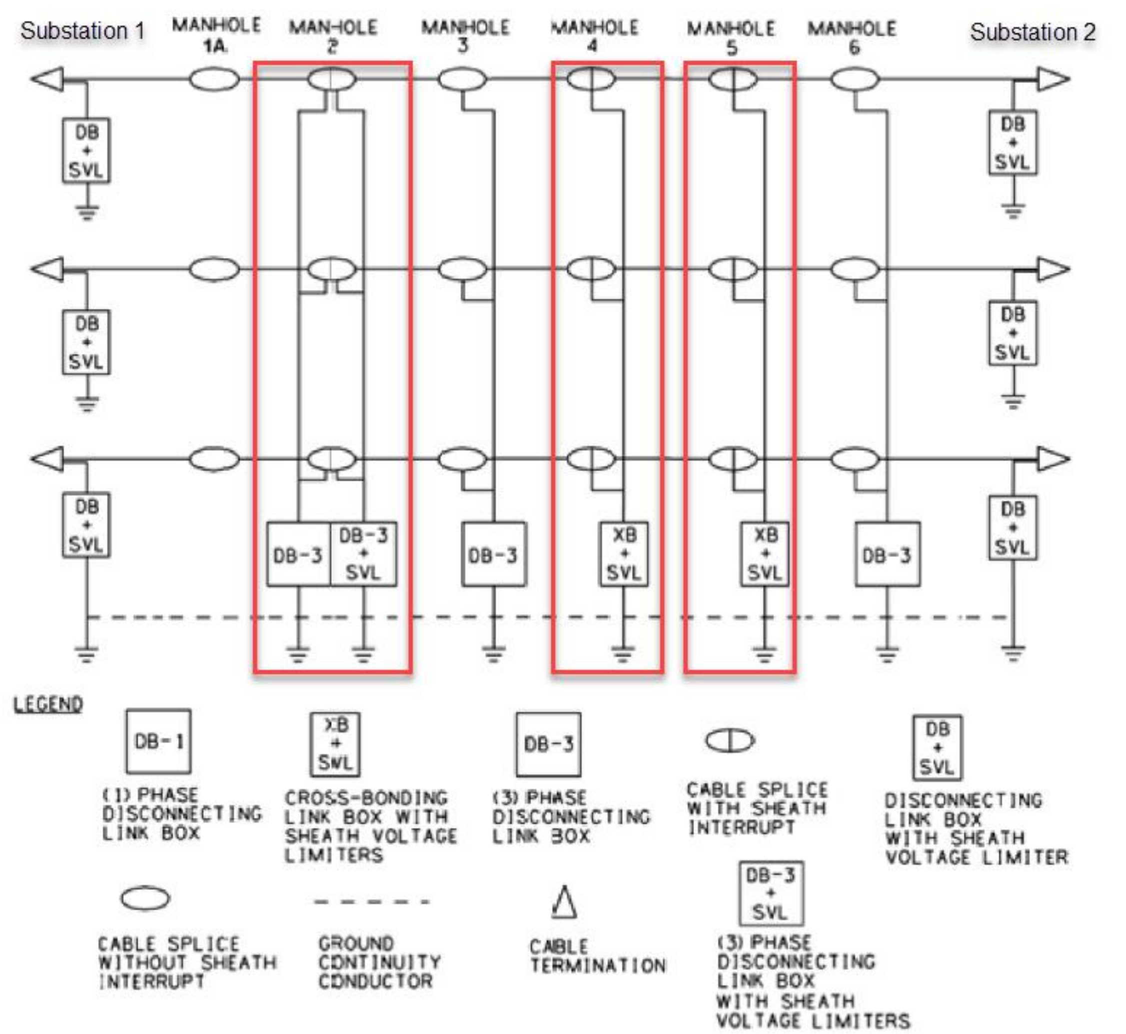


Figure 11: Sheath interruptions at manhole 2, 4 and 5 for Circuit#1.

DTS Fiber Documentation

Installation documentation is crucial information to collect and maintain with transmission power cables. Once a power cable is installed in the ground, it becomes very difficult to investigate whether or not the cable was installed according to the engineering design package. Verification on the location of any DTS fiber is crucial to constructing accurate thermal zones for the power cable. Depending on the length of the power cable, any fiber maintenance loops that are installed can have ripple effects on configured zone distances at the DTS analyser if they are not documented. For any new power cable installed with DTS fiber, in addition to the normal documentation for the power cable, special documentation and measurements of the install details of the DTS fiber should be collected. This will help with configuration of the DTS system, reducing unknowns and estimations for specific zone lengths.

Laboratory Testing

For historical pilot installations of monitoring devices, most of the time spent by the monitoring vendor and AEP personnel is on configuring the communication protocols of the devices at the substation. Project in service dates may be put in jeopardy if there are significant delays in commissioning of the equipment. If some preliminary testing were to be conducted in a laboratory type environment, many of the communication issues could be resolved prior to the actual installation and commissioning of monitoring equipment. Beginning in 2017, AEP began testing all new monitoring devices in their onsite lab environment. This testing of equipment allows for communication and network settings, alarms and the hardware itself to be tested in an environment that would mimic a standard AEP control house. This testing also allows for AEP engineers to become familiar with vendor software visualization packages. For both DTS vendors, the equipment was successfully tested in the AEP laboratory environment. If either system had not passed this testing, it would not have been deployed in the field. In this way, equipment is screened near the beginning of the project before reaching the final stages of a project where questions and issues could delay the overall project schedule.

V. Next Steps and Future Improvements

AEP will continue to analyse the data being collected by the cable PD and DTS monitoring systems. This data will be sent to the Asset Health Center for analysis by the asset performance algorithms. Modifications to these algorithms or creation of sub algorithms may be necessary to accommodate all possible data from the monitoring systems that have been deployed thus far.

There are two additional installations of DTS monitoring planned for 2020, using the same two DTS monitor vendors. During and after those installations are completed, AEP will evaluate the two DTS vendors, with the goal of creating a cost effective standardized package of monitoring equipment that can be installed on new power cables, when they are first installed as well as possibly retrofitting this equipment to existing critical power cables. It will then be determined how this standardized package of monitoring devices could be deployed to minimize risk to AEP's power cable assets across the AEP footprint.

One question that has come from the installations of DTS monitoring is whether or not DTS can be used on other transmission assets. For instance, if fiber could be wound inside a transformer, a very comprehensive temperature profile could be created for that transformer showing hotspots. New use cases for DTS on additional AEP substation and lines asset types to collect condition parameters is currently being explored.

For the cable PD monitoring systems, there will be continued evaluation of possible options on how to add PD sensors to the manholes where there are sheath interruptions. Possible options include power harvesting devices and utilizing wireless communication technologies to send data back to the centralized server. These will need to be evaluated and further installations may be planned.

VI. Conclusion

Over the past several years, AEP has deployed multiple installations of partial discharge and distributed temperature sensing monitoring devices on its underground transmission power cables. These systems are collecting real time data and sending it for engineering analysis to AEP's Station PI system. This condition information is useful for preventing asset failures, optimizing maintenance expenditures and assisting in asset renewal decisions. While an asset failure was not prevented in 2018, these initial pilot installations have provided many lessons learned which AEP will continue to improve upon. Future activities include additional DTS installations and a possible standardized monitoring package that can be deployed for new and retrofit applications. Additional analysis of new partial discharge sensors as well as new use cases for DTS fiber applications are planned. All of these efforts are driven by AEP's desire to redefine the future of energy, developing innovative solutions that power communities and improve lives.

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