Advanced Diagnostic Testing of Medium Voltage Utility Cable Systems

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SUMMARY

Traditionally, utilities have resorted to the run-to-failure mechanism towards maintaining their medium voltage (MV) cable infrastructure. However, the MV XLPE insulated cables installed in the 1970s and ’80s have exhibited much shorter in-service lifetimes than expected upon commissioning. Therefore, utilities are primarily looking to cable testing as a useful strategy to augment the remaining life of their in-service cables and improve upon the reliability of electric power delivery. In this background, this paper outlines some of the recommended advanced cable diagnostic tests, such as VLF Tan-Delta, Partial Discharge (PD) measurement, and Time Domain Reflectometry (TDR), that can detect several common failure mechanisms that occur in service-aged utility cable systems. The initiative also covers the application of some less explored techniques such as the Frequency Domain Spectroscopy (FDS) for MV XLPE cable condition assessment, based on the experience of the authors.

This paper presents a utility case study to demonstrate the application of cable testing to a proactive utility cable management program. It involves condition assessment and technical recommendations based on testing a select distribution of 27 kV single-phase MV XLPE type cables. The case study illustrates the different cost-effective remediations available to poor-performing cables, as an alternative to complete cable replacement which is highly cost-prohibitive in nature. The study will also involve a sensitivity analysis in terms of the costs associated with the two cable maintenance strategies (periodic cable testing and run-to-failure) and discuss the impact on the resulting system reliability, measured through the system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) indices.

KEYWORDS

XLPE cables, cable testing, partial discharge (PD), VLF Tan-Delta, Time Domain Reflectometry (TDR), Frequency Domain Spectroscopy (FDS), condition assessment.

INTRODUCTION

There are two major insulation types used in MV underground cables: (i) oil-filled (PILC - paper insulated, lead covered), and (ii) extruded dielectric (HMWPE - high molecular weight polyethylene, XLPE – cross-linked polyethylene, TRXLPE - tree-retardant XLPE, and EPR - ethylene propylene rubber). Extruded dielectric MV cables have been adopted in North America since the late 1960s [1]. In Canada, XLPE has been the ultimate choice of insulation in MV underground cables [2]. Repairs on older PILC cables are no longer viable, and such cables are slowly replaced with jacketed TRXLPE, especially in urban areas [3]. A majority of the existing MV cable infrastructure in Canada is a combination of the XLPE and TRXLPE types.

A traditional approach to managing utility cable systems was to operate them until failures were observed in the field. However, since the 1970s, utilities have been constantly faced with the ever-increasing pressure of escalated cable failure rates and the limited budget surrounding complete cable replacement. In this background, cable testing provides the means to carry out a thorough evaluation of each cable span and consolidate the results of the various diagnostic field-testing approaches, towards recommending a cost-effective intervention strategy with the corresponding timeline. This paper outlines an effective approach to the management of in-service utility cables, based on advanced field-testing methods. It also demonstrates the value proposition associated with cable testing, as observed with a utility through a two-year cable testing program.

MV CABLE HISTORY AND PERFORMANCE

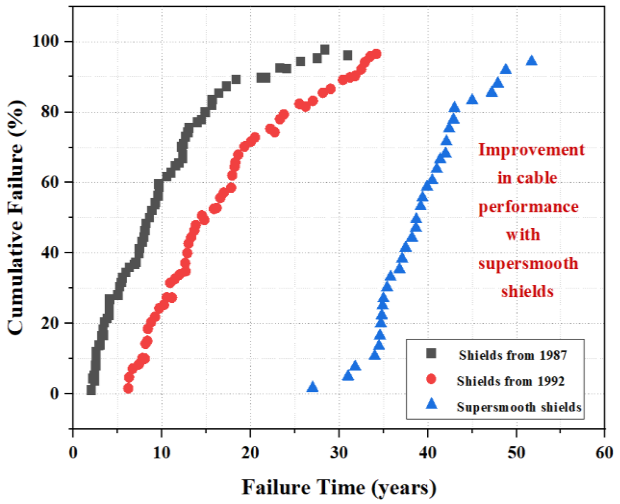
The earliest MV cables introduced in North America were of the PILC type. Over time, high failure rates and costs coupled with the complexity of handling lead and oil resulted in the use of polymers (HMWPE and XLPE) as a better alternative in the cable insulation manufacturing process [4]. However, the initial low failure rate of these polymers increased due to the phenomenon of water treeing in such PE-based insulated cables. In this regard, the most significant advancement in XLPE compounds was the introduction of TRXLPE to limit the growth of water trees in the cable insulation system [1]. The developments in North American MV cable designs are outlined in Table 1.

After the introduction of TRXLPE cables, in the mid-1980s, the industry's focus shifted to the topics of ionic cleanliness and smoothness of the cable semicon layer [1]. This led to the development of supersmooth shields made up of acetylene carbon black-based semicon compounds [1].

Table 1: Developments in North American MV Cable Designs (excludes wall thickness) [5].

Generation	Insulation	Semicon	Jacket	Barrier
1	HWMPE	C Tape	None	None
2		ThermoP		
3	XLPE or EPR	C Tape		
4		ThermoP		
5		ThermoS		
6			Jacket	
7	TRXLPE or EPR			
8				Part WB
9				Full WB

Figure 1 shows the overall improvement in XLPE cable performance due to improvements in cleanliness and smoothness of the conductor shield, as reported in [6]. In Canada, the most frequent enhancement is the use of a water blocking conductor followed by a supersmooth conductor shield [3]. Water blocking of conductors is an important step in the cable manufacturing process. This is achieved by applying a yarn in the center of the conductor and water-swellable tapes over each layer of the wire.



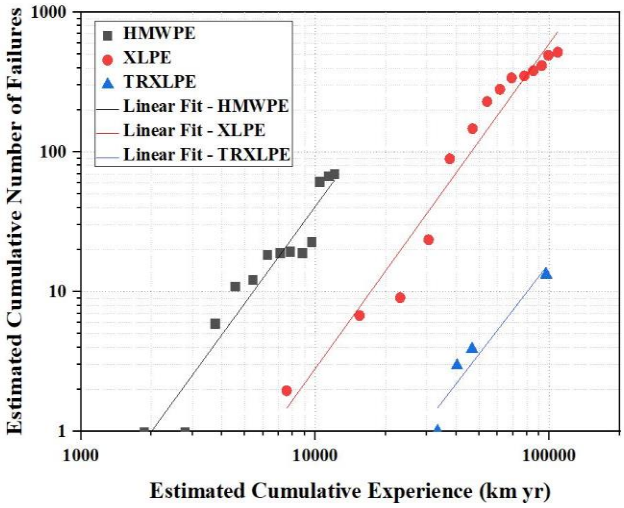


Figure 1: Aging characteristic of XLPE cables with different conductor shields.

Figure 2: Comparison of the performance of MV cables across three generations.

Figure 2 compares the performance of MV cables across three generations. The corresponding failure data is based on the analysis performed by a major North American utility on its in-house MV cables installed in the 1970s and early 1980s [7]. The plot shows the relationship between the estimated cumulative number of failures and the cumulative experience (cumulative product of the number of cables installed in a year and the corresponding number of years in service). From Figure 2, it can be observed that the performance of the MV cables improved drastically from HMWPE to the TRXLPE type, considering the increase in cumulative experience for any given cumulative number of failures.

ADVANCED FIELD TESTING OF MV CABLES

All cable systems do not age uniformly, and hence there is a need for proper diagnostic testing to establish their actual condition. There are two cable testing methods available: (i) online (which requires no power outage), and (ii) offline (which requires an outage and has a comprehensive range of advanced diagnostic tests), to meet a particular utility's requirement. The following diagnostic tests are recommended by the authors to evaluate MV cables, based on best industry practices:

A. VLF Tan-Delta Testing

VLF Tan-Delta is a popular offline diagnostic test that is used to estimate the amount of loss in a cable system. Tan-Delta (tan δ) is a parameter that provides the extent of real power dissipation (or loss) in a cable and is determined based on the phase difference between the applied AC test voltage and the resulting current produced. To utilize the increased sensitivity of the tan δ value at a lower frequency, the test is performed at 0.1 Hz and at voltage levels of 0.5 U_0, 1 U_0, and 1.5 U_0, where U_0 is the rated phase-to-ground voltage. IEEE Std. 400.2 is the industry guide for testing shielded power cables at lower frequencies (< 1 Hz), which applies to VLF Tan-Delta testing.

According to IEEE Std. 400.2, there are three parameters evaluated from this test: (i) Tan δ stability (standard deviation) at U_0, (ii) Mean tan δ at U_0, and (iii) Differential tan δ (between 0.5 U_0 and 1.5 U_0) [8]. These measured parameters are primarily influenced by the overall cable condition (based on the extent of aging, contamination, and moisture ingress) and are highlighted in Figure 3.

VLF Tan-Delta is a well-established procedure to identify the extent of aging in service-aged cables, before severe water and electrical treeing can develop. It is also useful to interpret the VLF Tan-Delta test results and analyze the cable system to explore the possibility of a cable rejuvenation or injection intervention strategy (if applicable) for extending the in-service life of the tested cables and providing alternatives to entire cable replacement.

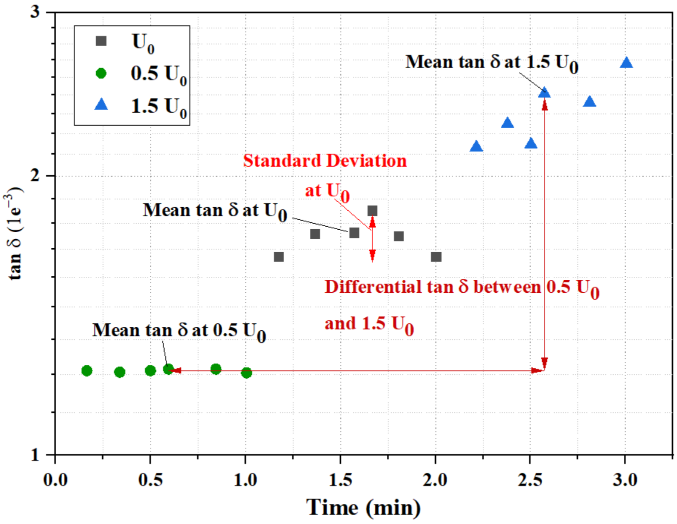


Figure 3: Parameters considered for MV cable condition assessment based on VLF Tan-Delta testing.

B. Partial Discharge (PD) Testing

A PD is developed due to the localized breakdown of a defect site within a cable system when subjected to high electrical stress. A PD test can be performed (either online or offline) to identify such issues within the cable insulation or at the termination. IEEE Std. 400.3 is the industry guide for the PD testing of shielded power cables in the field. The offline PD testing (most sensitive type) can be performed at the power frequency or 0.1 Hz, using a PD sensor such as a capacitive divider. It is often convenient to perform a combined VLF Tan-Delta and PD procedure at 0.1 Hz during maintenance testing, as both tests utilize the same portable VLF power supply.

The interpretation of the PD results requires sufficient expertise and knowledge of the test conditions and the cable under the test. Due to the sophistication of this test and the high degree of variability, there is no industry guidance on condition assessment based on PD testing currently. The IEEE Std. 400.3 is under revision to provide some direction in this respect. The recommended approach to PD testing and subsequent condition assessment involves analyzing the following information captured in the field: (i) PD magnitude (pC) at U_0 and 1.5 U_0, (ii) PD inception and extinction voltages (if PD is present), (iii) Number of PD pulses per unit time and the overall frequency content, (iv) Phase Resolved Partial Discharge (PRPD) pattern, and (v) Location of the PD (if present).

PRPD pattern is a plot that shows the intensity of the PD signal against the corresponding phase angle of the applied test voltage. PRPD patterns can be used to identify PD defects such as voids, surface discharge, and corona by comparing the unique signatures against background noise. In addition, the PD can be localized to either the cable or the termination through an online PD assessment using an ultrasonic microphone. Figure 4 shows an example of PD observed in the termination of a 27 kV rated cable, against a high background noise of 80 pC observed in the field. On the other hand, if a PD is localized to the cable through offline testing, an online PD monitoring system can also be established using high frequency current transformer (HFCT) sensors, to closely monitor the high-frequency current pulses produced by the cable discharges.

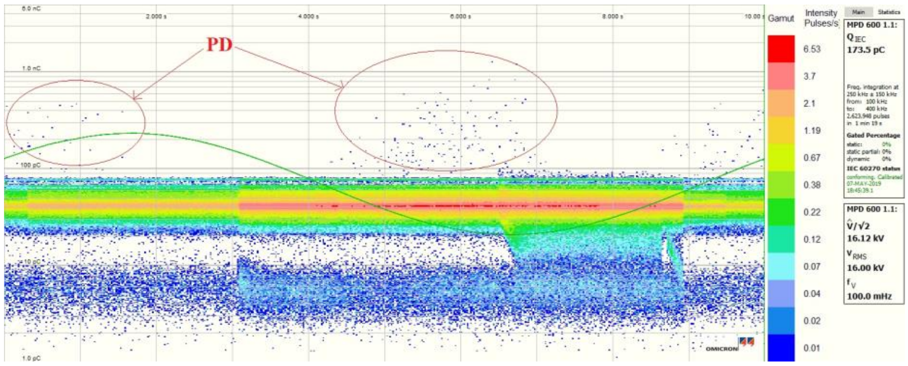


Figure 4: PRPD pattern indicating PD at the terminations of a 27 kV rated cable, tested at U_0 and 0.1 Hz.

C. Time Domain Reflectometry (TDR)

TDR is an offline diagnostic test procedure that can locate an inherent change in the cable system impedance due to issues such as corroded neutrals, shorts, or water ingress. It works by injecting a pulse with a fast rise time into the cable and observing the nature of any reflected pulses, due to an impedance discontinuity. TDR can also identify the overall cable length, location of splices, faults (shorts), bad connectors (due to high resistance), and any open connections in the cable system [9].

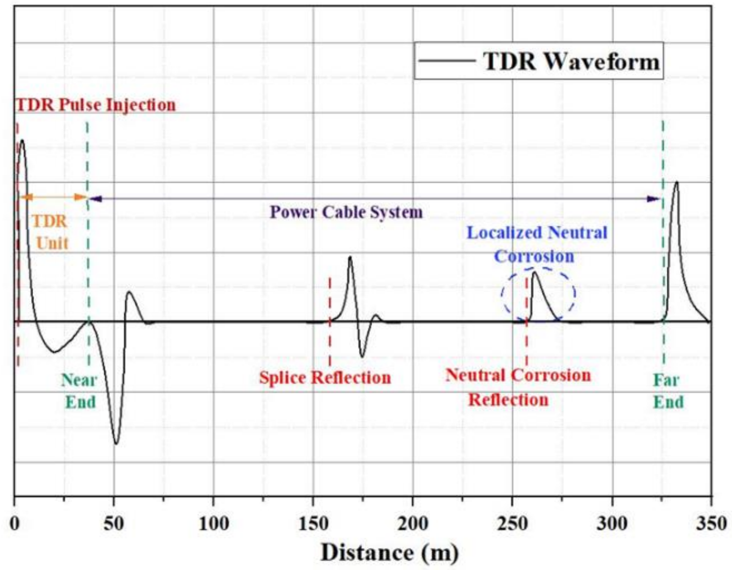


Figure 5: Identification of localized neutral corrosion based on a TDR waveform.

IEEE Std. 1617 and the NEETRAC CDFI – Chapter 5 are reliable practical guides for the TDR testing of cables. The interpretation of TDR waveforms also requires sufficient expertise and involves analyzing subtle variations in any reflections observed. This can further be used to develop the recommended cable replacement timelines, specific to the localized neutral corrosion issue.

D. Frequency Domain Spectroscopy (FDS)

FDS involves the discrete measurement of the dissipation factor and capacitance over a wide frequency range (from 1 mHz to 1 kHz) in an offline environment. Compared to the VLF Tan-Delta testing, a wide frequency sweep gives additional information that helps separate the different types of aging effects and also highlights the influence of accessories, as illustrated in Figure 6.

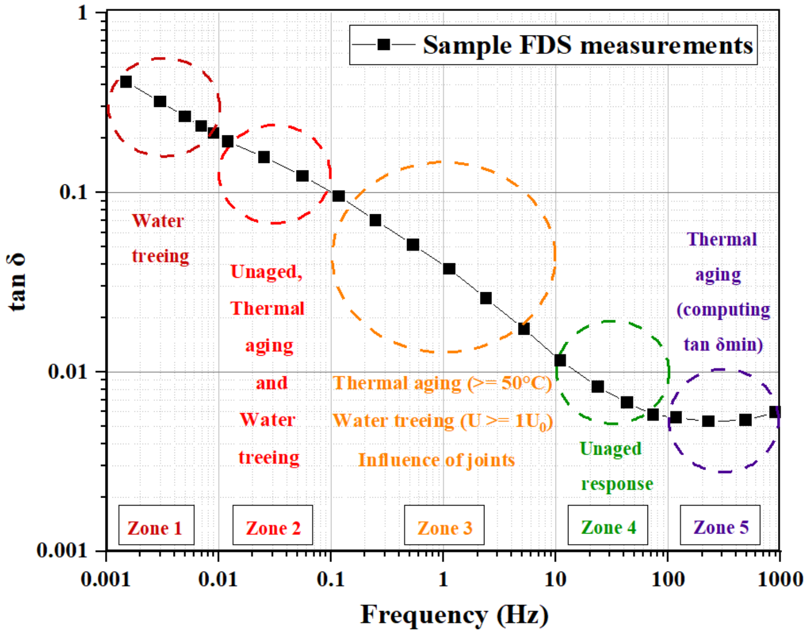


Figure 6: Separation of aging effects in MV XLPE cables through FDS.

More recently, the authors have established that dielectric response measurements can be analyzed to identify various failure modes in MV XLPE cables that affect the bulk of insulation such as moisture ingress, water treeing, and thermal aging, but cannot be used to locate the defects themselves [10]. FDS has also been extensively used to estimate the extent of aging in PILC cables, as outlined in [11]. However, the test voltage and applicable frequency range can be limited for longer cables due to higher capacitance and charging current requirements.

CASE STUDY

This case study demonstrates the application of cable testing to a proactive utility cable management program over two years. The authors were involved in condition assessment and providing technical recommendations based on testing approximately 5 km of a select distribution of 27 kV single-phase MV XLPE type cables, out of 333 km of underground cable infrastructure. The majority of the cables tested were located in residential divisions with a loop configuration.

An offline cable testing program was developed based on the cable type, cable circuit configuration, and outage restrictions provided. Based on the historical failure records, it was decided to perform VLF Tan-Delta, PD, and TDR testing. The cables were then categorized based on their condition using the results from cable testing. Subsequently, various intervention strategies were recommended, as shown in Figure 7.

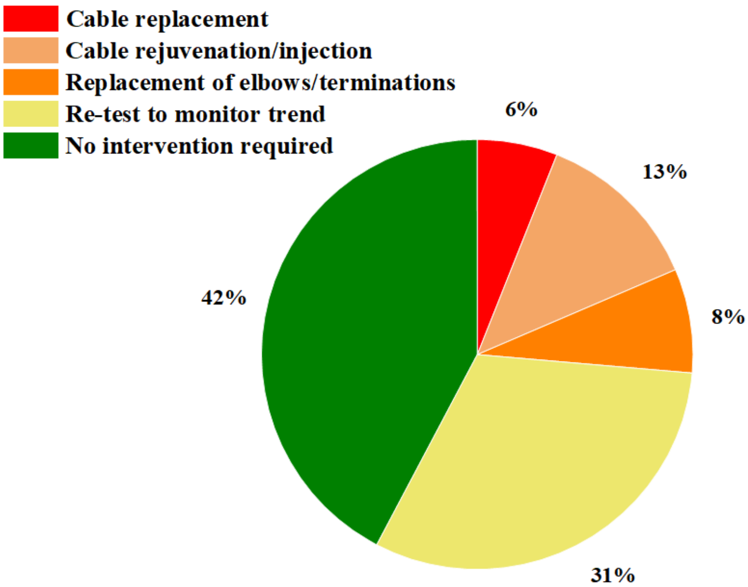


Figure 7: Summary of the recommended intervention strategies following cable testing.

Through advanced field testing and subsequent condition assessment, more cost-effective solutions than cable replacement were recommended such as cable rejuvenation/injection and replacement of elbows/terminations alone. The cable system was properly analyzed before proposing a solution such as injection since this remediation might not be applicable across all cable systems. Any cables with moderate signs of aging were also identified and recommended for re-testing in a three-to-five-year window, depending on the severity of the issues observed.

Figure 8 (a) shows the significant financial savings that could be realized by the utility by adopting the recommended intervention strategies, based on 5 km of the tested population. With the run-to-failure approach, the utility would save on any immediate expenditure but would have to make a significant investment in a couple of years to replace all the failed cables together. The overall reliability of the system will also get affected, coupled with the loss of power through critical feeders. Periodic cable testing, on the other hand, identifies only the essential cable circuits that need to be completely replaced and offers much more cost-effective solutions towards managing the rest of the deteriorating cables. This helps maintain the continued reliability of the cable system and optimize resource and cost allocation for implementing the required intervention promptly.

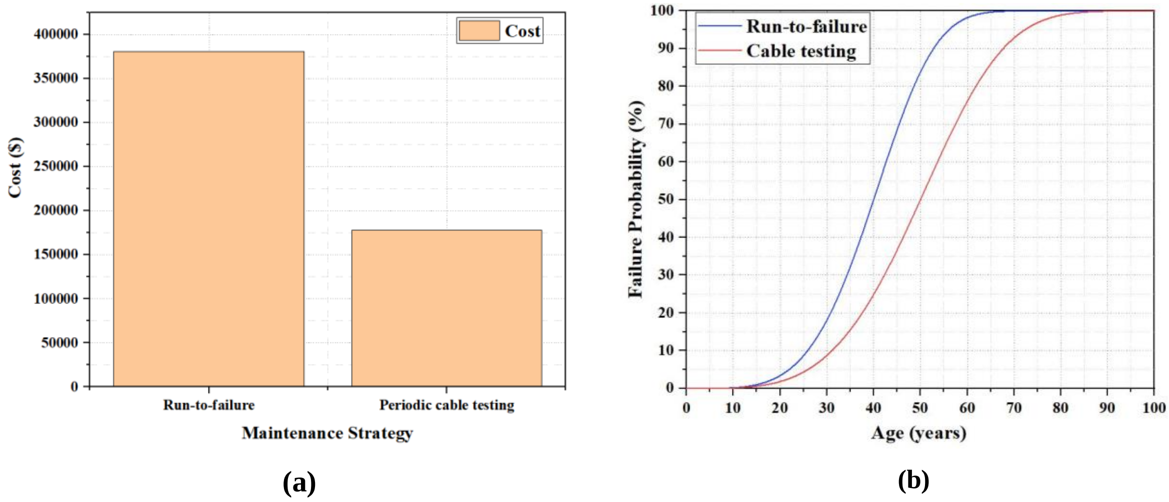


Figure 8: (a) Cost comparison between the two cable maintenance strategies, for 5 km of the tested cable population, (b) Comparison of the failure curves between the two cable maintenance strategies.

Periodic cable testing could modify the typical cable failure curve and reduce the failure probability in service-aged cables (excess of 20 years) due to an improvement in the expected median in-service life through the implementation of timely intervention strategies, as shown in Figure 8 (b). The reliability of the power delivery infrastructure is based on the indices SAIDI and SAIFI. Considering 5 km of the tested population, the annual SAIDI and SAIFI values provided by the utility related to outages caused by defective cables were found to be reduced by 0.5% due to periodic cable testing and implementing the subsequent technical recommendations. Extending the cable testing and management program to a bigger cable population (up to at least 100 km) would have a significant effect in improving the overall system reliability, by further reducing the SAIDI and SAIFI indices as shown in Table 2.

Table 2: Summary of reliability improvements based on the extent of cable testing.

Annual SAIDI (Run-to-failure) = 1.276		Annual SAIFI (Run-to-failure) = 0.549	
Cable Length Tested (km)	**Annual SAIDI (with cable testing)**	**Annual SAIFI (with cable testing)**	**Reliability improvement with cable testing**
5	1.269	0.546	0.5%
10	1.263	0.543	1.0%
50	1.211	0.521	5.1%
100	1.146	0.493	10.2%

CONCLUSIONS

Cables are critical assets, with the replacement of direct-buried cables being highly cost-prohibitive. Cable accessories (mainly elbows/terminations), affected by poor workmanship, are another weak link in utility cable systems. Thereby, an online PD test can be performed using an ultrasonic microphone to localize any PD activity to the cable accessories (if observed). Advanced cable diagnostic testing can identify several common degradation mechanisms in extruded cables, as shown in Table 3.

Table 3: Diagnostic tests applicable to detect the major degradation mechanisms in extruded cables.

Degradation Mechanism	Applicable Diagnostic Test(s)
Dry Electrical	VLF Tan-Delta, PD and FDS
Water Treeing and Chemical	VLF Tan-Delta and FDS
Neutral Corrosion	TDR
Thermal	FDS and PD

With an increasing number of in-service cable systems approaching their end-of-life, utilities have realized that the reactive cable replacement approach is no longer sustainable, as it depletes a sizeable portion of their operations and maintenance budget. The complete replacement of long cable spans would cost billions of dollars and drastically increase the need for manufacturing facilities for cables and accessories. Such significant investments are not feasible for utilities and cable/cable accessory manufacturers. It is therefore important that utilities take a proactive approach towards maintaining their in-house cable infrastructure through periodic cable testing and implementation of the recommended intervention strategies.

Cable testing helps utilities adopt a levelized spending pattern towards managing their cable systems, which fits better into their budget. In North America, defective equipment remains to be a primary cause for affecting system reliability. Therefore, by prolonging the expected useful life of critical feeders through timely intervention strategies (facilitated by cable testing), unexpected in-service failures can be prevented, resulting in much-improved system-wide reliability. It is important to provide condition assessment and recommendations for MV utility cables through testing on a case-by-case basis, with the corresponding timelines for implementation. Also, regional MV cable performance or failure modes must be considered in deciding the most applicable diagnostic tests. This allows establishing the best practices unique to each utility in its operating environment.

Each utility needs to develop its own cable maintenance and testing standard based on the power system topology, cable construction, geographic location, loading history, failure history, operation, and maintenance practices. All these factors shall also be considered for the economic justification of individual utility cable management programs. It is important to implement proactive cable management initiatives by training in-house utility personnel or by engaging third-party experts for cable testing. Cable testing should be incorporated into priority feeder proactive maintenance programs for predictive diagnosis and also be applied to cable systems prior to return to service, to validate workmanship efforts and confirm that all potential issues have been addressed.

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