Frequency Domain Reflectometry NDE for Aging Cables in Nuclear Power Plants

S.W. Glass[a)], A.M. Jones, L.S. Fifield, and T.S. Hartman

Pacific Northwest National Laboratory, P.O. Box 999, Richland, Washington 99352

[a)]Corresponding author: Bill.Glass@pnnl.gov

Abstract. Degradation of the cable jacket, electrical insulation, and other cable components of installed cables within nuclear power plants (NPPs) is known to occur as a function of age, temperature, radiation, and other environmental factors. Although system tests verify cable function under normal loads, demonstration of some cable's ability to perform under exceptional loads associated with design-basis events is essential to assuring plant integrity. The cable's ability to perform safely over the initial 40-year planned and licensed life has generally been demonstrated and there have been very few age-related cable failures. With greater than 1000 km of power, control, instrumentation, and other cables typically found in an NPP, replacing all the cables would be a severe cost burden. Justification for life extension to 60 and 80 years requires a cable aging management program that includes condition monitoring to justify cable performance under normal operation as well as accident conditions. A variety of tests are available to assess various aspects of electrical and mechanical cable performance, but none are suitable for all cable configurations nor does any single test confirm all features of interest. One particularly promising test that is beginning to be used more and more by utilities is frequency domain reflectometry (FDR). FDR is a nondestructive electrical inspection technique used to detect and localize faults in power and communication system conductors along the length of a cable from a single connection point. FDR detects discontinuities in the electrical impedance that arise due to cable splices or similar changes along the path of the conductor pair. In addition, FDR has the potential to provide sensitivity to insulation degradation by detecting small changes in impedance between the cable conductors being examined. The technique is also sensitive to cable bends, the particular lay of the cable in tray, proximity to other cable, and other factors that bear consideration when interpreting the test results. This paper examines various influences on the FDR approach and compares results of three different instruments to assess accelerated aging damage among several NPP representative cables.

INTRODUCTION AND BACKGROUND

As nuclear power plants (NPPs) consider applying for license renewal to extend their operating period from 60 years to 80 years, it is important to understand how the materials installed in plant systems and components age during that time and develop aging management programs (AMPs) to assure continued safe operation under normal and design basis events (DBEs).

Degradation of the cable jacket, electrical insulation, and other cable components of installed cables within NPPs is known to occur as a function of age, temperature, radiation, and other environmental factors. Although system tests verify cable function under normal loads, concern remains over cable performance under exceptional loads associated with DBEs. The cable's ability to perform safely over the initial 40-year planned and licensed life has generally been demonstrated and there have been very few age-related cable failures [1,2]. With more than 1000 km of power, control, instrumentation, and other cables typically found in an NPP, replacing all the cables would be a severe cost burden. License renewal to 60 years and subsequent license renewal to 80 years, therefore, requires a cable AMP in accordance with regulatory guidance [3] to justify cable performance under normal operation as well as accident conditions. Generally the AMP includes implementation of a condition monitoring program consisting of bulk electrical tests and local tests to assess the cable's fitness for service and remaining useful life. Although no single test is suitable as a stand-alone indicator of cable condition, frequency domain reflectometry (FDR) stands out as one of the most promising approaches. FDR is a nondestructive test for the entire cable that provides an indication of the location of

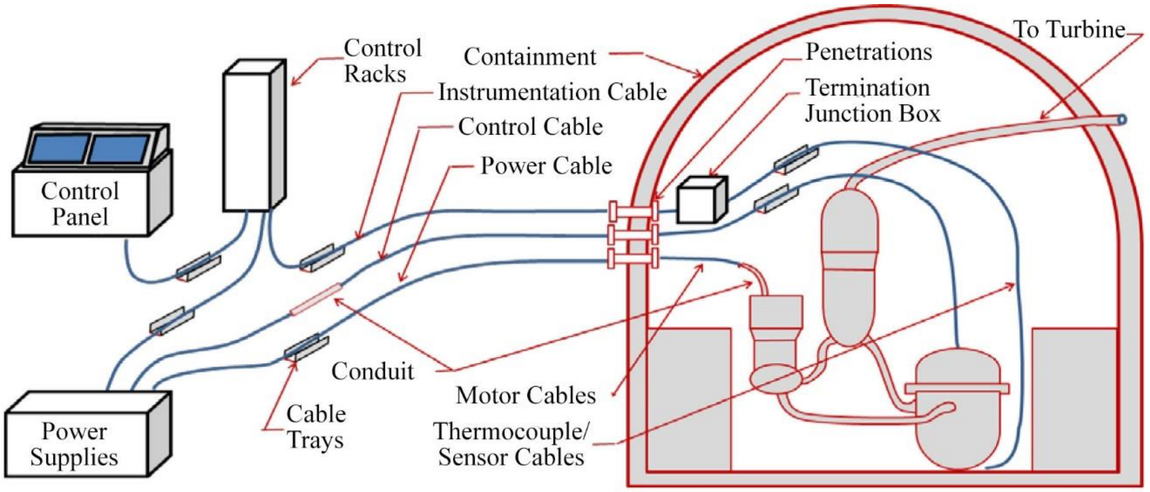

FIGURE 1. Typical cable layout allows access at control racks and termination junction boxes, but much of the cable is protected within cable trays and conduit thereby limiting access for local inspections.

the most severe degradation such that the cable may be subject to further local inspection or a splice-and-repair to remove a damaged segment if warranted. Damage location is particularly important considering the typical power plant configuration shown in Fig. 1. Only the cable ends and a small percentage of cables are accessible for visual inspection or local testing because cables are typically buried in conduit or grouped and piled with other cables within cable trays that may not be aligned with man-accessible walkways.

FREQUENCY DOMAIN REFLECTOMETRY

Frequency domain reflectometry is a nondestructive electrical inspection technique used to detect, localize, and characterize faults in power and communication system conductors along the length of a cable from a single connection point. FDR is based on the interaction of electromagnetic waves with conductors and dielectric materials as they propagate along the cable. The technique uses the principles of transmission-line theory to locate and quantify impedance changes in the cable circuit. These impedance changes can result from connections, faults in the conductors, or degradation in the cable polymer material [4,5]. For the measurement, two conductors in the cable system are treated as transmission lines, which propagate a low-voltage swept-frequency “chirp” waveform generated by a transceiver instrument to interrogate the cable length. As the excitation signal is swept over the frequency range and the associated electromagnetic wave travels down the cable, the impedance response is recorded at each frequency to characterize the wave interaction with the conductors and surrounding dielectric materials. Figure 2(a) shows the electric and magnetic vector field components for a propagating sinusoidal transverse electromagnetic (TEM) wave. For TEM waves traveling on a transmission line, the electric and magnetic fields are orthogonal to each other as well as the direction of propagation. Figure 2(b) shows cross-sectional views of the electric and magnetic field configurations for TEM waves traveling on coaxial and two-wire transmission lines. The electric fields start and end on current-carrying conductors and are influenced by dielectric materials and other metals. The magnetic fields form closed loops around current-carrying conductors and are influenced by magnetic materials.

Where TEM wave propagation analysis may be complicated by unknown and changing EM properties of the waveguide, for most practical applications a simplified form of analysis referred to as transmission-line theory is sufficient. In transmission-line theory, the electric fields relate to distributed (per unit length) capacitance and the magnetic fields relate to distributed inductance. The resistance of the metallic conductors and dielectric loss in the insulation attenuate the signal as it propagates along the cable. A schematic representation of the standard transmission line model is shown in Fig. 3 where the distributed circuit elements representing an infinitesimally short length may be cascaded with similar elements to model the overall behavior of the line. In the FDR method, forward and inverse Fourier transforms coupled with the cable velocity factor are used to develop the time and distance domain data which contains information on the wave interactions with the cable’s resistive, inductive, and capacitive material and which identifies the physical location of signal reflections [4,5].

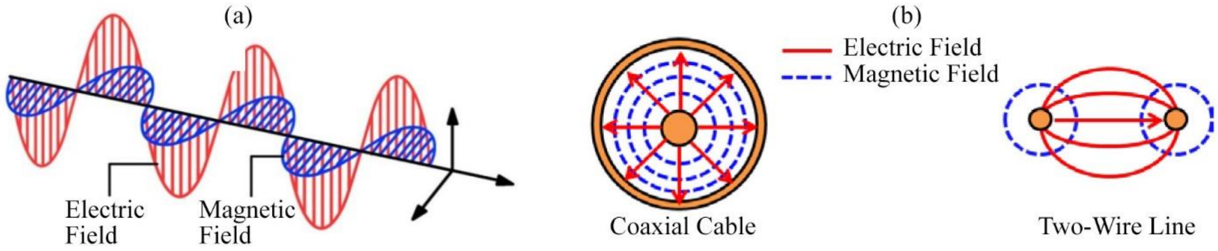

FIGURE 2. (a) Electric and magnetic field configurations for generalized sinusoidal TEM wave propagation; (b) Electric and magnetic field configurations for specific cable types.

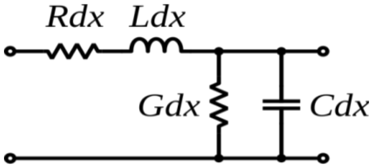

FIGURE 3. Impedance element transmission line circuit model distributed over an infinitesimally short length.

Practical implementation of the FDR method is illustrated in Fig. 4. The instrument is connected to the two conductors or the center conductor and shield of the cable under test. The swept frequency chirp is applied, and the reflected response is monitored as a frequency-domain spectrum, which is transformed into a time-domain or distance response. The remote end of the cable can be terminated in any arbitrary impedance different from the cable characteristic impedance, but is often grounded or open-circuited during the testing. Because the applied signal is low-voltage, the test is nondestructive and poses no special safety concerns to operators, assuming that routine electrical safety procedures are followed. In most cases, it is only necessary to de-energize the cables and de-termination is not required but typically one end of the cabling is de-terminated to connect the FDR system. This can reduce the required testing time and minimize the risk of improper re-termination. Frequently, cable systems are de-terminated anyway to minimize the risk of residual charge shock.

FDR has advantages that can yield better sensitivity to cable insulation degradations than time-domain reflectometry (TDR), which is best-suited for identifying open and short circuit conditions in the conductors [6]. For example, FDR is less susceptible to electrical noise and interference due to the availability of filtering and noise lowering algorithms in the frequency domain [7]. This can lead to increased sensitivity and accuracy. Additionally, FDR is better-suited for identifying and characterizing a series of multiple degradations for long cables because TDR pulses may have difficulty continuing in the forward direction after two to three significant reflections.

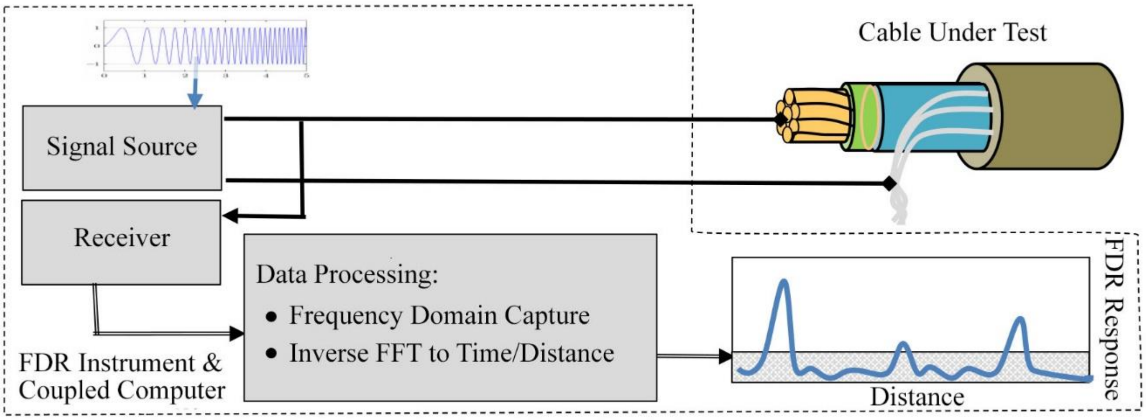

FIGURE 4. FDR instrument block diagram for test implementation.

INTRINSIC CABLE FACTORS AFFECTING FDR RESPONSE

Previous FDR measurement reports have demonstrated sensitivity to changes in cable routing such as reversals in direction [8]. A series of FDR measurements for a RG-174 coax cable subjected to various 180° bend radii indicated that a cable bend with a radius of curvature at least 10 times the cable diameter can prevent an increased FDR reflection at the bend location (Table 1). This result is consistent with general guidance provided for the use of commercially available systems.

TABLE 1. Influence of Cable Bend Radius on RG-174 Co-Axial Cable FDR Signal Response

Cable Type	Cable Length (ft.)	Cable Diameter (in.)	Bend Radius (in.)	Bend Radius: Cable Diameter Ratio	Amplitude at Bend (dB)	Bend Location (ft.)
RG-174	100	0.1	10	100	2.5	50
RG-174	100	0.1	8	80	2.5	50
RG-174	100	0.1	5	50	2.5	50
RG-174	100	0.1	2	20	2.5	50
RG-174	100	0.1	1	10	2.5	50
RG-174	100	0.1	0.5	5	5	50
RG-174	100	0.1	0.25	2.5	6	50
RG-174	100	0.1	0.125	1.25	6	50

The removal of conductor insulation can produce capacitive changes large enough to be detected when the measurement is performed for conductor pairs on which the insulation was removed [8]. However, degradations that are confined to the cable jacket material may not produce capacitive changes significant enough to be confidently identified. Cable construction, such as the presence of cable shielding, can also impact the ability to obtain consistent results using FDR. Measurements for an unshielded three-conductor cable with a mechanical defect (short section of insulation removed) demonstrated that the absence of shielding can allow the local environment to affect the amplitude of the signal reflection associated with the defect location. Different FDR responses were measured with the cable resting on various dielectric materials and metals as shown in Fig. 5. Corresponding measurements for a three-conductor shielded cable with a short section of the shield removed showed no noticeable changes for the different environmental conditions as shown in Fig. 6. Because unshielded cables are susceptible to electromagnetic interference from electrical machines and power lines, electromagnetic environmental factors should be considered when testing unshielded cables.

FDR detects discontinuities in the electrical impedance that arise due to cable splices or similar changes along the path of the conductor pair. The method must be sensitive to small changes in the distributed capacitance between two conductors along the cable in order to detect insulation damage or degradation. Because distributed capacitance and dielectric constant are proportional to each other in transmission line theory, similar changes in these two quantities yield similar results. Example changes that impact the insulation capacitance include exposure to heat, radiation, water damage, corrosion, or mechanical fatigue. A previous report [9] showed that the dielectric properties of EPR insulation specimens changed as a function of aging. Changes in polymer dielectric properties with age can contribute to measureable changes from an FDR measurement.

FDR FREQUENCY RESOLUTION AND BANDWIDTH

The spatial resolution is an important parameter for detection and localization of cable defects. The range resolution is a function of the swept-frequency bandwidth (BW), the speed of light (c), and the velocity factor (VF) of the cable [5] (Eq. 1):

$$\text{Resolution (m)} = (c*VF) / (2*BW) = 1.5E8*(VF/BW) \qquad (1)$$

where c = 3E8 m/s. The cable's velocity factor describes the wave velocity as a % of the speed of light expressed as a value less than unity and is inversely related to the square root of the dielectric constant of the insulation material. Typical velocity factors for cables found in NPPs range from 0.5 to 0.85 [10].

Another important parameter is the bandwidth of the swept-frequency signal that propagates along the cable. The maximum unambiguous range is also needed to interpret FDR results, and is a function of the resolution and the number of frequencies (NF) used to cover the bandwidth (Eq. 2):

$$\text{Range (m)} = \text{Resolution} * NF \qquad (2)$$

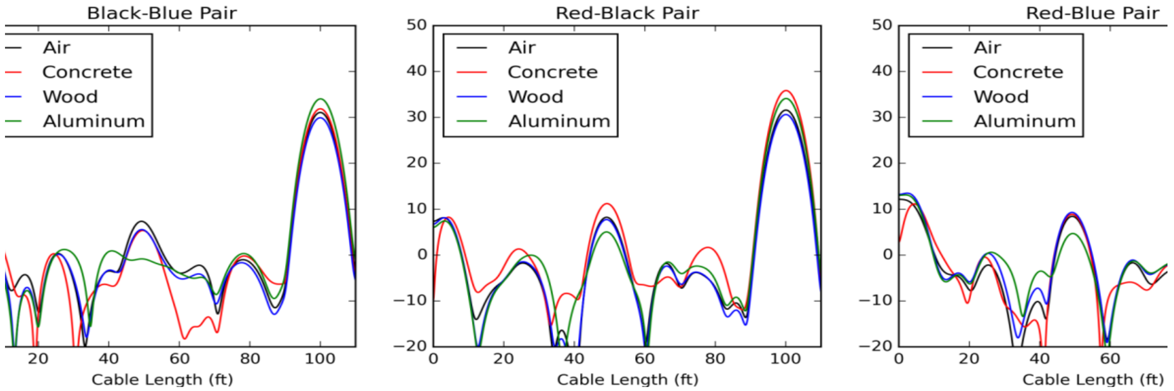

FIGURE 5. Unshielded cable shows differences among air, concrete, wood, and particularly aluminum at the 50 ft. location where both the damaged section is and where the underlying supporting material is.

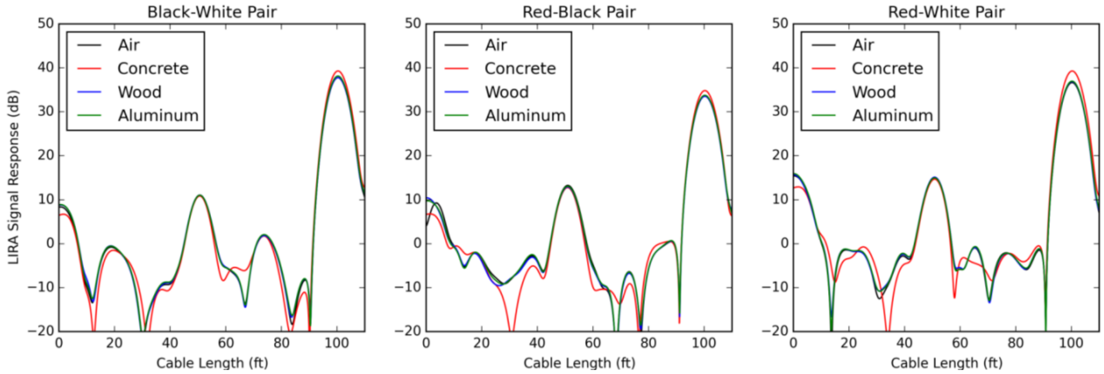

FIGURE 6. Shielded cable has virtually no different response to air, concrete, wood, or aluminum but the damaged area at 50 ft. still shows as a clear peak.

A higher bandwidth waveform allows for increased detection sensitivity, a shorter termination shadow, and improved localization of degradations due to better spatial resolution. However, higher bandwidth signals are more susceptible to signal attenuation along the cable, which can limit the inspection length. If the maximum frequency is too low, the cable length will not be sufficient to be treated as a transmission line and the measurement may not produce meaningful results. Typically, the electrical length of the cable should be at least one wavelength of the signal propagating along the cable in order to apply transmission-line theory. Thus, higher frequencies are required to characterize shorter cables to satisfy the cable length requirement, and lower frequencies are required to characterize longer cables to prevent the insertion loss from overcoming the measurement signal.

To illustrate the effects of swept frequency bandwidth on the FDR signature, a vector network analyzer (VNA) was used to measure a 200 ft. Okonite-FMR 600 V unshielded multi-conductor power and control cable, which had a 1.5 ft. section thermally aged for 1269 hours at 140°C. Figure 7 shows a photograph of the thermally aged cable section and the FDR responses for each of the conductor pairs using bandwidths of 100 MHz and 200 MHz. The higher bandwidth sweep provides a clearer indication of the local degradation present at 100 ft.

FDR COMPARISON TESTING

Two commercially developed FDR systems specifically adapted for cable condition monitoring measurements and a general-purpose VNA were used to measure 18 low-voltage cables having various thermally induced, radiation-induced, or mechanical damaged sections. The most significant specifications and test configurations for the three instruments are outlined below:

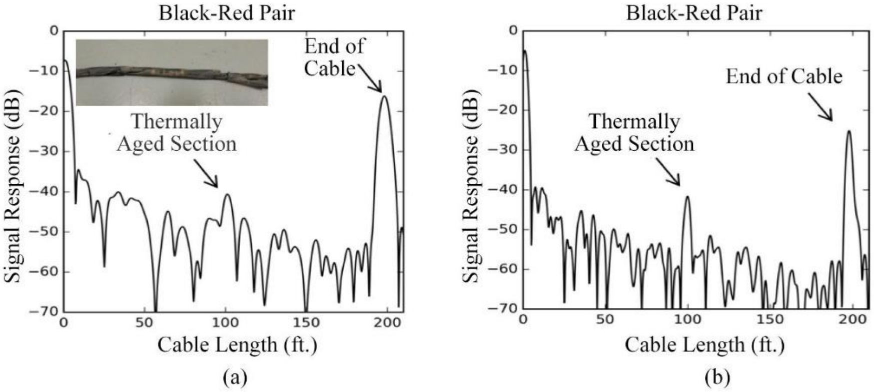

FIGURE 7. (a) 100 MHz FDR response acquired with VNA; (b) 200 MHz FDR response acquired with VNA.

- A Keysight Technologies E5061B VNA [11], with options for 5 Hz–3 GHz frequency range, high stability time base, and time-domain analysis, was connected to each test cable with BNC-to-alligator clip connectors. A Python script was used to automate the collection of frequency-domain and time-domain data sets using FDR bandwidths of 100, 200, 300, 400, and 500 MHz. The start frequency for each measurement was 5 Hz, and 1,000 frequency points were used to cover each bandwidth.
- A Wirescan LIRA Acquire [12], a second-generation LIRA system made commercially available in 2015, was connected to each test cable with BNC-to-alligator clip connectors. A laptop computer with Version 4.1 R7 of the LIRA software was used to control the hardware. The bandwidth of each measurement was 100 MHz, with a start frequency of 5 kHz and 10,000 frequency points.
- An AMS CHAR system [13], an integrated cable testing system made commercially available in 2012, was connected to each test cable with BNC-to-alligator clip connectors. A laptop computer with the CHAR FDR software was used to control the hardware. The bandwidth of each measurement was 100 MHz, with a start frequency of 100 kHz and 1,000 frequency points. Select cables were also measured using bandwidths of 500 MHz and 5,000 frequency points.

DATA NORMALIZATION

The VNA offered no built-in method to compensate for the roll-off in signal amplitude as a function of distance traveled, thereby allowing a simple threshold for assessing the severity of peaks within the data. Both commercial systems offer analysis aids to simplify data assessment. The LIRA system performs a regression analysis to estimate the nominal cable loss as a function of distance and correct for this in the displayed data. A stochastic noise level is also calculated and used to set a normalization threshold at 0 dB for reflections that are one standard deviation above the average fluctuation in the data. This enables analysts to focus on peaks that rise above the 0 dB threshold, which simplifies cable analysis and determination of cable disposition. The CHAR system normalizes and enhances the base FDR impulse response by integrating over time to obtain the step response. The result of the integral is expressed in terms of the reflection coefficient (ρ) as:

$$\rho = V_{\text{reflected}} / V_{\text{incident}} \tag{3}$$

This yields a display that resembles a TDR response to aid in interpretation by analysts familiar with TDR testing. Both approaches offer a simplified analysis aid that helps interpret the test results.

Direct comparisons were performed among the systems for a common bandwidth setting of 100 MHz by exporting the signature from each system's measurement of a given cable. Follow-up adjustments were necessary to enable direct comparisons among the data. First, the cable attenuation as calculated by LIRA was used to compensate for the cable loss in the VNA and CHAR signatures. This removed the downward slope, with the assumption that the loss is the same because all three systems used the same bandwidth. Then the VNA and CHAR data sets were adjusted so that the reflection amplitude from the far end of the cable was the same for all three systems. This effectively used the dynamic normalization feature in LIRA to set the 0 dB reference location for all three systems. The region below 0 dB was shaded in each signature plot to visually represent the noise threshold. With this procedure, local reflections that appeared above 0 dB were interpreted as significant.

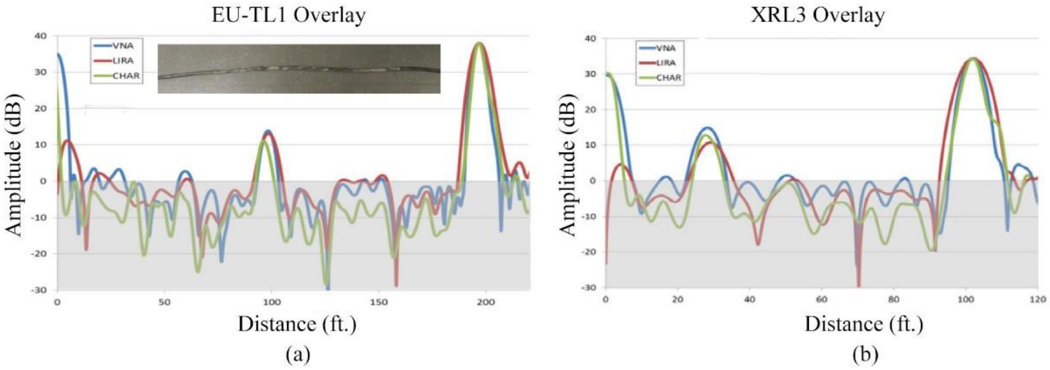

FIGURE 8. (a) Cable EU-TL1 with thermally aged section at 100 ft.; (b) FDR signature plot for cable XRL3 with thermally aged section at 26 ft. using three measurement systems.

TABLE 2. Cables tested during FDR comparison study including fault description, location, and detection results.

ID	#C	Shield	Insulation	Jacket	Length (ft.)	AWG	Fault Type	Fault Length (ft.)	Fault Description	Location (ft.)	Detected @ 100 MHz	Detected > 100 MHz
EU-TL1	3	N	EPR	PVC	196.8	14	Local thermal	1.5	1269 hrs. @ 140°C	95	Y	Y
EU-TL2	3	N	EPR	PVC	100	14	Local thermal	1.5	1281 hrs. @ 140°C	50	N	Y
EU-TG1	3	N	EPR	PVC	100	14	Global thermal	100	1165 hrs. @ 140°C	All	N	N
EU-B	3	N	EPR	PVC	101	14	None	N/A	N/A	N/A	N/A	N/A
ES-TL1	3	Y	EPR	CPE	100	16	Local thermal	50	1281 hrs. @ 140°C	50	N	N
ES-TG1	3	Y	EPR	CPE	100	16	Global thermal	100	1165 hrs. @ 140°C	All	N	N
ES-RL1	3	Y	EPR	CPE	100	16	Local radiation	1	60k Grey	50	N	N
ES-B	3	Y	EPR	CPE	100.8	16	None	N/A	N/A	N/A	N/A	N/A
XS-RL1	2	Y	XLPE	CSPE	101	16	Local radiation	1	60k Grey	50	N	N
XS-B	2	Y	XLPE	CSPE	100.5	16	None	N/A	N/A	N/A	N/A	N/A
EDC3	2	Y	EPR	CSPE	101.6	16	Cut	<1	Part way to cond.	19.7	Y	Y
EIL4	2	Y	EPR	CSPE	100.6	16	Local thermal	3.5	500 hrs. @ 150°C	72.2	Y	Y
EOG3	3	N	EPR	CSPE	92.3	12	Gouge	<1	One conductor	19.7	N	Y
XRL1	3	N	XLPE	CSPE	99.75	12	Local thermal	3.5	1000 hrs. @ 150°C	26.25	Y(2/3)	Y

XRL3	3	N	XLPE	CSPE	101.9	12	Local thermal	3.5	1300 hrs. @ 150°C	26.25	Y	Y
XRL4	3	N	XLPE	CSPE	100.7	12	Local thermal	3.5	1450 hrs. @ 150°C	26.25	Y	Y
XRW1	3	N	XLPE	CSPE	101.5	12	Local thermal	3.5	504 hrs. @ 150°C	29.3	Y	Y
X5G2	3	N	XLPE	CSPE	99.9	12	Gouge	<1	0.02” into insul of 2 wires	19.7	N	Y

RESULTS

Using this approach, signature plots were generated and analyzed for the 18 cables listed in Table 2. Two representative common signature plots for cables designated EU-TL1 and XRL3 are shown in Fig. 8. Although the plots do not exactly overlay, particularly below the 0 dB threshold, good agreement was observed for the detection of both local thermally aged sections. This was typical of all overlay plots. Each system produced a significant reflection at the degraded location for five of the eight cables which had undergone local thermal aging. Good agreement was obtained among all the 100 MHz FDR measurements.

Excluding the un-aged cables from the data, all FDR instruments detected 6 of 12 flawed areas using 100 MHz bandwidth and 10 of 13 using bandwidths higher than 100 MHz. Thermally induced damage was more readily detected than radiation-induced or mechanical damage.

In addition to the detection of local damage, the commercial systems offer indicators of global aging degradation. Three parameters examined for these cables were capacitance and velocity factor emphasized within the CHAR system and Delta-G parameter emphasized within the LIRA system. For one globally thermally aged cable that was aged for an elongation at break of over 50%, AMS has reported a change in the cable velocity of over 13% [14]. This change in velocity factor is directly related to capacitance from circuit theory. The LIRA system offers a parameter called Delta-G that is a function of the measured and calculated dielectric loss at multiple frequencies in the collected bandwidth. A comparison of these global aging parameters for two sets of globally aged cables among our cable set is shown in Table 3. The capacitance and velocity factors remained the same or only changed slightly for the two sets of cable conditions. Moreover, the trend was increasing for the ES cable and decreasing for the EU cable as a function of global aging. Only the Delta G term showed a consistent trend as a function of cable aging and the Delta G relative change was significantly higher than the other metrics of velocity factor and capacitance.

TABLE 3. Selected extracted parameters from commercial FDR systems for globally aged cables.

	LIRA Velocity Factor		LIRA Delta G		Lira Capacitance		AMS Capacitance	
Cable	Value	% Change	Value	% Change	(pF/ft.)	(% Change)	(pF/ft.)	(% Change)
ES-B	0.60		25.5		30.3		30.9	
ES-TG1	0.57	−5	40.3	+58	30.9	+2	33.1	+7
EU-B	0.63		14.9		17.3		18.2	
EU-TG1	0.63	0	17.4	+17	16.3	−6	17.6	−3

SUMMARY AND CONCLUSION

FDR represents a powerful tool for NPP cable condition monitoring programs. Advantages and disadvantages are summarized in Table 4. Comparative FDR spectra measured using three different systems were quite similar, but not identical. Moreover, normalization to aid in data interpretation was managed differently with the two commercial cable test systems. This poses additional uncertainty if instruments are changed when the data is being used to monitor subtle trends.

Approximately 50% of the induced faults in the test-cable set were detected by all systems using a measurement bandwidth of 100 MHz. Detection improved to over 75% for measurement bandwidths above 200 MHz. The FDR tests were more sensitive to local thermal aging than local mechanical damage, local radiation, or global thermal aging.

Several indicators of global cable aging can be obtained from FDR measurements. The LIRA Delta-G parameter, which is based on the cable insulation conductance parameter in transmission-line theory, showed the greatest change for the globally aged samples examined.

TABLE 4. Advantages and Disadvantages of FDR Testing

Advantages	• Inspection of entire cable length from single-ended access • Low voltage safe, non-destructive test • Rapid inspection times (several minutes) • Systems commercially available • Sensitive detection and location of localized degradations • In most cases, there is no need to de-terminate cable ends
Disadvantages	• Global aging indicators still in development for correlation to established methods • Baseline data sets helpful to assess cable condition • Specialized training required for system operation and data analysis • Cannot currently be used on energized cables

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REFERENCES

1. EPRI, *Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis – Update*, TR-3002005321 (Electric Power Research Institute, Palo Alto, CA, 2015).
2. A. Mantey, "Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis—Update," in *IEEE Proceedings of the Power and Energy Society Insulated Conductors Committee*, November 1-4, 2015, Tuscon, AZ.
3. NRC, *Regulatory Guide 1.218, Condition Monitoring Techniques for Electric Cables Used in Nuclear Power Plants* (U.S. Nuclear Regulatory Commission, Washington, DC, 2012).
4. J. Minet, S. Lambot, G. Delaide, J. A. Huisman, H. Vereecken and M. Vanclooster, "A Generalized Frequency Domain Reflectometry Modeling Technique for Soil Electrical Properties Determination," Vadose Zone Journal **9**(4), 1063–1072 (2010).
5. Mohr and Associates, *Application Note: TDR vs. FDR: Distance-to-Fault* (Mohr and Associates, Richland, WA, 2010). Available at http://www.mohr-engineering.com/TDR_vs_FDR_Distance_to_Fault-A.php.
6. K. Murty (Ed.), *Materials Ageing and Degradation in Light Water Reactors*, 1st Ed. (Woodhead Publishing, Cambridge, UK, 2013).
7. IEC/IEEE 62582-2, "Nuclear Power Plants – Instrumentation and Control Important to Safety – Electrical Equipment Condition Monitoring Methods – Part 2: Indenter Modulus" (IEC/IEEE, Geneva, 2011).
8. S. W. Glass, L. S. Fifield, G. Dib, J. R. Tedeschi, A. M. Jones and T. S. Hartman, *State of the Art Assessment of NDE Techniques for Aging Cable Management in Nuclear Power Plants FY2015*, M2LW-15OR0404024, PNNL-24649 (Pacific Northwest National Laboratory, Richland, WA, 2015).
9. P. Ramuhalli, L. S. Fifield, M. S. Prowant, G. Dib, J. R. Tedeschi, J. D. Suter, A. M. Jones, M. S. Good, S. W. Glass and A. F. Pardini, *Assessment of Additional Key Indicators of Aging Cables in Nuclear Power Plants -- Interim Status for FY2015*, PNNL-24309 (Pacific Northwest National Laboratory, Richland, WA, 2015).
10. Megger, *Basic TDR Operation, Application Note 58* (Megger, Dallas, TX). Available at https://portalvhds963slh4m3fqg2.blob.core.windows.net/megger-products/TDR_AN58_EN_V02.pdf.
11. Keysight Technologies, *E5061B ENA Series Network Analyzer* (Keysight Technologies, Inc. Santa Rose, CA, 2016). Accessed July 30, 2016. Available at http://www.keysight.com/en/pdx-x201771-pn-E5061B/ena-series-network-analyzer?cc=US&lc=eng .
12. Wirescan AS, *LIRA Acquire* (Wirescan, Trollasen, Norway, 2016). Accessed June 26, 2016. Available at http://www.wirescan.no/products/lira-acquire/

13. AMS, *Integrated Cable Testing System, CHAR 2012 System* (Analysis & Measurement Services Corporation [AMS], Knoxville, TN, 2012). Accessed August 1, 2016. Available at: http://198.61.192.138/amscorp.info/public_html/wp-content/uploads/2012/04/CHAR-System5.pdf.
14. S. W. Glass, A. M. Jones, L. S. Fifield and T. S. Hartman, *Bulk Electrical Cable Non-Destructive Examination Methods for Nuclear Power Plant Cable Aging Management Programs*, PNNL-25634 (U.S. Department of Energy, Washington, DC, 2016).